Improving the energy efficiency of lighting systems for a marine equipment manufacturing plant through retrofitting, daylighting, and behaviour change

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1. Introduction

Industry is responsible for one-third of the world's energy consumption and 24% of global greenhouse gas emissions (GHGs) (IEA, 2020). Because of the overwhelming concerns about global warming and climate change, almost all industrial sectors have been feeling great pressure in terms of climate change adaptation and are being forced to do their fair share to enable a transformation towards sustainable energy systems and net zero emissions. The maritime industry is responsible for annual consumption of 265 million tons of fuel (Maloni et al., 2013) and 2.89% of global emissions (IMO, 2020). However, these figures only account for the operation phase of the ship's life at sea, ignoring the construction in shipyards and the manufacturing of ships' machinery and equipment in marine equipment manufacturing plants (MEMPs). Currently, all efforts, including the associated regulations, measures, research, and investment in terms of energy consumption and environmental emissions in the marine industry, have primarily focused on the design and operation phases of the ship's life cycle, neglecting the manufacturing phase, which entails considerable energy-consuming and environmentally polluting activities in shipyards and MEMPs (Vakili et al., 2021a). As the shipping industry transitions to more carbon-free fuels as a result of the ongoing efforts, the manufacturing phase of a ship's life cycle will emit significantly more GHG and air emissions than the operational activities (Vakili et al., 2022), as demonstrated by Nordtveit (2017) for a ferry and by Nordal (2021) for a containership. For this reason, it is essential to improve the energy efficiency of manufacturing facilities in the shipbuilding industry, such as MEMPs, in order to reduce energy-related emissions associated with the manufacturing phase of ships.

Marine equipment manufacturing is a strategic and pillar industry for coastal countries and regions (Kexiang Ma and Sung-Won Lee, 2020). The European MEMPs generate an annual added value of around €70 billion and contribute to the direct employment of more than 320,000 people (SEA Europe, 2022a). The shipbuilding market is one of the most competitive in the world (Stopford, 2009), forcing MEMPs to enhance their competitiveness. MEMPs manufacture a range of ship equipment and machinery, including propellers, stern tubes, rudders, deck cranes and machinery, etc. The production of these requires a number of diverse manufacturing processes and systems, such as melting, machining, surface treatment, and heat treatment, which consume a substantial amount of energy, resulting in a substantial energy cost that has a substantial impact on the competitiveness of energy-intensive industries (Horne and Reynolds, 2017). Energy costs are now an important competitiveness factor for the European MEMPs more than ever. While they have been impacted more by the COVID-19 pandemic than their state-aided competitors in China and South Korea, the recent issues of access to energy and rising energy prices as a result of the international sanctions imposed on Russia following the war in Ukraine have diminished their competitiveness (SEA Europe, 2022b). In addition, MEMPs' energy use results in significant direct and indirect environmental and climate impacts. Although MEMPs are land-based sectors not governed by the IMO and other maritime regulations, they are covered by the Paris Agreement (Pruyn and Cozijnsen, 2020), implying that governments can include emissions from MEMPs in their NDCs to meet the Paris Agreement's requirements. Therefore, it is envisaged that MEMPs, together with shipyards, will inevitably come up on the agenda, compelling them to undergo a green transition to reduce energy use and environmental impacts.

The promotion of energy management and cleaner production in industry through energy efficiency, electrification, and behaviour change is recognized as a key factor in the transition to a carbon-neutral economy and in addressing environmental issues (IEA, 2021; Román-Collado and Economidou, 2021; Trianni et al., 2014). MEMPs can benefit from clean production, energy management, and increased energy efficiency in their production to enhance their competitiveness and reduce their negative environmental impacts. Although energy efficiency is regarded as critical to addressing current energy issues, implementation of energy efficiency solutions in industry is hampered by companies' risk aversion due to the cost of production interruption caused by the implementation of energy-saving measures (Cagno et al., 2015; Trianni et al.as, 2016, 2013a). For example, Vakili et al. (2021a) demonstrated for a shipyard that the risk of production interruption cost is one of the most significant obstacles to implementing energy-saving measures. At this point, starting with lighting systems to increase energy efficiency may be a strategic instrument for overcoming the risk aversion of industrial companies for energy efficiency. This is because lighting systems are less complex than other energy-consuming systems in industrial plants; energy-saving upgrades and retrofits will have minimal impact on production (Trianni et al., 2014). Also, lighting is a remarkable contributor to global energy demand and GHG emissions, accounting for 15% of global energy consumption and 5% of global GHG emissions (U.S. Department of Energy, 2015). Industrial sectors account for around 16% of the global energy used for lighting, and this share is projected to increase in the future (Halonen et al., 2010). The transition to energy-efficient lighting is therefore viewed as a highly promising strategy to increase energy efficiency across all industries industry and is currently a top priority for many nations (Laurea, 2012; Trianni et al., 2014). In view of these, energy-efficient lighting can promote clean production and energy management cultures in MEMPs and pave the way to increasing their competitiveness while reducing environmental impacts.

Despite the importance of lighting systems for their potential to save energy and the dissemination of energy management culture in industrial facilities, the study of energy-efficient lighting in industrial scale application is limited, and the existing research has been primarily focused on different applications such as residential lighting (e.g., de Souza et al., 2019), office lighting (e.g., Ryckaert et al., 2010; Safranek et al., 2020), street lighting (e.g., Campisi et al., 2018), greenhouse lighting (e.g., Katzin et al., 2021; Singh et al., 2015), and lighting for educational buildings (e.g., Anand et al., 2019; Belany et al., 2021; Gentile et al., 2018; Gorgulu and Kocabey, 2020). Industrial facilities such as MEMPs are more energy-intensive and may have greater illumination needs than these applications (Chen et al., 2014).

Recent research by Johansson et al. (2022) indicates that lighting systems are among the systems with the greatest potential for energy savings in industrial facilities. Energy-efficient lighting technologies such as LED offer industrial companies simple and cost-effective solutions with a considerably longer lifespan than inefficient conventional lamps (UNEP, 2012). According to the International Energy Agency's (IEA) tracking report, increased adoption and use of higher-efficiency LED lighting technology will be crucial to the 2050 scenario of reaching the Net Zero emissions (IEA, 2022). Another energy-saving option for lighting systems in industrial facilities is daylighting. Introducing natural light into interior places through skylights installed on the rooftops of industrial plants can minimize the use of artificial lighting, thereby providing significant reductions of electricity use, cost, and emissions (Konis, 2013; Pellegrino et al., 2017; Sharp et al., 2014). In addition to financial and environmental benefits, daylighting makes a workplace more psychologically positive and comfortable, thereby making it more efficient and healthier (Sharp et al., 2014). When daylight is used, the productivity of employees can increase by 5 to 16 % (Edwards et al., 2002). Nowadays, it is more relevant than ever to design energy-efficient buildings using LED lighting, intelligent control technology, and the integration of electric and daylight measures (Hemmerling et al., 2023). However, adopting technical measures alone is not sufficient to realize the full potential for energy savings in lighting (Gentile, 2022). According to a study by Uitdenbogerd et al. (2007), changing behaviour for energy efficiency can potentially yield a 19% energy saving. Given the fact that energy is not a part of most employees' jobs and is typically not included in performance assessments, it could be argued that they simply do not care or act on energy-saving (Leygue et al., 2017). The contribