UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING AND AUTOMATION

Lauri Karppi

MODERNISATION OF POWER PLANT LIGHTING WITH LED LIGHTING

Master's thesis for the degree of Master of Science in Technology, submitted for inspection in Vaasa 05.04.2013

Supervisor	Kimmo Kauhaniemi
Instructor	Thomas Pellas
Evaluator	Timo Vekara

ACKNOWLEDGEMENTS

I thank my supervisor, instructor and wife for their help and support.

-Lauri Karppi

TABLE OF CONTENTS

ABBREVIATIONS AND SYMBOLS

CCT	Correlated colour temperature
CFL	Compact fluorescent lamp
CIE	Commission Internationale de l´Eclairage - International Comission on Illumination
CRI	Color rendering index
ELWIS	Wärtsilä electric wisdom database
Em	Maintained Illuminance
HID	High-intensity discharge lamp
LED	Light emitting diode
LFL	Linear fluorescent lamp
Lm	Lumen
Lx	Lux
OLED	Organic light emitting diode
Ra	Color rendering index
SSL	Solid State Lighting
UGR	Unified glare rating
UGRL	Unified glare rating limit
Uo	Illuminance uniformity
W	Watt
WIMCE	Wärtsilä installation cost estimator tool

UNIVERSITY OF VAASA	
Faculty of technology	
Author:	Lauri Karppi
Topic of the Thesis:	Power Plant Lighting Modernisation with LED Lighting
Supervisor:	Professor Kimmo Kauhaniemi
Instructor:	Engineer Thomas Pellas
Evaluator:	Professor Timo Vekara
Degree:	Master of Science in Engineering
Department:	Department of Electrical Engineering and Automation
Degree Programme:	Degree programme in Electrical and Energy Engineering
Major of Subject:	Electrical Engineering
Year of Entering the University:	2001
Year of Completing the Thesis:	2013 **Pages: 69**

ABSTRACT

A substantial part of the power consumption of a power plant on stand-by is due to lighting. As the need to cut power plant's own electrical energy usage grows, the power consumption of lighting becomes a potential area of improvement.

The objective of this thesis is to study the possibility of installing light emitting diode (LED) lighting in a Wärtsilä power plant. Additionally, the objective is to list the relevant international lighting standards.

The LED lighting technology appears to have desirable properties, which is why LED lamps were chosen to be compared in this study. Real life examples of power plant rooms were chosen as a base for simulations. Original lighting simulations were compared against a new set of simulations with LED technology lighting. Quality of lighting, energy use and costs of installation and maintenance interval were compared.

In three different simulations of engine hall, LED lamps did not appear to be the preferable choice for lighting. Compared to linear fluorescent lamps, LED lamps either consumed more electrical energy, required more luminaires to be installed or lowered the lighting quality of the engine hall, depending on the chosen LED lamp types.

In conclusion, LED lighting was found not being suitable for this application. The lamps based on LED lighting technology seem to be unable to compete against the older lighting technology lamps such as linear fluorescent tubes and high intensity discharge lamps in aspects of energy consumption and light distribution in an industrial setting. Tested LED lamps did not produce enough lumens per watt and did not distribute the light well enough when compared to the older solution.

KEYWORDS: lighting, light sources, LED lamps, power plant

VAASAN YLIOPISTO		
Teknillinen tiedekunta		
Tekijä:	Lauri Karppi	
Diplomityön nimi:	Voimalaitoksen valaistuksen nykyaikaistaminen LED -valaistuksella	
Valvoja:	Professori Kimmo Kauhaniemi	
Ohjaaja:	Insinööri Thomas Pellas	
Tarkastaja:	Professori Timo Vekara	
Tutkinto:	Diplomi -insinööri	
Laitos:	Sähkö- ja automaatiotekniikka	
Koulutusohjelma:	Sähkö- ja energiatekniikan koulutusohjelma	
Suunta:	Sähkötekniikka	
Opintojen aloitusvuosi:	2001	
Diplomityön valmistumisvuosi:	2013	**Sivumäärä: 69**

TIIVISTELMÄ

Valmiudessa olevan voimalaitoksen sähköenergian kulutuksesta menee merkittävä osa valaistukseen. Siksi valaistuksen sähkönkulutus on hyvä kehityksen kohde kun energiansäästötavoitteet kasvavat.

Tämän työn tarkoituksena on selvittää, onko LED-valaistusta mahdollista käyttää Wärtsilän voimalaitoksessa. Lisätavoitteena on listata tärkeimmät aihetta käsittelevät kansainväliset standardit.

Työssä vertailtavaksi valittiin LED-lamput, sillä LED-teknologia näyttää omaavan toivottuja ominaisuuksia. Simulaatioiden pohjaksi valittiin olemassa olevan voimalaitoksen huoneita, joiden suunnitteluvaiheessa tehtyjä simulaatioita verrattiin uusiin, LED-teknologiaa käyttäviin simulaatioihin. Vertailua tehtiin valaistuksen laadusta, energiankulutuksesta, asennuksen hinnasta ja huoltovälistä.

LED-lamput eivät vaikuttaneet olevan paras valinta valaistukseen missään kolmesta moottorihallisimulaatiosta. Riippuen valitun LED-lampun tyypistä, LED-valaistus kulutti enemmän energiaa, vaati useampia valaisimia asennettavaksi tai vähensi valaistuksen laatua verrattuna loisteputkiin.

Johtopäätöksenä on, että LED-valaistus ei ole sopiva tähän käyttötarkoitukseen. LED-valaistusteknologia ei pysty kilpailemaan vanhempiin valaistusteknolgioihin perustuvien lamppujen, kuten loisteputkien ja suurpainepurkauslamppujen kanssa energiatehokkuudessa ja valonjaon tasaisuudessa teollisessa ympäristössä. Testatut LED-lamput eivät tuottaneet yhtä monta lumenea wattia kohden tai jakaneet valoa kuten alkuperäiseen ratkaisuun valitut lamput.

AVAINSANAT: valaistus, valonlähteet, LED-lamput, voimalaitos

1. INTRODUCTION

With advent of large wind parks and solar PV, variations in the weather can rapidly and drastically change the output needed from fuel-based power plants (Hotakainen et al. 2011: 143). Therefore, the role of combustion based power plants slowly changes from base load towards peak control and standby. This trend will, in turn, increase the demand for lowering the power plant's own energy consumption to lower the expenses incurred by a power plant that is not currently running.

Lighting consumes a notable amount of energy worldwide. According to OECD/IEA (2006: 65) 19 % of total global electricity production is consumed by grid-based electric lighting.

Led lighting is a new technology that is developing rapidly. It shows great promise in energy saving and increasing maintenance interval. This thesis work will focus on determining the viability of light emitting diode (LED) lighting at a Wärtsilä power plant to decrease energy used for lighting and to increase maintenance interval.

1.1. Company introduction: Wärtsilä

The subject for this thesis was provided by Wärtsilä Finland Oy, Power Plants, Engineering management office. According to Wärtsilä company statement:

"Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. By emphasising technological innovation and total efficiency, Wärtsilä maximises the environmental and economic performance of the vessels and power plants of its customers. In 2011, Wärtsilä's net sales totalled EUR 4.2 billion with approximately 18,000 employees. The company has operations in nearly 170 locations in 70 countries around the world. Wärtsilä is listed on the NASDAQ OMX Helsinki, Finland."

Wärtsilä has three main areas of business: Power Plants, Marine Solutions, and Services & Support. Engineering management office is a part of Wärtsilä power plants.

Wärtsilä Power Plants is a major supplier of flexible base load power plants operating on various liquid and gaseous fuels. Power Plants also provides unique, dynamic solutions for grid stability, reserve, peaking, load following and intermittent power generation. The portfolio covers the capacity range from 1 MW to more than 500 MWs.

Wärtsilä has delivered several power plants around the globe, and in this thesis one of them is used as a reference base when comparing the simulated effects of LED lighting to conventional lighting. The power plant, Kipevu III, is located in Kipevu, suburb of Mombasa, Kenya. Kipevu III is the largest diesel power plant in East Africa and comprises of seven diesel engines and is connected to the national grid via a new 132 kV switchyard extension. Figure 1 shows the overview of Kipevu III.

Figure 1. Kipevu III power plant constructed by Wärtsilä Oy to KenGen (KenGen 2013).

1.2. Objective, scope and structure of the thesis

The objective of this thesis work is to study the possibility of installing LED lighting in a Wärtsilä power plant. The scope includes documenting the current lighting design practices, guidelines and standards in use in Wärtsilä power plant lighting design process. The main concern is determining the viability of implementing LED lighting in near future and examining the processes, practices and instructions within the company that have an impact to lighting design.

Halonen et al. (2010: 3) lists ways of improving energy efficiency of lighting installations. Incandescent lamps can be replaced to almost any other lamp type to improve energy efficiency. These are compact fluorescent lamps, infrared coated tungsten halogen lamps, LED lamps, high pressure sodium lamps and metal halide lamps. The choice of ballast can also affect energy efficiency. Controllable electronic ballasts incur low losses. Lighting design can make use of efficient luminaires and localized task lighting. Lighting controlling, including dimming by daylight or presence sensors, provides additional ways to save energy, as well as the use of daylight in lighting and building design. Halonen also mentions the use of high efficiency LED based lighting systems.

These are all valid measures to cut down energy consumption for lighting. In this thesis the possibility of choosing LED based lighting systems over the currently used types of lamps is explored.

The theoretical part of the thesis reviews topics that will make the rest of the thesis work easier to comprehend. These are light, colour, lighting units, lighting design and lighting related national and international standards. Lighting technologies and lamp types relevant to this study are also introduced.

Chapter 5 of the thesis portrays the current lighting design practices in Wärtsilä and properties of a standard Wärtsilä power plant lighting solution.

In Chapter 6 the simulations are compared. The properties of the proposed LED lighting options are compared to the original, conventional lighting solution. Figures from simulations and calculations are compiled as tables for each comparable attribute.

In Chapter 7 the results are stated and conclusions are drawn. Assessment is made in terms of achieving the objectives.

2. LIGHT, VISION AND COLOUR

This thesis work is about lighting. To be able to delve deeper in the dynamics of lighting design and lamp properties, one needs to understand basics of visible light, vision and colour. Basics of lighting and the human eye physique are explained. National and international standards are also discussed.

2.1. Colour and light

Visible light is electromagnetic radiation with wavelength from 380 nm to 780 nm (ABB 2000: 1). By definition it travels via radiation. It is no coincidence that the highest levels of sunlight are in the visible range, our eyes have evolved to use the available light (Virginia Department of Mines, Minerals and Energy 2008: 107).

Figures 2 and 3 describe the energy and wavelengths, that is, intensity and colours, of solar radiation reaching the earth's surface.

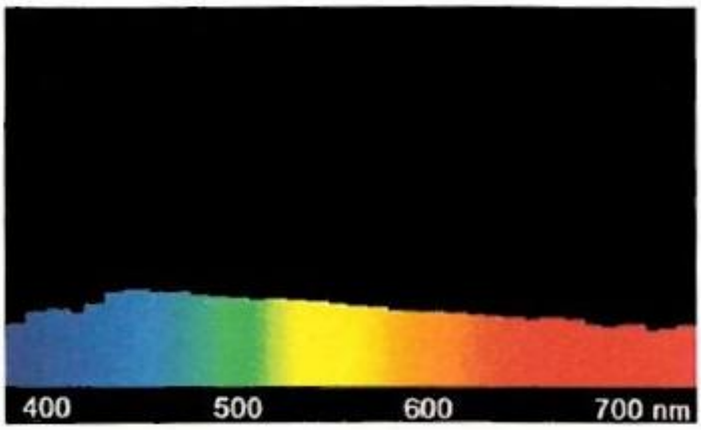


Figure 2. The spectral composition of natural daylight (Turner 1998: 28).

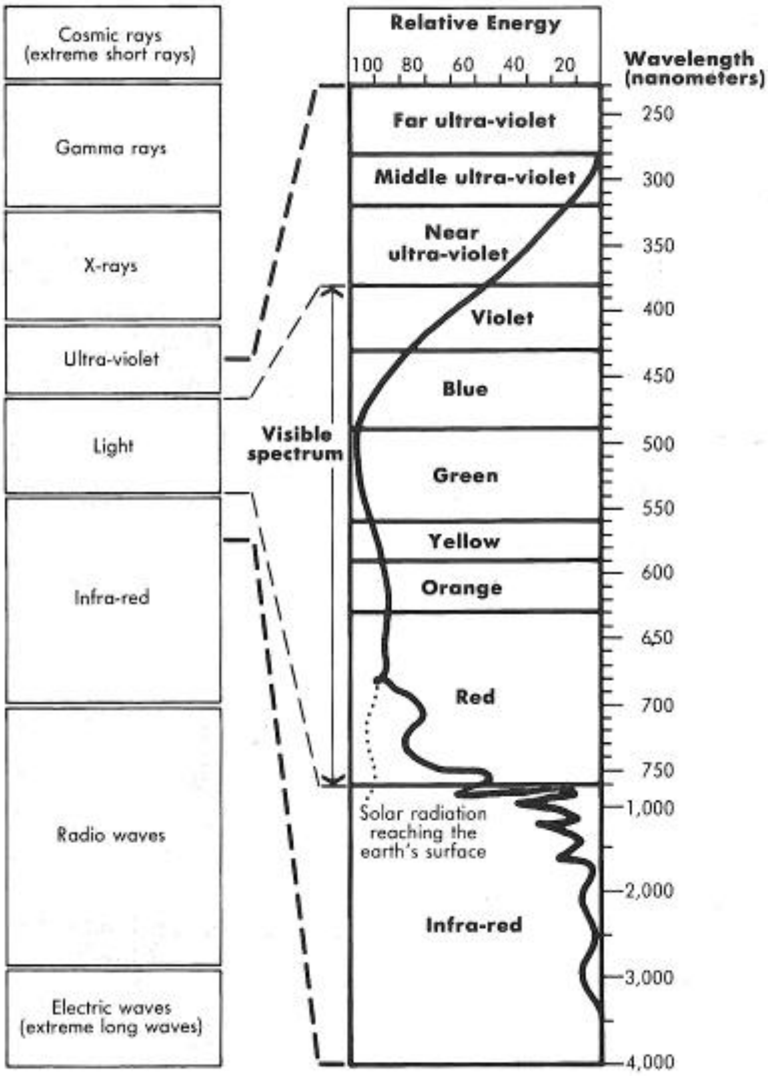


Figure 3. The visible electromagnetic spectrum. (Steffy 1990).

In literature and science, colour is determined by the wavelength of radiation. But actually colour is determined by the human vision. Other living beings can sense also other parts of the spectrum, and with varying sensitivities. The human eye has a mat of tiny photoreceptors, that detect quantities of light. The human day vision relies on three types of cone photoreceptors, that wary in sensitivities to different wavelengths (Halonen & Lehtovaara 1992: 96). These three types are often referred as red, green and blue cones. This naming is somewhat misleading, since the cones are not maximally sensitive in the red green and blue parts of the spectrum. Blue cones are most sensitive in the violet wavelengths and the red cones are most sensitive in the yellow-green part of spectrum. For this reason, most physicists prefer to call them the long-wavelenght-sensitive, middle-wavelenght-sensitive and short-wavelenght-sensitive cones instead (CVRL 2012).

Individual cones signal only the rate at which they absorb photons, without regard to their wavelength. Wavelenght only affects the probability of absorption that different cones react to photons, not the neural effect after absorption. The human ability to perceive colour depends of the comparison of the cones' sensations, that is, the rate at which each of them absorb photons. All three types of cones have some amount of sensitivity to all three basic colours but these nine sensitivities are unknown. Traditionally, these have been estimated by assuming different types of colour blindnesses to represent normal vision with one type of photoreceptor cones disabled (CVRL 2012).

These cone sensitivities affect how the human eyes see. If the three color sensitivity functions are combined, the result is the luminous efficiency function for photopic vision, presented in Figure 4. The human eye can be replaced by this sensitivity function, namely the International Comission on Illumination (CIE) standard of photopic observer (NIST 1997: 1).

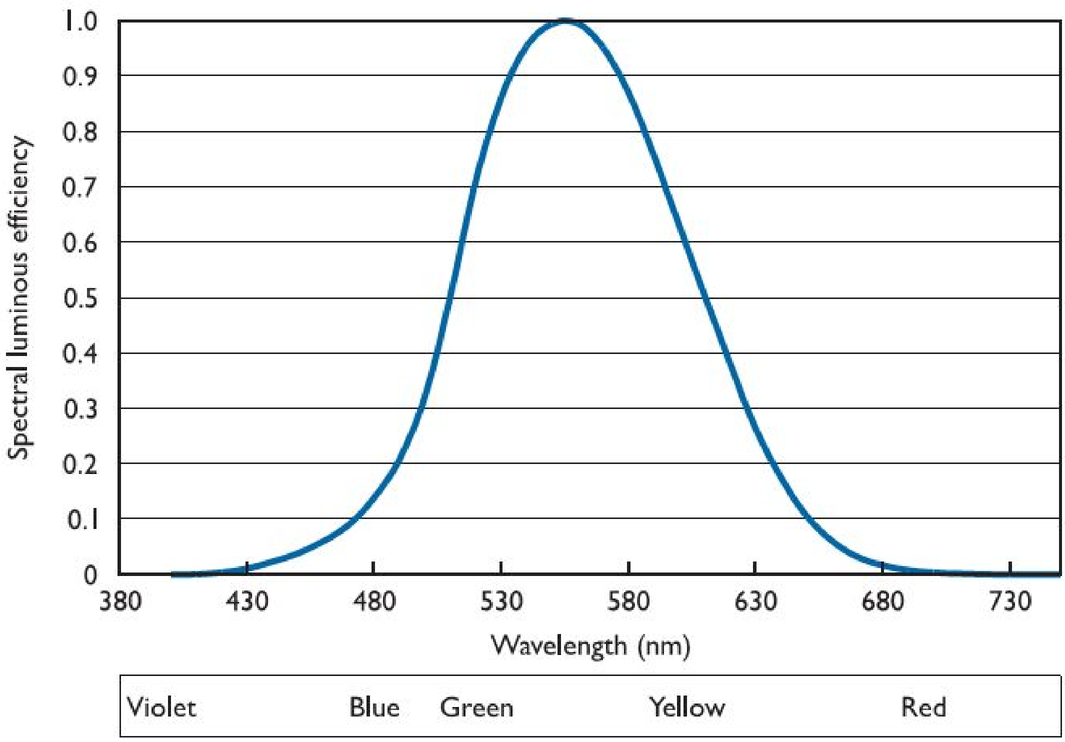


Figure 4. The luminous efficiency function for photopic vision (OECD/IEA 2006: 72).

2.2. Spectral power distribution of light

The luminous efficiency function for photopic vision represents what we see and how. This is important to understand when talking about light and lamps. That what we call light is only the wavelengths that we can sense and have varying sensitivity to. Thus, lamps that emit wavelengths that we can't see well or at all, have inherently poor energy to light ratio. If we manufacture a light source that only emits one wavelength, it would not be very useful or comfortable to use in home, office or factory.

Murphy (2012) states that a monochromatic source at 555 nm will produce 638 lm/W of light output. This is the peak of the photopic sensitivity curve. For other monochromatic wavelengths, the luminous efficacy is reduced according to the photopic function. At 633 nm the sensitivity of the eye is only 23.5 % of the peak value resulting in 160 lm/W.

The colour characteristics of light in space are determined by the spectral power distribution of the light source and the reflectance properties of the surfaces in the room. The intensity of light emitted by any given lamp varies across the range of the visible light spectrum with the result that different lamp types have different colour characteristics. The colour of light sources is usually described by two properties, namely the correlated colour temperature (CCT) and general colour rendering index (CRI). Both are defined according to international standards that are adhered to by lamp manufacturers around the world. The CRI is defined by the International Comission on Illumination (CIE). The distinction between two characteristics is that while the CCT describes the colour appearance of the lamp itself, the CRI or describes the colour appearance of the surfaces being illuminated by the lamp. Note that the CRI metric is known to be imperfect, and alternatives are being actively considered (OECD/IEA 2006: 105 - 106, Hung & Tsao 2012: 1, Halonen et al. 2010: 46).

The CCT is expressed in degrees kelvin and corresponds to the chromaticity that matches that of a "black body" heated to the same temperature. For example, incandescent lamps with CCT of 2700 K have a yellowish color appearance and their light is described as warm. Certain type of fluorescent lamps or white LEDs have CCT of around 6000 K with bluish appearance and light described as cool (OECD/IEA 2006: 105 - 106, Hung & Tsao 2012: 1, Halonen et al. 2010: 46).

The CRI measures how well a given light source renders a set of test colours relative to a reference source of the same correlated color temperature as the light source in question. The general CRI of the CIE is calculated as the average of special CRIs for eight test colours. The reference light source is Planckian radiator (incandescent type source) for light sources with CCT below 5000 K and a form of a daylight source for light sources with CCT above 5000 K. The higher the general CRI, the better is the color rendering of a light source, the maximum value being 100 (OECD/IEA 2006: 105 - 106, Hung & Tsao 2012: 1, Halonen et al. 2010: 46).

There seem to be clear cultural and chromatic-matching issues that influence preferences for lighting chromatic characteristics. In more northerly latitudes there is a market preference for lighting with low correlated colour temperature (CCT), while in more equatorial latitudes the preference is usually for higher CCTs. In part this may be explained by a desire for the chromaticity of artificial light to not overly diverge from that of natural light given that the average colour of daylight tends to be warmer (i.e. toward lower CCT values) in less equatorial latitudes and cooler (i.e. toward higher CCT values) in more equatorial latitudes. But cultural preferences are also a strong factor; for example, the standard CCT of fluorescent tubes in Japan is 5 000 K, whereas in the United States 3 500 K is common. (OECD/IEA 2006: 83).

The CRI is a reasonably reliable measure of the degree to which the colours of an object illuminated by a lamp will match those of the same object illuminated by daylight, where a maximum score of 100 implies a perfect match and a score of 0 a perfect mismatch. In part because they emit light across a full visible spectrum, incandescent lamps have CRI scores of almost 100 while other light sources are usually less. However, the other reason for incandescent CRI scores being so high is because they are measured by comparison with incandescent lamps. This means that the CRI is a somewhat loaded measure, i.e. to achieve a high score requires a lamp's spectrum to be similar to that of an incandescent lamp. Efficient light sources are available across every range of CCT, but still none has a CRI that attains 100; however, this thought needs to be tempered by several other considerations. First, the human eye can not distinguish differences in CRI of less than 3–5. Second, choosing a lamp with a CRI of 100 does not guarantee that the delivered illumination also has a CRI of 100 because this depends on light interactions with the luminaire, room shape, surface colours and reflectance, overall illumination level and whether daylight is present. Third, while there is some evidence to suggest that a high CRI may enhance visual acuity, the sensitivity of visual performance to CRI becomes insignificant for CRIs above a minimum level. Fourth, human vision adapts to chromatic differences (OECD/IEA 2006: 106 - 107).

While light sources with a colour rendering index (CRI) below 60 are unacceptable for indoor lighting because of the unnatural colours they render and those with a CRI above 80 tend to give more saturated surface colours that allow a perception of greater brightness and visual clarity, there is little evidence to suggest that people really make finer distinctions based on CRIs or that there is a strong preference either way for specific CRI levels between 80 and 100 (OECD/IEA 2006: 84).

2.3. Light units, measures and terms

Lumen, lm, is a unit of light flow. The intensity [watt] of a certain wavelength of light is multiplied by the spectral luminous efficiency function, V(λ), and then with a constant 683 lm/W. This means a unit of lumen is not interchangeable with other lumens in terms of absolute radiated power. Therefore, a unit of lumen is normalized to designate "an amount of light sensed by the human eye". (ABB 200: 1, Halonen, Lehtovaara: 119).

Illumination is measured in terms of the flow of light *arriving on a square metre*. If 1000 lumens fall on 5 m^2, the average illumination, or illuminance, is said to be 1000/5, that is 200 'lux' The approved symbol is 'lx'. Some typical levels of illumination are shown in Table 1.

Table 1. Levels of illumination (Boud 1973: 6).

Environment	Illumination (lx)
strong, direct sunlight	50 000
dull, overcast sky	5000
drawing office	500
domestic living room	50
moonlight	0 - 5

The significant thing about these figures is the enormous range – the human eye is dynamic, and therefore cabaple of vision over brightnesses varying by a million to one. Also notable is the subjective impression of change of brightness is broadly similar in going from 50 to 500 lux, average living room to drawing office, and from 5000 to 50 000 lux dull day to strong sunlight. The significance is in the ratio of the levels, not in the linear difference (Boud 1973).

Candela, cd, is the SI unit of luminous intensity. One candela is one lumen per steradian. Formerly “candle” (OECD/IEA 2006: 521).

Luminance is a measure of light *travelling through* or from a surface area in one direction. Its unit is candela per square metre, cd/m^2 (ABB 2000: 2).

Luminaire is a complete lighting unit consisting of a lamp (or lamps), or ballasts where applicable, together with the parts designed to distribute the light, position and protect lamps and connect them to the power supply (OECD/IEA 2006: 526).

2.4. Lighting design

The purpose of lighting is to enable human vision. Lighting design’s target is to enable people to work, occupy and move about safely and efficiently. However, there is no straight-forward path to follow in creating visually comfortable luminous environments. Several lighting related factors may cause visual discomfort (Halonen et al. 2010: 45).

The standard EN 12665:2011 states that the lighting requirements for a space are determined by the need to provide:

- illumination for safety and movement,
- conditions that enable colour perception and visual performance and
- visual comfort for the occupants in the space.

Lighting designers must learn to think of light in two ways. First, certain levels of illumination are necessary for us to use a space, that is, to see well enough to *function* at our designated tasks. This is not a trivial matter and is not to be taken for granted. However, in addition, the forms and spaces themselves are perceived in terms of light. How we feel about the building is also determined by light (Schiler 1992).

Visual acuity, or sharpness of vision, depends on how much light there is. We recognise this almost without a second thought; we acknowledge this every time we take something with small detail or subtle contrast to the window or the desk lamp to examine it.

Visual acuity can be determined formally, and quantified in terms of the angle subtended at the eye by the smallest detail that can be perceived. Its relationship to illumination, the concentration of incident light, can then be studied experimentally (Boud 1973).

Lighting design has to consider several factors at once. The amount of light has to be high enough to enable people to see, work and move in the space as intended. Colour of the light should be correct for the purpose, usually meaning sufficient colour rendering. Completely uniformly lighted space can be felt undesired, as well as too non-uniform lighting can cause distraction or discomfort. Glare is caused by high luminances or excessive luminance differences in the visual field. Glare can cause disability or discomfort. Surfaces and objects can cause veiling reflections, reducing the perceived contrast needed for working on a task. Shadows can affect the viewing experience both positively and negatively, depending on the application (Halonen et al. 2010: 46 - 48).

Glare and other aspects of lighting can be calculated before installing the luminaires. DIALux is a simulation tool used for lighting design produced by DIAL GmbH. The same tool was used to design the original power plant Kipevu III lighting, and will be used in this thesis to study lighting options based on LED lighting (DIAL 2012).

3. TECHNICAL STANDARDS

Technical standards state limits, levels, norms and requirements about various technical areas. There are several different standards organizations that provide and maintain technical standards. There are three types of standards in use at Wärtsilä, internal standards, national standards and international standards. No internal standard at Wärtsilä involves lighting. Therefore, only national and international standards will be examined here. Wärtsilä does have lighting design guides, complete designs and best practices. These will be described in Chapter 5.

For one that had never searched and browsed standards before, national and international standards can first appear as disorganized and incoherent. It is not a trivial matter to find the name of a standard that covers the topic at hand. The abstracts of the standards are public, but the documents themselves need to be bought from standards organisations. Standard documents vary greatly in length. When browsing for standard documents, one can not avoid encountering independent standards correction documents and new editions. These correct or edit misspellings or individual figures in standards, resulting in the requirement to read several documents simultaneously to decipher their contents. This can be confusing at first. Standards use cross referencing, and finding one standard even close to the intended topic will often lead to find the correct one.

By definition, national standards are not universal. Globally, different countries, states, counties or even city parts might have their own set of standards regarding, for example fire protection or wiring. Therefore, these requirements change between projects, clients and countries and it is not possible or reasonable to create a comprehensive list, containing every possible standard regarding lighting. International standards and European standards, however, are a good place to start.

3.1. International and national lighting standards

Following is a non-comprehensive list of international or European lighting and lighting design standards.

SFS-EN 1837:1999+A1 Safety of machinery. Integral lighting of machines
SFS-EN 1838:1999 Lighting applications. Emergency lighting
SFS-EN 12464-1:2011 Light and lighting. Lighting of work places. Part 1: Indoor work places
SFS-EN 12464-2:2007 Light and lighting. Lighting of work places. Part 2: Outdoor work
SFS-EN 12665:2011 Light and lighting. Basic terms and criteria for specifying lighting requirements
SFS-EN 15193:2007 Energy performance of buildings. Energy requirements for lighting
SFS-ISO 3864-1:2011 Graphical symbols -Safety colours and safety signs- Part 1: Design principles for safety signs and safety markings
SFS-ISO 3864-2:2004 Graphical symbols. Safety colours and safety signs. Part 2: Design principles for product safety labels
ISO 23539:2005 Photometry — The CIE system of physical photometry
ISO 8995:2002(E) ISO 8995 CIE S 008/E Lighting of indoor work places
IEC 60598-1 Luminaires – Part 1: General requirements and tests
IEC 60598-2-1 Luminaires – Part 2-1: Particular requirements – Fixed general purpose luminaires
IEC 60598-2-2 Luminaires – Part 2-2: Particular requirements – Recessed luminaires
IEC 60598-2-5 Luminaires – Part 2-5: Particular requirements – Floodlights
IEC 60598-2-22 Luminaires – Part 2-22: Particular requirements – Luminaires for emergency lighting

Marking of EN denotes European standard, ISO and IEC are International standards. Prefix SFS indicates a standard that also has the status of a Finnish national standard.

3.2. Lighting standard notes and comparison

From the technical standards listed, most relevant in regards to this thesis are the ones that mention power plants. Table 2, from International standard ISO 8995, describes lighting requirements for power stations. Lighting requirements include three qualities of light that are maintained illuminance, discomfort glare limit and colour rendering index. Maintained illuminance, E_m is the lux value below which the average illuminance on the specified surface should not fall. Unified glare rating UGR is The CIE discomfort glare measure limit, where 13 represents the least perceptible discomfort glare. The UGR scale is: 13 - 16 - 19 - 22 - 25 - 28. UGR_L limits the UGR value in a room. R_a is the minimum colour rendering index. Referring to the previous chapter, the colour rendering index is also known as CRI.

Table 2. Clause 5 of ISO 8995, schedule of lighting requirements, power stations (ISO 8995: 13).

Type of interior, task or activity	$\overline{E_m}$ lux	UGR_L	R_a	Remarks
16. Power stations				
Fuel supply plant	50	28	20	Safety colours shall be recognisable.
Boiler house	100	28	40	
Machine halls	200	25	80	For high-bay: see also clause 4.6.2.
Auxiliary rooms, e.g pump rooms, condenser rooms, switchboard, etc.	200	25	60	
Control rooms	500	16	80	1. Control panels are often vertical. 2. Dimming may be required. 3. For VDT work see clause 4.10.

Clauses 4.10 and 4.6.2 of ISO 8995 referred to in the Table 2 state additional requirements and information regarding work with visual display terminals and high-bay lighting in machine halls, respectively.

The clause 4.6.2 of ISO 8995 states, that high-bay lighting can be an exception to the colour rendering limitation of 80 stated for machine halls in Table 2. Still, the clause stresses the importance of high colour rendering index for humans in terms of visual performance and comfort. For this reason, lamps with colour rendering index less than 80 should not be used in interiors where people live, work or stay for long periods of time. Safety colour recognition is also mentioned. The colour rendering of safety signs is depending on the colour rendering index of the lighting, and safety colours must always be recognisable.

The clause 4.10 of ISO 8995 states requirements regarding lighting for visual display terminals (VDT). If the work station involves work with VDT, the lighting must be also appropriate for all related tasks such as writing on paper and reading from the screen. Main concern is on the disability and discomfort glares. These are to be avoided with proper luminaire placement, angle and management.

European and Finnish Standard SFS-EN 12464-1 uses the same qualities to specify the requirements of lighting than ISO 8995, but adds a separate U_o to each task or area. U_o is the minimum illuminance uniformity on the reference surface for the maintained illuminance. ISO 8995 states the uniformity value requirement regarding all areas as follows:

The uniformity of the illuminance is the ratio of the minimum to average value. The illuminance shall change gradually. The task area shall be illuminated as uniformly as possible. The uniformity of the task illuminance shall not be less than 0.7. The uniformity of the illuminance of the immediate surrounding areas shall be not less than 0.5.

In the lighting simulations discussed in this thesis, the illuminance uniformity appears to be the most difficult criteria to meet.

Table 3 shows the power stations lighting requirements of the European and Finnish Standard SFS-EN 12464-1. The similarities between SFS-EN 12464-1 and ISO 8995 are apparent. In power stations, not counting the illuminance uniformity ratio and fuel supply plant discomfort glare limit, the requirements of SFS-EN 12464-1 are identical to those of ISO 8995.

Table 3. Clause 5, schedule of lighting requirements, Power station (SFS-EN 12464-1: 51).

Ref. no.	Type of area, task or activity	$\bar{E}_m$ lx	UGR_L –	U_o –	R_a –	Specific requirements
5.20.1	Fuel supply plant	50	–	0,40	20	Safety colours shall be recognisable.
5.20.2	Boiler house	100	28	0,40	40	
5.20.3	Machine halls	200	25	0,40	80	
5.20.4	Side rooms, e.g. pump rooms, condenser rooms, etc.; switchboards (inside buildings)	200	25	0,40	60	
5.20.5	Control rooms	500	16	0,70	80	1. Control panels are often vertical. 2. Dimming may be required. 3. DSE-work, see 4.9.

Clause 5, schedule of lighting requirements of SFS-EN 12464-1 also refers to another clause explaining more about display devices. Instead of the term VDT, visual display terminals that is mentioned in ISO 8995, SFS-EN 12464-1 uses the term DSE, display screen equipment. Clause 4.9 of SFS-EN 12464-1, Lighting of work stations with Display Screen Equipment (DSE) is very similar to the clause 4.10 of ISO 8995, regarding VDT. The clause 4.9 of SFS-EN 12464-1 states, that lighting shall be appropriate for all tasks on the work station, including reading printed text, writing on paper and using keyboard. High brightness reflections are to be avoided by lighting designer by choosing equipment and by planning the mounting positions accordingly.

Regarding DSE/VDT, also known as computer screens, both SFS-EN 12464-1 and ISO 8995 have a table to explain the average limits of luminaires which can be reflected in flat screens. These can be compared in Tables 4 and 5.

Table 4. Average luminance limits of luminaires, which can be reflected in flat screens (SFS-EN 12464-1: 33).

Screen high state luminance	High luminance screen $L > 200\ cd \cdot m^{-2}$	Medium luminance screen $L \leq 200\ cd \cdot m^{-2}$
Case A (positive polarity and normal requirements concerning colour and details of the shown information, as used in office, education, etc.)	$\leq 3\ 000\ cd \cdot m^{-2}$	$\leq 1\ 500\ cd \cdot m^{-2}$
Case B (negative polarity and/or higher requirements concerning colour and details of the shown information, as used for CAD colour inspection, etc.)	$\leq 1\ 500\ cd \cdot m^{-2}$	$\leq 1\ 000\ cd \cdot m^{-2}$
NOTE: Screen high state luminance (see EN ISO 9241-302) describes the maximum luminance of the white part of the screen and this value is available from the manufacturer of the screen.		

Table 5. The luminance limits for downward flux of luminaires which may be reflected in the screens for normal viewing directions (ISO 8995: 8).

Screen classes see ISO 9241-7	I	II	III
Screen quality	good	medium	poor
Limit of average luminance of luminaires	$\leq 1000\ cd/m^2$		$\leq 200\ cd/m^2$

Comparing Tables 4 and 5, ISO 8995 has tighter requirements. Note that ISO 8995 and SFS-EN 12464-1 do not use the same metric for screen quality. Both have their own standard for measuring screen quality and these are not included in the scope of this thesis.

4. TECHNOLOGY OF LIGHTING

The first industrially manufactured incandescent lamp was made 1879, that is over 130 years ago. This same technology is still used and holds 79 % of global lamp sales volume. Incandescent lamp has since gained many competitors. In this chapter an overview of some lighting technologies and principles is given (Halonen & Lehtovaara 1992: 18, OECD/IEA 2006: 37).

4.1. Solid-state lighting

Solid-state lighting (SSL) refers to lighting with light emitting diodes, organic light emitting diodes (OLED) or light emitting polymers. At the moment there is no official definition for solid-state lighting, but the expression refers to the semiconductor structure of the technology (Halonen et al. 2010: 111).

A light emitting diode is a semiconductor, pn junction, emitting light spontaneously from an external electric field. A LED is similar to a semiconductor diode, allowing current flow only in one direction (Halonen et al. 2010: 111).

White LED can be built by mixing the emission of different coloured LEDs or by utilising phosphor. Phosphor converted white LEDs are usually based on blue or ultraviolet LEDs. Depending on the properties of the phosphor layer or layers used, white light of different qualities can be produced. These is approaches to produce white light are shown in Figure 5. Due to the layered nature of this technology, the CRI of LED lamps will be less than the CRI of incandescent lamps.

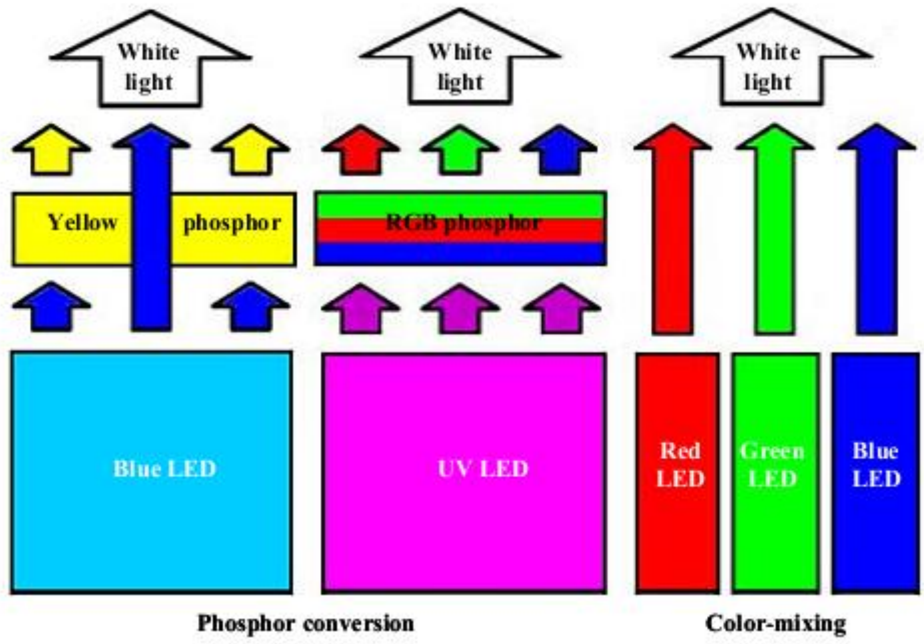


Figure 5. Two main types of approaches of creating white light with LEDs (Halonen et al. 2010: 113).

4.2. Components of LED luminaires

As LED lighting has evolved, a number of product configurations have appeared in the market. Two essential levels of product can be identified based on whether or not the product includes a driver, and a number of terms can be defined for each level. These definitions reflect the agreed definitions in IES Standard RP-16 Addendum b, as up-dated and released in 2009. DOE (2012: 55 - 56) lists these definitions under component level and subassemblies. Component level definitions are LED, LED package and LED array or modules. Subassembly and system definitions are LED lamp, LED light engine, LED driver and LED luminaire.

LED is a p-n junction semiconductor device that emits radiation when forward biased. This radiation can either be on the visible band, or outside it. The longer and shorter wavelengths are called infrared and ultraviolet radiation, respectively. An example of a LED semiconductor is shown in Figure 6.

Figure 6. Definitions of LED components (DOE 2012: 57).

LED package refers to a group of LEDs connected by optical, electrical or mechanical means. Power source and standardized base are not included. An example of a LED package is shown in Figure 6.

LED array refers to a group of LED package connected by optical, electrical or mechanical means. LED array contains interfaces intended to be connected to a LED driver. LED array does not contain a power source or a standard base.

LED lamp refers to a lamp with ANSI standard base, ready to be connected to a luminaire. Integrated LED lamps can be connected directly branch circuit. All LED lamps contain mechanical, electrical, optical and thermal components. Non-integrated LED lamps are intended to be connected to a LED driver of a LED luminaire and cannot be directly connected to branch circuit.

LED light engine is an integrated assembly of LED packages or LED arrays with LED driver and optical, electrical, mechanical and thermal components. LED light engine is intended to be connected directly to branch circuit. A LED light engine is shown in Figure 6.

LED driver is a power source and control circuitry for LED package, LED array or LED lamp.

LED luminaire is a complete unit of lighting, containing a lamp, a driver, means to distribute light and a package to protect and position the elements correctly. A LED luminaire is intended to be connected directly to branch circuit. A LED luminaire is shown in Figure 6.

4.3. Fluorescent lamps

A linear fluorescent lamp, LFL, is a low-pressure discharge lamp that consists of a soda lime glass tube internally coated with phosphors and tungsten wire electrodes coated in a thermionic emitter sealed into each end of the tube. This is filled with one or more inert gases and trace amounts of mercury. Ultraviolet light is emitted by passing an electric current between the electrodes, creating a low-intensity arc that excites the mercury vapour and thereby produces ultraviolet radiation. This in turn excites the phosphors lining the glass tube, and these then emit visible light. Fluorescent lamps need a ballast to regulate the input current and voltage in a way that will initiate the lamp discharge and then maintain it at the required level. Fluorescent lamps are also diffuse light sources, meaning the light is emitted almost evenly from each point on the lamp wall. These characteristics require the lamp to be housed in a luminaire that enables the light to be redirected to where it is needed, and this means an assessment of the lamp's performance must be based on how successfully it functions in conjunction with the luminaire (OECD/IEA 2006: 115).

Compact Fluorescent lamp, CFL, is a compact variant of the fluorescent lamp. The overall length is shortened and the tubular discharge tube is often folded into two to six fingers or a spiral. For a direct replacement of tungsten filament lamps, such compact lamps are equipped with internal ballasts and screw or bayonet caps. There are also pin base CFLs, which need an external ballast and starter for operation. The luminous efficacy of CFL is about four times higher than that of incandescent lamps. Therefore, it is possible to save energy and costs in lighting by replacing incandescent lamps with CFLs. CFLs also have long life, 6000 - 12000 h which is close to LFLs' life of 10000 - 16000 h (Halonen et al. 2010: 100 - 102).

Advantages of fluorescent lamps are inexpensiveness, good luminous efficacy, long life and large variety of CCT and CRI. Disadvantages are ambient temperature affecting switch on speed and light output, the need of ballast and starter, light output dropping with age, containing mercury and short burning cycle affecting lamp life (Halonen et al. 2010: 100).

4.4. Energy efficiencies of lighting technologies

When comparing lighting technologies in an effort to cut down energy consumption and improve cost effectiveness, the most revealing quality of a lamp is its luminous efficacy. Luminous efficacy signifies the portion of energy that turns to visible light in a lamp. The rest of the energy is transformed to heat. Luminous efficacy can be reported as a percentage or lumens per watt value. Incandescent lamps typically emit 12 lm/W. The rest of the energy is transformed to heat. OECD/IEA states that 12 lm/W translates to 5 % energy to light ratio, which in turn suggests that 100 % efficacy would be $100\ \% / 5\ \% \cdot 12\ \text{lm/W} = 20 \cdot 12\ \text{lm/W} = 240\ \text{lm/W}$ (Halonen & Lehtovaara 1992: 18, OECD/IEA 2006: 37).

However, reporting lumens per watt ratio as a percentage is problematic, since the colour of the light source in question greatly affects it. As Murphy (2012) points out, there is no generally accepted maximum luminous efficacy for white light, only estimations. Estimations, that depend on chosen or supposed CCT and CRI. Therefore, one can not report luminous efficacy as a percentage of that maximum. Efficacy of 100 %, would consist of only one colour, green, 555 nm, at 683 lm/W. Leaving aside the efficiency with which photons are generated, any white-like spectrum confining itself to visible wavelengths is likely to achieve a spectral luminous efficacy in the range 250 - 350 lm/W.

Matsumoto & Makoto (2010) suggest that an incandescent lamp could be modified to yield even 400 lm/W. Murphy (2012) argues that the inherent properties of the colour of light emitted by a “white” light source will always prevent higher than 350 lm/W efficacy, without even addressing the efficacy at which the photons are produced with.

A major group of lighting is formed by high-intensity discharge (HID) lamps including mercury vapour lamps, high- and low pressure sodium lamps and metal halide lamps. These high power lamps provide light at medium to high efficacy levels, 35 - 150 lm/W. Mercury vapour lamps represent inefficient technology among HID lamps, but still holds a significant share of total HID installations (OECD/IEA 2006). Figure 7 visualises the differences of lamp efficacies.

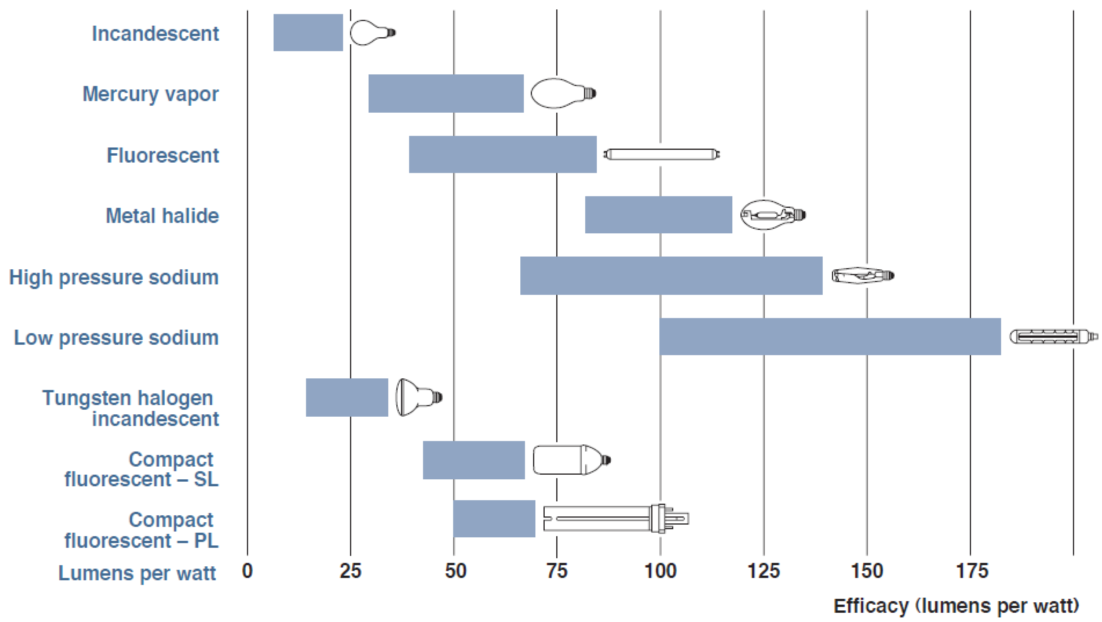


Figure 7 Lamp efficacy ranges by lamp type, lumens per watt (Virginia Department of Mines, Minerals and Energy 2008: 106)

DOE (2012) presents a comprehensive report on light source technologies' performance, including efficacy with or without ballast. It reports values, not ranges, for example 15 lm/W for incandescent lamps and 108 lm/W for linear fluorescent lamps with ballast. Perhaps OECD/IEA and Virginia Department of Mines, Minerals and Energy reported values in ranges to include history. Also DOE report seems to be concentrated in the best results of each respective technology, not the full range or median of them. Yet, the oldest of these sources, OECD/IEA in 2006 reports ranges with high end higher than Virginia Department of Mines, Minerals and Energy in 2008 or DOE in 2012. OECD/IEA assumedly did not include ballasts in its efficacy ranges.

Luminous efficacy, while being the most important quality, is not the only one that needs to be evaluated when designing energy and cost saving lighting. Lifetime affects maintenance costs, as burned out or expired lamps require changing. Luminous output affects installation costs, as lamps with low luminous output require several lamps to be installed to achieve necessary lighting levels. Table 6 compares performances of different lighting technologies as reported in April 2012. It should be noted that LED laboratory prototypes reach higher efficacies than those listed in Table 6.

In 2010 Cree, a multinational manufacturer of semiconductor materials and devices, announced to have broken the research and development barrier of 200 lumens-per-watt efficacy. In the end of 2012 Cree announced an industrially manufactured product that can reach 200 lm/W (Cree 2012).

HID lamp used in the original Kipevu III simulation has a luminous efficacy of 142 lm/W, and 93 lm/W for the linear fluorescent lamps. For the LED lamps used in the simulations the manufacturer reported >80 lm/W luminous efficacy. Comparing these figures with the Table 6, and browsing manufacturer catalogues, it is apparent there are variations of luminous efficacy between different models inside a same lighting technology.

Table 6. Lighting technology performance comparison (DOE 2012: 41).

Product Type	Luminous Efficacy	Luminous Output	Wattage	CCT	CRI	Lifetime
LED White Package (Cool)	144 lm/W	144 lm	1.0 W	2600-3700K	70	50k hours
LED White Package (Warm)	111 lm/W	111 lm	1.0 W	5000-8300K	80	50k hours
LED A19 Lamp (Warm White)	93 lm/W	910 lm	9.3 W	2727K	93	25k hours
LED PAR38 Lamp (Warm White)	74 lm/W	1,000 lm	13.5 W	3000K	92	25k hours
LED 2'x4' Troffer (Warm White)	110 lm/W	4000 lm	36 W	3500K	90	75k hours
OLED Panel	60 lm/W	76 lm	1.3 W	3500K	80	15k hours
HID (High Watt) Lamp and Ballast	123 lm/W 115 lm/W	38700 lm	315W 337W	3100K	90	30k hours
Linear Fluorescent Lamp and Ballast	118 lm/W 108 lm/W	3050 lm 6100 lm	26W 56W	4100K	85	25k hours
HID (Low Watt) Lamp and Ballast	110 lm/W 103 lm/W	7700 lm	70W 75W	3000K	89	16k hours
CFL	63 lm/W	950 lm	15W	2700K	82	12k hours
Halogen	22 lm/W	1100 lm	50 W	3000K	100	5k hours
Incandescent	15 lm/W	890 lm	60W	2760K	100	1k hours

When comparing the efficacy of lighting technologies, one needs to note that the sources don't always group lamps and technologies the same way. An example of this is the fluorescent lamp. While both types, compact and linear fluorescent lamps, work technologically on the same principle, as lamps, they are different and have a significant difference in luminous efficacy. Still, OECD/IEA publication reports their properties as being only one group. Figure 8 clearly visualises their differences. It shows luminous efficacies of lighting technologies of the past and future, basing on market research made in 2011.

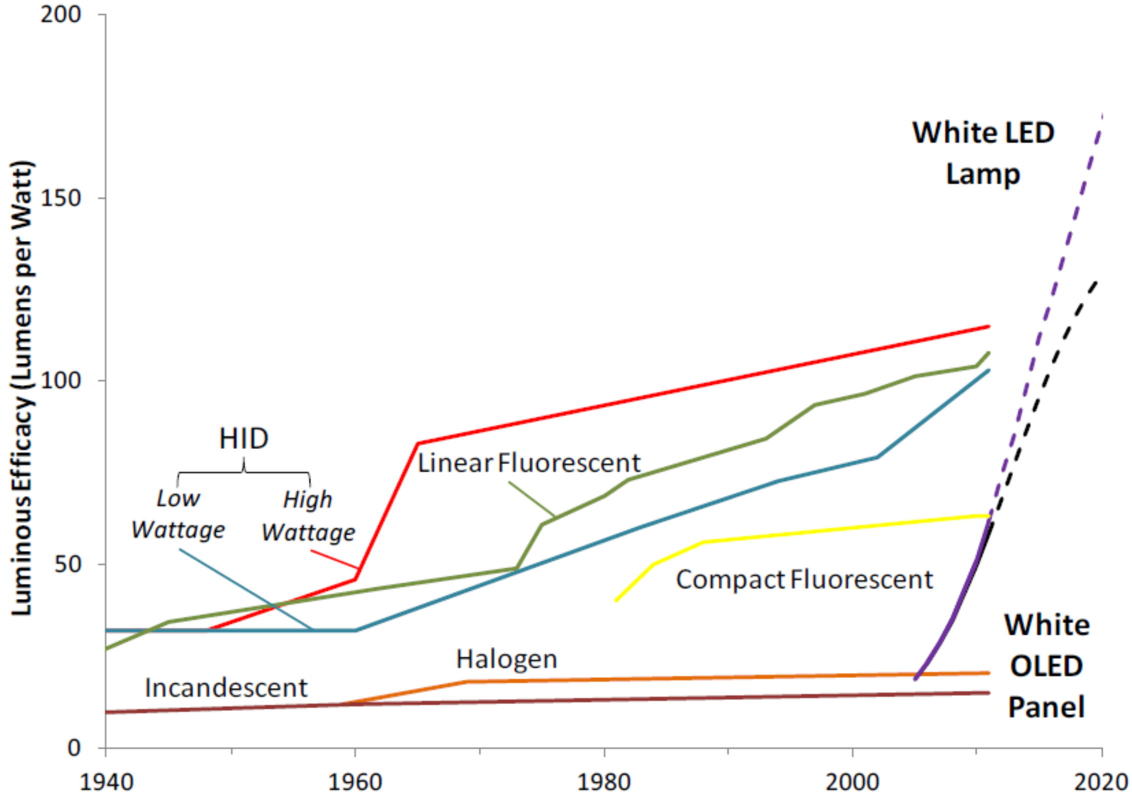


Figure 8. Historical and predicted efficacy of light sources (DOE 2012: 38)

5. WÄRTSILÄ POWER PLANT LIGHTING

Lighting is a small part of a complex and large scale project when building power plants. According to interviews with sales tools general manager Mats Ribacka (2012) and electric installation costing estimator Jani Aurell (2012), typical lighting and electrification of Wärtsilä power plant structures makes up for less than one percent of the total building costs, and lighting's share of that is about one fifth.

The process of power plant lighting and lighting design can be viewed in chronological order. The customer is offered a power plant that includes a Wärtsilä standard lighting solution that meets the agreed standards. Following steps include lighting design, procurement of materials and installation.

As stated earlier in Chapter 1, lighting control is also a potential solution to save energy in lighting. Lighting control design is not in the scope of this thesis.

5.1. The standard lighting design solution

Wärtsilä has several internal guidelines for lighting design requirements. Wärtsilä's electrical wisdom database, ELWIS, lists the following lighting level requirements:

-Engine hall: 300 lux
-Control room: 500 lux
-Office: 500 lux
-Switchgear room: 200 lux
-Workshop: 300 lux
-Store: 200 lux
-Fuel treatment house: 300 lux
-Outdoor: 20 lux
-Other rooms: 200 lux

When a customer of a Wärtsilä is shown the description of the system he is being offered, the document is called the Technical specification. When delivering power plants globally, every aspect of a project can be subject to change, and lighting design is no exception. For instance, the international protection rating of the luminaires can change. The Table 7 shows illumination level values that the technical specification contains by default.

Table 7. Illumination level requirements stated in Wärtsilä technical specification.

Area	Illumination level requirement, lux
Engine hall	200
Engine hall, maintenance platform	300
Auxiliary equipment area	300
Other rooms	150 - 200
Lighted outdoors areas	20

Comparing the differences of illumination level requirements in technical specification and ELWIS, ELWIS only mentions engine hall once, while technical specification also mentions maintenance platform inside the engine hall. Technical specification does not mention control room or office at all, and has no values over 300 lx.

Regarding lighting, the technical specification only mentions one standard, i.e. IEC 60598. IEC 60598 is a large standard with over 20 parts for different types of luminaires, and describes requirements on the luminaires themselves, not illumination level requirements.

Comparing ELWIS to standards ISO8995 and SFS-EN 12464-1, the standards have the same requirement for minimum average illumination level as ELWIS in the control room area. The standards only require 200 lx for engine hall, whereas ELWIS states requirement of 300 lx.

One difficulty in comparing the illumination level requirements is due to the naming of areas or tasks. International and national standards name five areas or tasks in a power station, and it is not immediately clear, what areas they correspond with in the real life example. According to interview with electrical engineering manager Thomas Pellas (2013), boiler does not have its own house in a Wärtsilä power plant, so boiler room lighting level requirement is not applicable at all. Table 8 lists all the names of the relevant areas mentioned in ELWIS, technical specification and international standards, and the values of each respective illumination level requirement. One of the objectives of this thesis is to compare existing lighting guidelines against international standards.

Table 8. Comparison of requirements for minimum average illumination levels for different areas, and area naming in ELWIS, Wärtsilä standard technical specification, ISO 8995 and SFS-EN 12464-1.

	ELWIS	Technical specification	ISO8995 and SFS-EN 12464-1
Engine hall	300	200	200
Engine hall maint. area		300	
Control room	500		500
Office	500		
switchgear room	200		
workshop	300		
store	200		
fuel treatment house	300		
outdoor	20	20	
other rooms	200	150 - 200	
auxliary area			
canteen, corridor			
auxliary equipment area		300	
fuel supply plant			50
boiler house			100
auxliary rooms, pump rooms, condenser rooms, switchboards			200

5.2. Lighting design and simulation

According to interview with electrical & automation design engineer Ove Haldin (2012), lighting design calculations in Wärtsilä projects are done with DIALux, a free software for professional light planning. Together with the program MagiCAD, he can compose the lighting of any room. Simply put, the lighting designer outlines some luminaires in a model of a room and simulates the resulting lighting values in that room. If the values were not satisfactory, the designer then adds, moves, or replaces some luminaires and tries again. Experience and understanding of the light distribution forms of different luminaires helps to choose the ones that are required for meeting the lighting level requirements. The selection range of the luminaires available for each project can change, depending on project decisions like should luminaires be bought from the country the project is taking place in, or from Finland. Supplier's storage situation and prices can also affect the design process by changing what luminaires are available (Progman Oy 2012).

The DIALux simulation tool requires a small file, or a plugin, for each luminaire to be used in the simulation. These plugins contain values about light distribution of the luminaires. After simulation, the resulting report states different qualities of lighting on different surfaces. The default surfaces are work plane, floor, ceiling and walls. On each surface, used or resulted values are reported. DIALux simulation summary page lists different planes, but for simulation purposes reflection factor does not exist for the work plane as it is not a real surface, but an abstract concept. Work plane is an imaginary horizontal plane at the height where most of the work is expected to be done. Next value is the average maintained illuminance, followed by minimum and maximum illuminance values and the uniformity factor. DIALux can also be used to calculate the unified glare rating, UGR, but that feature was not used in the LED test simulations.

Figure 9 shows an example of the summary page from a DIALux simulation report. On the top there is the name of the lighting designer and the building in question. Next there is an overview of a room, showing approximate locations of luminaires and how the simulated illumination values are located in the room. In the middle there are the simulated lighting values on surfaces. On the bottom there is a list of the luminaires used and their properties, including combined power usage. DIALux report does include other pages, containing short introduction of the luminaires used, values of illuminances on each individual wall and the portions of direct and indirect illuminances.

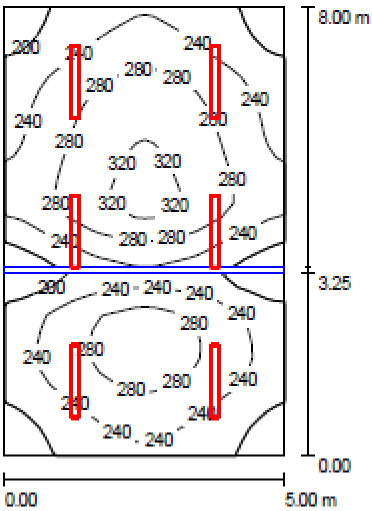
DIALux can also produce raytraces, rendered images, of the simulated lighting. These can help to better understand the how intended lighting is distributed in the space, especially in more complicated cases. An example of a raytrace produced by DIALux is shown in Figure 10.

KIPEVU III DIALux

19.03.2010

Operator Pradnyesh
Telephone
Fax
e-Mail

Chemical Storage Shelter / **Summary**



Height of Room: 4.450 m, Mounting Height: 4.000 m, Light loss factor: 0.70

Values in Lux, Scale 1:103

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	252	137	335	0.543
Floor	20	200	64	270	0.319
Ceiling	80	68	49	79	0.726
Walls (4)	50	152	57	272	/

Workplane:
Height: 0.800 m
Grid: 32 x 32 Points
Boundary Zone: 0.000 m

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.636, Ceiling / Working Plane: 0.270.

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ [lm]	P [W]
1	6	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W (1.000)	6700	72.0
		Total:	40200	432.0

Specific connected load: 10.80 W/m² = 4.28 W/m²/100 lx (Ground area: 40.00 m²)

Figure 9. Example of a DIALux lighting simulation report, summary page

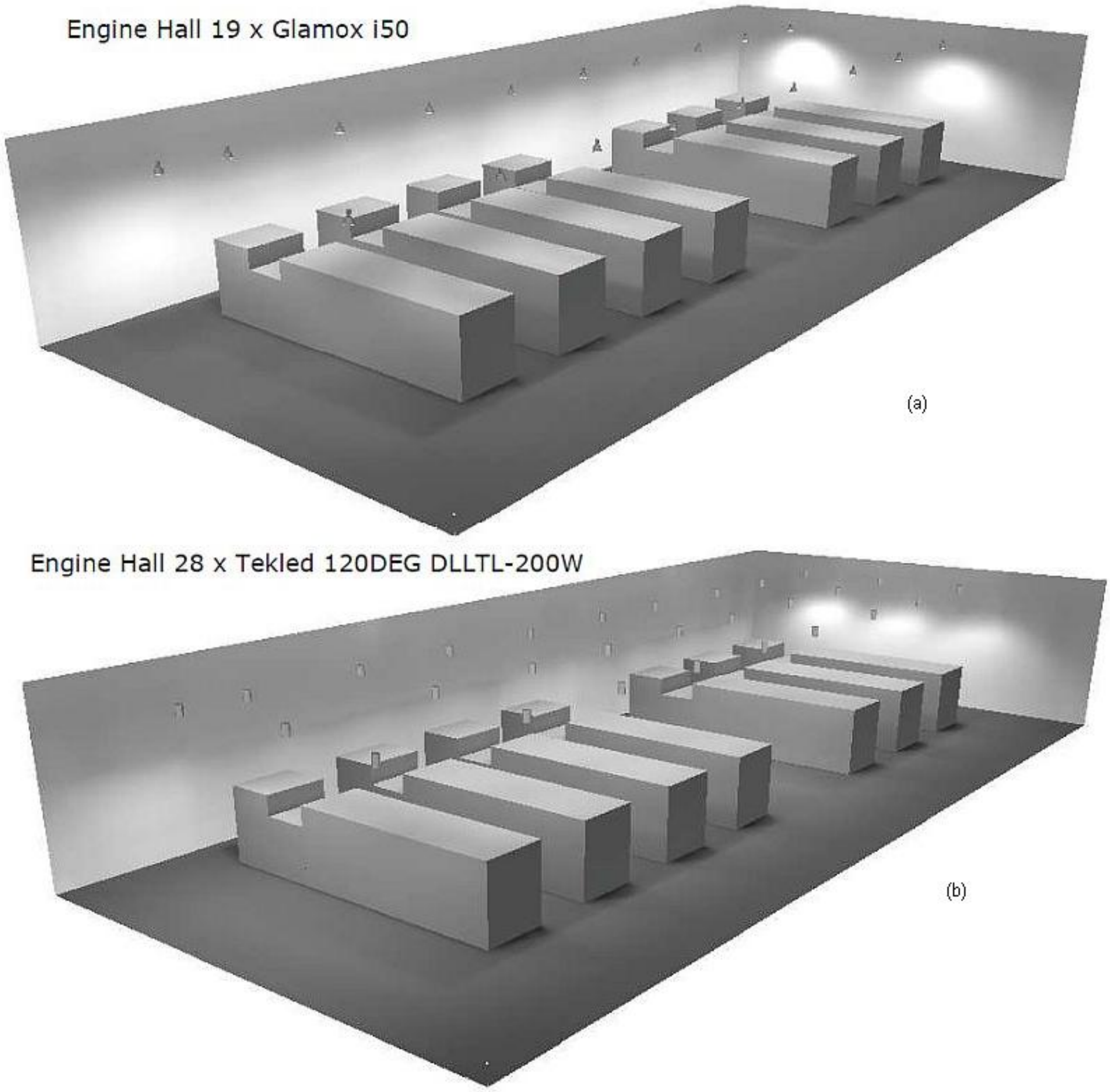


Figure 10. Raytraces produced by DIALux, with Glamox luminaires (a) and with Tekled luminaires (b).

5.3. Lighting installation cost calculation

Costs are important to any real world application. Cost estimation provides a way to compare different technologies and asses their viability. Wärtsilä has developed a specialised tool to calculate installation costs. Wärtsilä installation cost estimation tool, WIMCE, has several inputs and outputs. Figure 11 shows the interface used to configure the costing calculator.

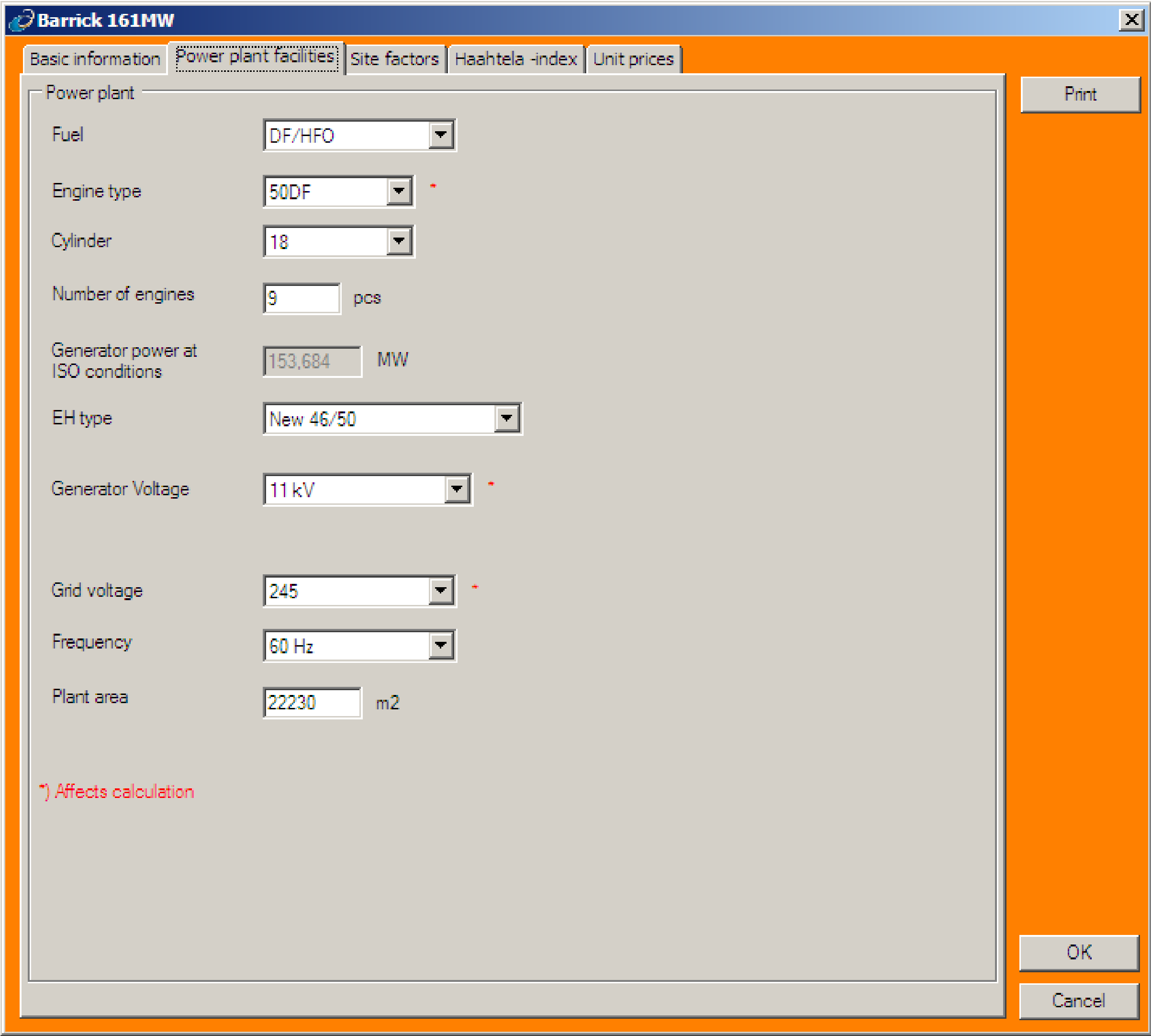


Figure 11. User interface of WIMCE program.

Basic inputs of WIMCE include layouts of site, engine hall and section, scope of supply, location, country, nearest city, fuel, engine type, number of engines generator voltage, grid voltage and frequency. From the lighting design phase, WIMCE receives a material list of luminaires and related items such as brackets, suspension rails and cables.

WIMCE produces a bill of quantities, i.e. amounts, of tasks or items that can then be priced. The bill of quantities is itself a tool when asking for offers from subcontractors, making it possible to clearly communicate the needed tasks. Price of a task depends greatly on the country the project is taking place in. After every relevant item and task has a price, WIMCE can report the complete cost estimation of the lighting installation. An example of a price calculation result is shown in Figure 12.

Elemental estimate - Electrical Works

EPC, C0 (Mat. + Work),C1 (Mat. + Work),C2 (Mat. + Work),C3 (Mat. + Work),W (Mat. + Work)

14.1.2013 11:52

SAP	Sep.	Item	Qty	*	Unit	Mat. €/unit	Work €/unit	€/Unit	€	Total €
1069031	Lighting and building electrification									
		LV Cable, 1kV YY 3G2.5re, mounted into conduit	506		m	[illegible]	[illegible]	[illegible]	1 458	
		LV Cable, 1kV YY 5G2.5re, mounted into conduit	464		m	[illegible]	[illegible]	[illegible]	1 696	
		LV Cable, 1kV YY 5G120rm, mounted into conduit	35		m	[illegible]	[illegible]	[illegible]	2 906	
		LV Cable, 1kV YCY 3x10+10rm, bounded, on ladder	142		m	[illegible]	[illegible]	[illegible]	1 392	
		LV Cable, 1kV YCY 3x25+16rm, bounded, on ladder	324		m	[illegible]	[illegible]	[illegible]	5 332	
		LV Cable, 1kV YY 3G2.5re, bounded, on ladder	686		m	[illegible]	[illegible]	[illegible]	2 355	
		LV Cable, 1kV YY 5G2.5re, bounded, on ladder	464		m	[illegible]	[illegible]	[illegible]	1 952	
		LV Cable, 1kV YY 5G120rm, bounded, on ladder	15		m	[illegible]	[illegible]	[illegible]	1 314	
		LV Cable, 1kV YCY 3x10+10rm, bounded, on ladder (h>4m)	75		m	[illegible]	[illegible]	[illegible]	765	
		LV Cable, 1kV YCY 3x25+16rm, bounded, on ladder (h>4m)	144		m	[illegible]	[illegible]	[illegible]	2 427	
		LV-cable termination, cable lug, wire mark, 5<wire area<20mm2	96		pcs	[illegible]	[illegible]	[illegible]	980	
		LV-cable termination, cable lug, wire mark, 100<wire area<200m	10		pcs	[illegible]	[illegible]	[illegible]	282	
		BLI Lighting panel	1,0		pcs	[illegible]	[illegible]	[illegible]	4 952	
		Fluorescent luminaire, EX protected	76		pcs	[illegible]	[illegible]	[illegible]	15 385	
		Fluorescent luminaire	49		pcs	[illegible]	[illegible]	[illegible]	7 648	
		High bay luminaire	21		pcs	[illegible]	[illegible]	[illegible]	9 581	
		Exit luminaire	6,0		pcs	[illegible]	[illegible]	[illegible]	1 568	
		Luminaire, outside	14		pcs	[illegible]	[illegible]	[illegible]	7 835	
		Receptacle	22		pcs	[illegible]	[illegible]	[illegible]	1 665	
		Receptacle 3-phase	11		pcs	[illegible]	[illegible]	[illegible]	338	
		Switch	4,0		pcs	[illegible]	[illegible]	[illegible]	221	
		Lighting rail	400		m	[illegible]	[illegible]	[illegible]	5 851	
		Aluminium conduit 20mm	650		m	[illegible]	[illegible]	[illegible]	2 971	
		Aluminium conduit 40mm	250		m	[illegible]	[illegible]	[illegible]	2 867	

Figure 12. Installation cost estimation result from WIMCE program.

6. COMPARISON OF LIGHTING SIMULATIONS

Purpose of this study is to explore properties of LED lighting as an option for a Wärtsilä power plant. Notable differences compared to the original lighting solution will likely occur in amounts of luminaires installed, procuring costs, installing costs, maintenance interval and power consumption. This question will be approached by comparing an existing Wärtsilä power plant simulation with conventional lighting to LED lighting simulations for that same power plant. The original simulation of Kipevu III power plant lighting is used as a base for the comparison and a new lighting using LED technology is designed for a selection of same size buildings. The LED test simulations were made and edited according to my requests by Ove Haldin, design engineer at Citec Engineering, during the autumn 2012 and January 2013. Engineering management office of Wärtsilä decided the pool of LED luminaires to be used in this comparison.

6.1. Simulation parameters

The parameters and values affecting DIALux lighting simulations are:

- -The design file, or plugin, to DIALux, that is available from manufacturer of the luminaire or lamp.
- -The amount, position and types of luminaires used
- -The form and dimensions of the room and any large obstacles in the room
- -The reflection factors used on floor, ceiling and walls

In each consecutive simulation, the reflection factors and room dimensions have not been modified. The only parameters that have been changed are the luminaires or lamps, their positions and amounts. The luminaire design files that were used in the original simulation, shown in Appendix 1, are assumed to be the same ones used in the newer simulations, shown in Appendices 2 to 4, when applicable. These plugins are provided by the manufacturers of luminaires or lamps.

In the selected three rooms of the original Kipevu III power plant lighting simulation (Appendix 1), three different kinds of luminaires were used. These luminaires are shown in the Figure 13. Figure 14 shows luminaires used in first LED test simulation (Appendix 2). Figure 15 shows all the luminaires and lamps used in the second and third LED test simulations (Appendices 3 and 4). The third LED test simulation (Appendix 4) is made without the luminaire Glamox MIRZ67 236, that is included in the second LED test simulation (Appendix 3). Figures 13, 14 and 15 also show light distribution from the luminaire in polar coordinates.

After the first LED test simulation, more simulations were requested because of difficulties in acquiring pricing for the example luminaires used. This also allows for a more thorough comparing of different LED lighting options in regards to technical aspects.

The second and third LED test simulations were the results of this request, but only concerning the engine hall. The first LED test simulation also contains two other rooms, starting & working air room and switchgear room.

In the second LED test simulation (Appendix 3), difficulties came up in the simulations when LED technology tubes (DLL-T83A12-20W) were to be used in the place of the fluorescent tubes (2x36W T8) in the luminaire body (Glamox MIRZ67 236). This was circumvented by simulating using fluorescent tubes with manually changed value of luminous flux to correspond with the LED technology tubes. The incurred errors in the simulation accuracy are debatable, but assumed negligible.

The third LED test simulation (Appendix 4) is similar to the second LED test simulation (Appendix 3), with the exceptions that the luminaire body has been removed, and the actual corresponding LED technology tube lamp design file, plugin, was used. In reality, lamps do not function without the body of a luminaire, so the third LED test simulation (Appendix 4) answers a question “what if LED tubes were powered and used without a luminaire body”. This way it is possible to see how the LED tubes function without the luminaire body, but as such it is does not represent an option for implementing or price estimation. In the second LED test simulation (Appendix 3), each of the Glamox luminaires contains two LED tubes, and therefore the amount of LED tubes

(DLL-T83A12-20W) is the same in both second (Appendix 3) and third (Appendix 4) LED test simulation. That is, 238 LED tubes.

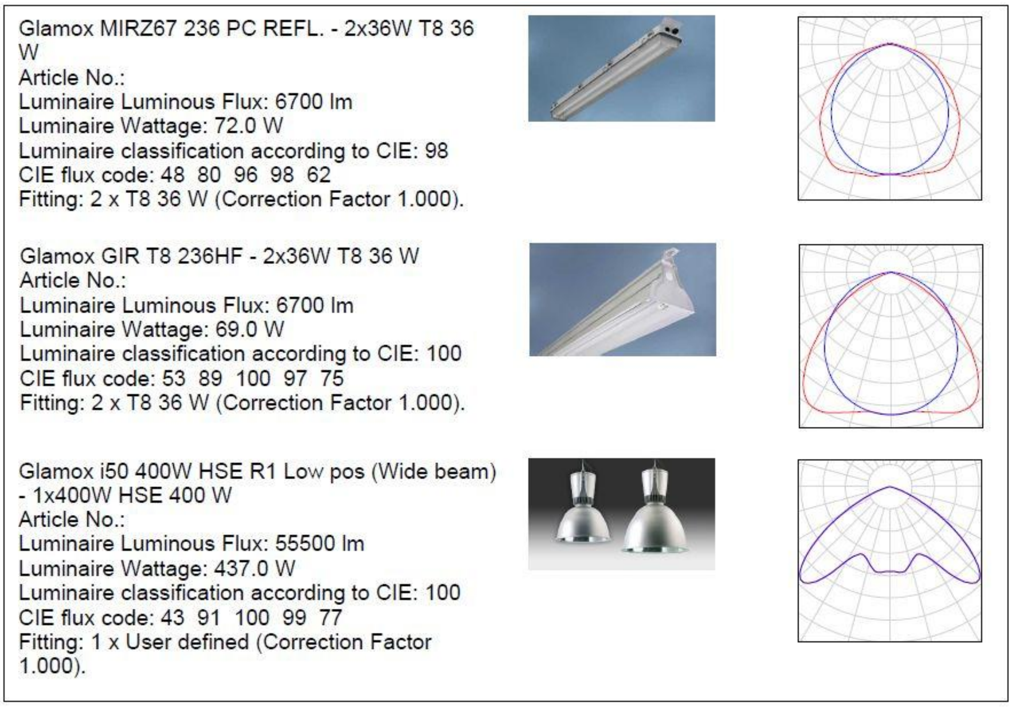


Figure 13. Luminaires used in Kipevu III power plant. Data from the original Kipevu simulation file.

Figure 14. Luminaire data used in first LED test simulation (Tekled 2012).

Product model	DLL-T83A12-20W
Input voltage	100-240V AC, 50/60Hz
LED Quantity	312pcs 3528
Size	1200*30mm
Power consumption	21W
Luminous flux	1900-2100lm
CCT	warm white:3000K—3500K， pure white:4000K—4500K, cool white:5500K—6500K

Figure 15. Luminaires and lamps in the second and third LED test simulations (Tekled 2012).

The HID lamp used in the original Kipevu III simulation has a luminous efficacy of 142 lm/W, and 93 lm/W for the linear fluorescent lamps. For the LED lamps used in the simulations the manufacturer reported >80 lm/W luminous efficacy.

6.2. Comparison of quantities

The most apparent changes between the simulations shown in Appendices 1 to 4 are the amounts and qualities of luminaires or parts used. These are collected to Table 9. The changes in amounts of luminaires in engine hall were not significant. In the smaller space, starting & working air room, between original and first LED test simulations, a change of luminaire amount from 6 to 3 is a substantial relative difference. Note that the original simulation uses 2 x 119 standard T8 fluorescent tubes inside the Glamox MIRZ67. The Glamox MIRZ67 luminaires house a total of 238 tubes also in the second LED test simulation, but in that simulation their lm value has been changed to match the LED tube DLL-T83A12-20W.

Table 9. Quantities of luminaires or parts in all simulations.

	luminaire or part	Original Kipevu III	First sim.	Second sim.	Third sim.
Engine hall	Glamox i50 400W HSE R1 Low pos - 1x400W HSE 400 W	19			
	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W	119			
	DREAM LED LIGHT by MATRIX 120DEG DLLIL-200W-1		28		
	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W		120		
	Glamox MIRZ67 236 PC REFL. - 2x *modified* T8			119	
	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W			29	29
	DLL DLL-T83A12-20W LED				238 (=2x119)
Starting & Working Air	Glamox GIR T8 236HF - 2x36W T8 36 W	6			
	DREAM LED LIGHT by MATRIX DLLTL-120W		3		
Switchgear Room	Glamox GIR T8 236HF - 2x36W T8 36 W	16			
	DREAM LED LIGHT by MATRIX DLLTL-120W		10		

6.3. Quality of lighting in simulations

Looking at the properties of lighting of the different simulations two most important values stand out. E_{av} is the value of average illumination, whereas u0 denotes the uniformity of lighting, highest value divided by the lowest value. Both E_{av} and u0 are mentioned in the standards examined in Chapter 3, and have different requirements depending on the area and standard. I assume the most important plane to review is the so called work plane, the plane 0.8 metres from floor, where most of the work and interaction between the man and the surroundings are assumed to take place. The illuminance of the ceiling, for example, is not interesting. In Table 10, the uniformity and average illuminance values of work planes are collected from all simulations shown in Appendices 1 to 4.

The first LED test simulation, shown in Appendix 2, seems to have the highest average illumination in all rooms, and highest lighting uniformity in the engine hall. The second and third LED test simulations do not meet any requirements for lighting stated in Wärtsilä's own guidelines or international standards. Engine hall lighting uniformity is insufficient in all four cases when comparing to either ISO 8995 or SFS-EN 12464-1. Although, the engine hall area under study is almost 30 m · 70 m. Over 2000 m^2 area is demanding both to simulate and to balance illuminance amounts at, as any spike in luminance or a darker area immediately lowers the uniformity value for the whole area.

The first LED test simulation (shown in Appendix 2) has lower lighting uniformity in starting & working air room. This is due to using only three luminaires. The first LED test simulation does not meet either the international or the European standard in lighting uniformity. The original Kipevu III simulation (shown in Appendix 1) in starting & working air room does meet the lighting uniformity requirements stated in SFS-EN 12464-1 but not the requirements stated in ISO 8995.

In switchgear room, both the original Kipevu III and first LED test simulations meet both standards in maintained illuminance, but not in lighting uniformity.

Table 10. Average illumination and uniformity of lighting on work planes in all simulations.

	Aspect of lighting	Original Kipevu III	First sim.	Second sim.	Third sim.
Engine hall	Eav [lx]	315	418	135	194
	u0	0.307	0.348	0.319	0.095
Starting & Working Air	Eav [lx]	389	542		
	u0	0.564	0.305		
Switchgear	Eav [lx]	275	356		
	u0	0.024	0.023		

6.4. Power consumption

Comparing the electrical energy usage of different lighting options is one of the main objectives for this thesis work. Power consumption from all the simulations in Appendices 1 to 4 are shown in Table 11.

In terms of electrical energy consumption, the second (Appendix 3) and the third LED test simulation (Appendix 4) contain same equipment, so their power consumption is identical. In engine hall, the second LED test simulation (Appendix 3) does report less power than original Kipevu III lighting simulation (Appendix 1). In the first LED test simulation (Appendix 2) the power consumption is almost double of the power consumption in the original Kipevu III simulation (Appendix 1) (30619.6 W / 16871 W ≈ 1.849 ≈ 185 %). In starting & working air and switchgear rooms the differences between the original Kipevu III and the first LED test simulations are relatively insignificant. In Starting & working air room the power consumption is slightly less in the first LED test simulation (Appendix 2), and slightly higher in switchgear room area, compared to the original Kipevu III simulation (Appendix 1).

Table 11. Power consumption in all lighting simulations.

		Original Kipevu III	First sim.	Second sim.	Third sim.
Engine hall	Power [W]	16871	30619,6	10853	10853
Starting & Working Air	Power [W]	432	395,7		
Switchgear	Power [W]	1104	1319		

6.5. Maintenance interval

Lamp manufacturers report their products' expected lifespan in their data sheets. LED lamps consist of multiple small LEDs, and when the individual LEDs expire, it affects the lamp's brightness, but a LED lamp does not burn out all at once like lamps based on conventional lighting technology do.

Additionally, manufacturers of luminaires declare the ambient temperature, to which their luminaire is suitable. Most lamps don't usually have reported ambient temperatures, since they are assumed to be fitted inside the luminaires. LED lamps appear to be an exception to this, possibly because the semiconductor technology, upon which LEDs are based on, functions the better the lower the temperature is.

In the Table 12, lamp life and luminaire rated ambient temperature are collected for all items used in the simulations in Appendices 1 to 4. With the LED tube DLL-T83A12-20W, lifespan and ambient temperature values were unavailable, and thus values from a similar lumen LED product of manufacturer OSRAM were used. LED luminaires are promised almost twice the lifespan compared to linear fluorescent T8 lamps. However, a 400 W HID technology lamp has a longer life expectancy than most LED products listed. LED luminaires also have mostly lower rated ambient temperature, Ta. According to Wärtsilä's internal mechanical database heat load calculations, the engine hall ceiling temperature can be 15 °C higher than the rest of the room. This will have an adverse affect on the lifespan of lamps, especially if the ambient temperature rises higher than the luminaire rated ambient temperature value.

Table 12. Luminaire ambient temperature rating and lamp lifespan.

Room	Luminaire	Lamp, if applicable	Lamp life [h]	Ta [°C] of luminaire
Engine hall	Glamox i50 400W HSE R1 Low pos - 1x400W HSE 400 W	MASTER SON(-T) PIA - SON-T PIA Plus 400W E40 - Philips	38000	40
	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W	T8 MASTER TL-D Super80 - TL-D 36W/835 G13 - Philips	20000	40
	DREAM LED LIGHT by MATRIX 120DEG DLLIL-200W-1		35000	25
	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W		35000	25
		DLL DLL-T83A12-20W LED	(40000)	(50)
S & W Air and Switchgear	Glamox GIR T8 236HF - 2x36W T8 36 W	T8 MASTER TL-D Super80 - TL-D 36W/835 G13 - Philips	20000	45
	DREAM LED LIGHT by MATRIX DLLTL-120W		35000	25

6.6. Installation and procurement costs

When determining viability of a new technology, costs provide important information required to compare different options. The calculation was done by electric installation costing estimator Jani Aurell. Installation cost difference is more interesting in relative than absolute values, as absolute values will change in every project, depending on the factors explained earlier in Chapter 5. The lighting installation costs in engine hall are 12.5 % higher in second LED test simulation (Appendix 3) compared to the original Kipevu III engine hall (Appendix 1).

Procurement cost difference is substantial, both absolute and relative difference. The luminaires and parts used in second LED test simulation (Appendix 3) cost 3,9 times the amount than that of the original Kipevu III luminaires and parts (Appendix 1). In other words, the original lighting parts cost was 25.6 % of the cost of the parts of second LED test.

7. CONCLUSIONS

The main objective of this thesis work was to study the viability and potential of LED lighting in a Wärtsilä power plant. According to the studies made in this thesis, the goal of lowering energy use of power plant lighting by installing LED technology luminaires seems to be unattainable. None of the simulated LED lighting options were satisfactory. They either used more power than the original lighting system, or did not produce acceptable amount and quality of illumination. In the engine hall area, it remains unclear if the LED lamps and luminaires can withstand the ambient heat, and how greatly their life spans are affected. In addition, the LED lighting is significantly more expensive to procure.

The secondary objective of this thesis was to document the current lighting design guidelines of Wärtsilä and listing of the relevant standards. This objective was met. Tables comparing and representing the key differences between internal guidelines and international standards were compiled.

The lamps of LED technology did show some advantages and hints of potential in the simulation comparisons. In a small room the LED lighting can consume less energy than other solutions, but the illuminance uniformity limit will be challenging to meet. The LED tubes have twice the lifetime of the fluorescent counterpart, but the total luminance flux of the LED tubes is significantly lower.

However, it is to be noted that LED lighting technology is presently undergoing fast development and its luminous efficacy is expected to be superior in near future.

As a conclusion, LED lighting is not a viable option of saving electrical energy in Wärtsilä power plants. The existing lighting solutions consists of lamps with higher lumen-per-watt ratio and some even have better life expectancy than the LED technology based alternatives explored in this thesis. However, one should remember that this thesis was by no means a comprehensive comparison of all existing LED lamps and luminaires. Better alternatives can be out there in the market and were just not noticed yet. This will most likely be the case in the future, when the LED lighting technology progresses. Improvements will be required in the areas of total luminous flux, operating temperature and power consumption to make LED lamps a viable option for Wärtsilä power plant lighting.

REFERENCES

ABB (2000). *Teknisiä Tietoja ja Taulukoita*. 9th edition. Vaasa, Finland. ISBN: 951-99366-0-2. 626 p.

Aurell, J. (2012). Interview with the Electric Installation Costing Estimator of Wärtsilä Power Plants. Vaasa, Finland. 30 November 2012.

Boud, John (1973). *Lighting design in buildings*. Stevenage, England: Peter Peregrinus Ltd. ISBN: 0-901223-37-5. 178 p.

Cree (2012). Press release 18.12.2012 *Cree Reaches LED Industry Milestone with 200 Lumen-Per-Watt LED*. Available online: <URL:http://www.cree.com/news-and-events/cree-news/press-releases/2012/december/mkr-intro>

CVRL (2012). Colour & Vision Research Laboratory, University College London: *Colour & Vision Research laboratory and database*. Available online: <URL:http://www.cvrl.org/>

DIAL (2012) Software centre for DIALux und Product Management Systems. Available online: <URL: http://www.dial.de>

DOE (2012). U.S. Department of Energy. Solid-State Lighting Research and Development: *Multi-Year Program Plan April 2012*. Available online: <URL:http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2012_web.pdf>

Haldin, O. (2012). Interview with the Design Engineer of Citec Engineering Electrical & Automation. Vaasa, Finland. 23 August 2012.

Halonen, Liisa, Jorma Lehtovaara (1992). *Valaistustekniikka*. Jyväskylä, Finland: Gummerus Kirjapaino. ISBN: 951-672-145-1. 456 p.

Halonen Liisa, Tetri Eino, Bhusal Pramod (2010). *Annex 45- Guidebook on energy efficient electric lighting for buildings*. Aalto University. Espoo, Finland. Available online: <URL:http://lightinglab.fi/IEAAnnex45/>

Hotakainen Markus, Klimstra Jacob & Wärtsilä Finland Oy (2011). *Smart power generation*. Helsinki, Finland: Avain Publishers. ISBN: 978-951-692-846-6. 194 p.

Hung, Po-Chieh & Tsao, Jeffrey Y (2012). *Maximum White Luminous Efficacy of Radiation Versus Color Rendering Index and Color Temperature: Exact Results and a Useful Analytic Expression*. Journal of Display Technology, Volume PP, Issue 99. Digital Object Identifier : 10.1109/JDT.2012.2224638. ISSN: 1551-319X.

IEC 60598-1 (2008). International Standard: *Luminaires – Part 1: General requirements and tests*. ISBN: 2-8318-9707-6.

IEC 60598-2-1 (1979). International Standard: *Luminaires – Part 2-1: Particular requirements – Fixed general purpose luminaires*.

IEC 60598-2-2 (2011). International Standard: *Luminaires – Part 2-2: Particular requirements – Recessed luminaires*. ISBN: 978-2-88912-772-6.

IEC 60598-2-5 (1998). International Standard: *Luminaires – Part 2-5: Particular requirements – Floodlights*. ISBN: 2-8318-4212-3.

IEC 60598-2-22 (2008). International Standard: *Luminaires – Part 2-22: Particular requirements – Luminaires for emergency lighting*. ISBN: 2-8318-9659-2.

ISO 23539 (2005). International Standard: *Photometry - The CIE system of physical photometry*. ISO 23539:2005(E) CIE S 010/E:2004.

ISO 8995 (2002). International Standard: *Lighting of indoor work places*. ISO 8995:2002(E) CIE S 008/E-2001.

KenGen (2013) Kenya Electricity Generating Company. *Power plants - Thermal Plants*. Available online: <URL:http://www.kengen.co.ke> Cited 10.01.2013.

Matsumoto Takahiro & Makoto Tomita (2010). *Modified blackbody radiation spectrum of a selective emitter with application to incandescent light source design*. Optical Society of America: Optics Express, Vol. 18, Issue S2, pp. A192-A200.

Murphy, Thomas W. (2012). *Maximum spectral luminous efficacy of white light*. Journal of Applied Physics, Volume 111, Issue 10. ISSN: 1089-7550.

NIST (1997). National Institute of Standards and Technology. *NIST Measurement Services Special publication 250-37, Photometric Calibrations*. Available online: <URL:http://www.nist.gov/calibrations/upload/sp250-37.pdf>

OECD/IEA (2006). The Organisation for Economic Co-operation and Development, International Energy Agency. *Policies for Energy-efficient Lighting -Lights Labour's Lost*. Paris, France: Actis. ISBN: 92-64-10951-X. 560 p.

Pellas, T. (2013). Interview with the Electrical Engineering Manager of Wärtsilä Power Plants Engineering Management Office. Vaasa, Finland. 16 January 2013.

Progman Oy (2012) Developer and supplier of MagiCAD. Available online: <URL:http://www.magicad.com>

Ribacka, M. (2012). Interview with the Sales Tools General Manager of Wärtsilä Power Plants Sales. Vaasa, Finland. 29 November 2012.

Schiler, Marc (1992). *Simplified Design of Building Lighting*. United States of America: Wiley-Interscience publication ISBN: 0-471-53213-4. 155 p.

SFS-EN 1837+A1 (1999). European and Finnish Standard. *Safety of machinery. Integral lighting of machines.*

SFS-EN 1838 (1999). European and Finnish Standard. *Lighting applications. Emergency lighting*.

SFS-EN 12464-1 (2011). European and Finnish Standard. *Light and lighting. Lighting of work places. Part 1: Indoor work places*.

SFS-EN 12464-2 (2007). European and Finnish Standard. *Light and lighting. Lighting of work places. Part 2: Outdoor work places*.

SFS-EN 12665 (2011). European and Finnish Standard. *Light and lighting. Basic terms and criteria for specifying lighting requirements*.

SFS-EN 15193 (2007). European and Finnish Standard. *Energy performance of buildings. Energy requirements for lighting*.

SFS-ISO 3864-1 (2011). International and Finnish Standard. *Graphical symbols -Safety colours and safety signs- Part 1: Design principles for safety signs and safety markings*.

SFS-ISO 3864-2 (2004). International and Finnish Standard. *Graphical symbols. Safety colours and safety signs. Part 2: Design principles for product safety labels*.

Steffy, Gary R. (1990). *Architectural lighting design*. New York, United States of America: Van Nostrand. ISBN: 0-442-20761-1 202 p.

Tekled (2012) Dream Led Light by Matrix Available online: <URL:http://www.tekleds.com/>

Turner, Janet (1998). *Designing with light*. Switzerland: RotoVision SA. ISBN: 2-88046-333-5. 159 p.

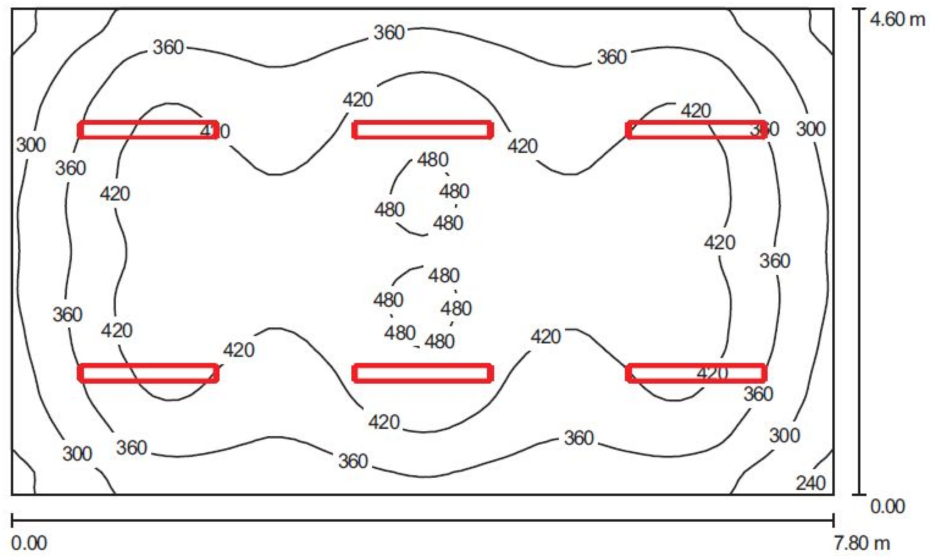
Virginia Department of Mines, Minerals and Energy (2008). *The Virginia Energy Savers Handbook*. Third edition. 168 p. Available online: <URL: http://www.dmme.virginia.gov>

Waymouth, J.F. (1996) Where we are in light source performance; where we would like to get. Plasma Science Conference Record. ISSN: 0730-9244.

APPENDICES

Appendix 1. Original DIALux simulations

Starting & Working Air Room / Summary



Height of Room: 3.034 m, Mounting Height: 2.700 m, Light loss factor: 0.70

Values in Lux, Scale 1:60

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	389	219	492	0.564
Floor	20	326	221	418	0.678
Ceiling	80	85	61	100	0.722
Walls (4)	50	192	74	317	/

Workplane:		**UGR**	Lengthways-	Across	to luminaire axis
Height:	0.800 m	Left Wall	21	21	
Grid:	64 x 64 Points	Lower Wall	20	21	
Boundary Zone:	0.000 m	(CIE, SHR = 0.25.)			

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.500, Ceiling / Working Plane: 0.218.

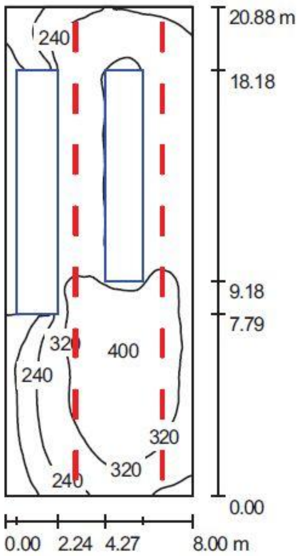
Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ [lm]	P [W]
1	6	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W (1.000)	6700	72.0
		Total:	40200	432.0

Specific connected load: 12.04 W/m² = 3.10 W/m²/100 lx (Ground area: 35.88 m²)

Figure 16. Original Kipevu III lighting simulation first summary page, starting & working air room.

Switchgear Room / Summary



Height of Room: 4.280 m, Mounting Height: 3.700 m, Light loss factor: 0.70

Values in Lux, Scale 1:269

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	275	6.57	403	0.024
Floor	20	194	1.05	366	0.005
Ceiling	80	55	29	75	0.528
Walls (4)	50	111	7.43	291	/

Workplane:
Height: 0.800 m
Grid: 128 x 64 Points
Boundary Zone: 0.000 m
Illuminance Quotient (according to LG7): Walls / Working Plane: 0.405, Ceiling / Working Plane: 0.200.

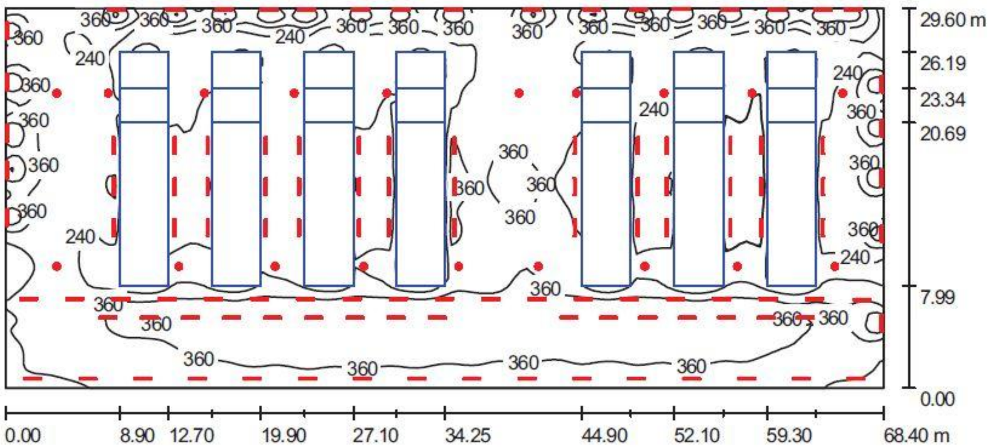
Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ [lm]	P [W]
1	16	Glamox GIR T8 236HF - 2x36W T8 36 W (1.000)	6700	69.0
		Total:	107200	1104.0

Specific connected load: 6.61 W/m² = 2.41 W/m²/100 lx (Ground area: 167.04 m²)

Figure 17. Original Kipevu III lighting simulation second summary page, switchgear room.

Engine Hall / Summary



Height of Room: 10.900 m, Light loss factor: 0.70 Values in Lux, Scale 1:490

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	315	97	678	0.307
Floor	20	220	2.13	457	0.010
Ceiling	80	79	42	97	0.530
Walls (4)	50	152	45	923	/

Workplane:
Height: 0.800 m
Grid: 128 x 128 Points
Boundary Zone: 0.000 m
Illuminance Quotient (according to LG7): Walls / Working Plane: 0.466, Ceiling / Working Plane: 0.249.

Luminaire Parts List

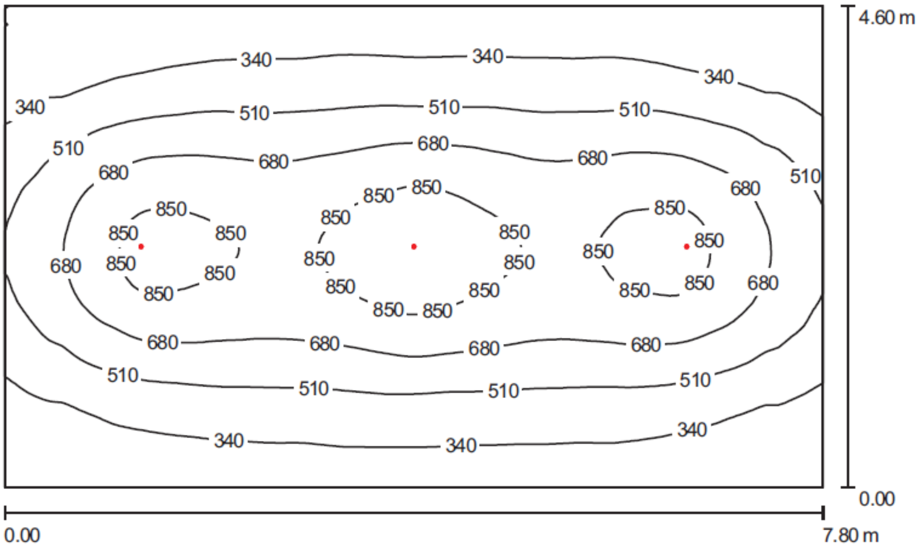
No.	Pieces	Designation (Correction Factor)	Φ [lm]	P [W]
1	19	Glamox i50 400W HSE R1 Low pos (Wide beam) - 1x400W HSE 400 W (1.000)	55500	437.0
2	119	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W (1.000)	6700	72.0
		Total:	1851800	16871.0

Specific connected load: 8.33 W/m² = 2.64 W/m²/100 lx (Ground area: 2024.64 m²)

Figure 18. Original Kipevu III lighting simulation third summary page, engine hall.

Appendix 2. First LED test simulations

Starting & Working Air Room LED test / Summary



Height of Room: 3.034 m, Mounting Height: 2.700 m, Maintenance factor: 0.70 Values in Lux, Scale 1:60

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	542	166	967	0.305
Floor	20	462	216	660	0.469
Ceiling	80	86	59	100	0.687
Walls (4)	50	181	60	536	/

Workplane:
Height: 0.800 m
Grid: 128 x 128 Points
Boundary Zone: 0.000 m
Illuminance Quotient (according to LG7): Walls / Working Plane: 0.290, Ceiling / Working Plane: 0.158.

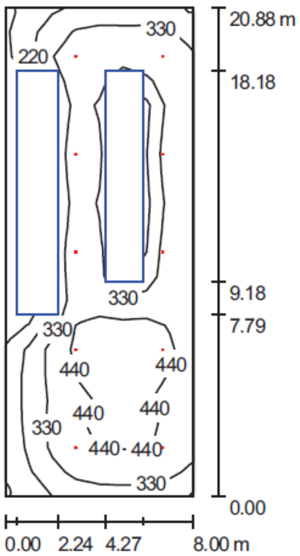
Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	3	DREAM LED LIGHT by MATRIX DLLTL-120W (1.000)	9887	9907	131.9
			Total: 29662	Total: 29722	395.7

Specific connected load: 11.03 W/m² = 2.03 W/m²/100 lx (Ground area: 35.88 m²)

Figure 19. First LED test simulation first summary page, starting & working air room.

Switchgear Room LED test / Summary



Height of Room: 4.280 m, Mounting Height: 3.700 m, Maintenance factor: 0.70

Values in Lux, Scale 1:269

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	356	8.17	512	0.023
Floor	20	252	1.13	461	0.004
Ceiling	80	68	35	94	0.507
Walls (4)	50	129	8.29	453	/

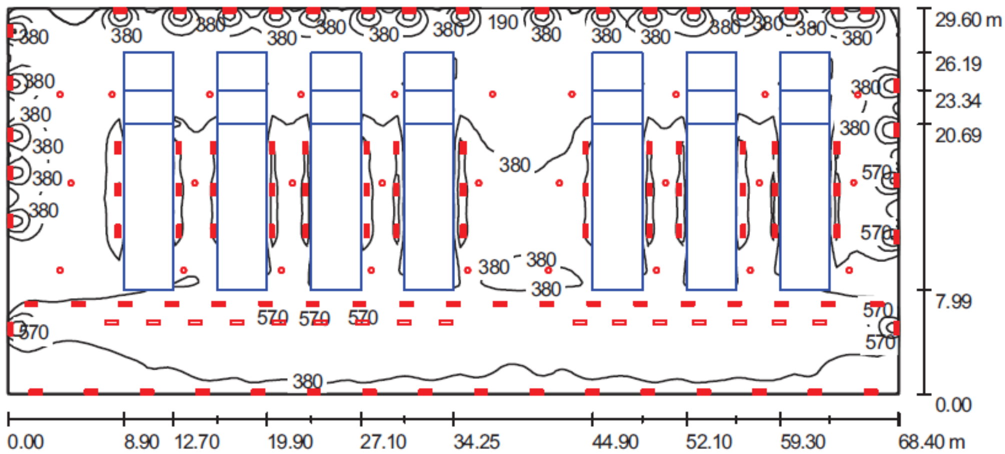
Workplane:
Height: 0.800 m
Grid: 20 x 8 Points
Boundary Zone: 0.000 m
Illuminance Quotient (according to LG7): Walls / Working Plane: 0.357, Ceiling / Working Plane: 0.192.

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	10	DREAM LED LIGHT by MATRIX DLLTL-120W (1.000)	9887	9907	131.9
			Total: 98875	Total: 99074	1319.0

Specific connected load: 7.90 W/m² = 2.11 W/m²/100 lx (Ground area: 167.04 m²)

Figure 20. First LED test simulation second summary page, switchgear room.



Height of Room: 10.900 m, Maintenance factor: 0.70 Values in Lux, Scale 1:490

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	418	146	1079	0.348
Floor	20	436	193	717	0.442
Ceiling	80	81	55	96	0.680
Walls (4)	50	141	61	474	/

Workplane:
Height: 0.800 m
Grid: 128 x 128 Points
Boundary Zone: 0.000 m
Illuminance Quotient (according to LG7): Walls / Working Plane: 0.320, Ceiling / Working Plane: 0.194.

Luminaire Parts List

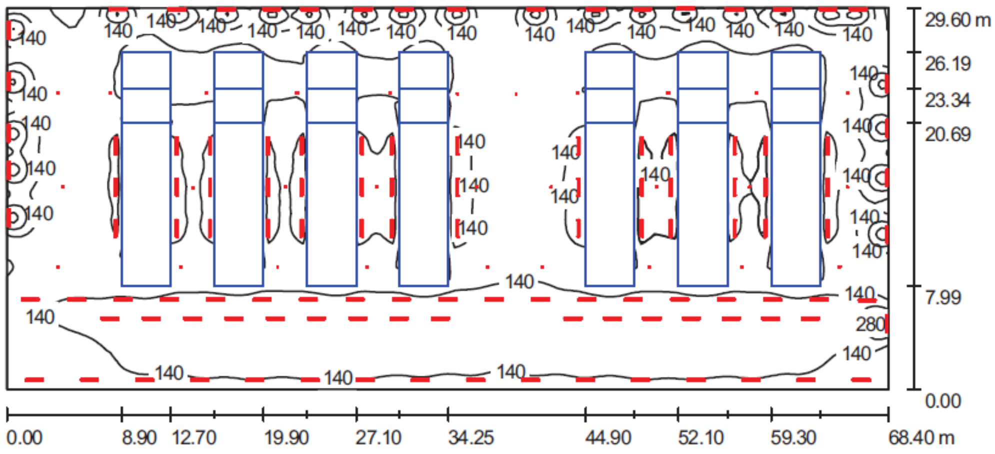
No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	120	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W (1.000)	6071	14189	206.0
2	28	DREAM LED LIGHT by MATRIX 120DEG DLLIL-200W-1 (1.000)	19345	19328	210.7
		Total:	1270187	Total: 2243912	30619.6

Specific connected load: 15.12 W/m² = 3.62 W/m²/100 lx (Ground area: 2024.64 m²)

Figure 21. First LED test simulation third summary page, engine hall.

Appendix 3. Second LED test simulation

Engine Hall / Summary



Height of Room: 10.900 m, Maintenance factor: 0.70

Values in Lux, Scale 1:490

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	135	43	362	0.319
Floor	20	95	2.53	237	0.027
Ceiling	80	31	21	38	0.677
Walls (4)	50	55	23	609	/

Workplane:

Height: 0.800 m

Grid: 128 x 128 Points

Boundary Zone: 0.000 m

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.393, Ceiling / Working Plane: 0.228.

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	29	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W (1.000)	6071	14189	206.0
2	119	Glamox MIRZ67 236 PC REFL. - 2x36W T8 36 W (Type 1)* (1.000)	2926	4720	41.0
			Total: 524266	Total: 973173	10853.0

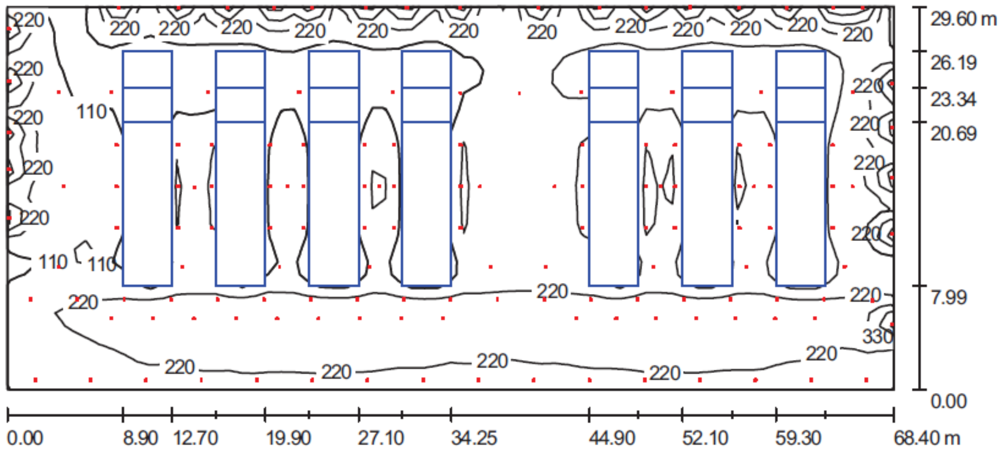
*Modified Technical Specifications

Specific connected load: 5.36 W/m² = 3.97 W/m²/100 lx (Ground area: 2024.64 m²)

Figure 22. Second LED test simulation, engine hall.

Appendix 4. Third LED test simulation

Engine Hall / Summary



Height of Room: 10.900 m, Maintenance factor: 0.70 Values in Lux, Scale 1:490

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	194	18	610	0.095
Floor	20	136	4.74	356	0.035
Ceiling	80	41	28	52	0.678
Walls (4)	50	77	32	4192	/

Workplane:

Height: 0.800 m
Grid: 30 x 68 Points
Boundary Zone: 0.000 m

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.378, Ceiling / Working Plane: 0.211.

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	238	DLL DLL-T83A12-20W LED (1.000)	2360	2360	20.5
2	29	DREAM LED LIGHT by MATRIX LED FLOOD LIGHT 200W (1.000)	6071	14189	206.0
			Total: 737636	Total: 973054	10853.0

Specific connected load: 5.36 W/m² = 2.76 W/m²/100 lx (Ground area: 2024.64 m²)

Figure 23. Third LED test simulation, engine hall.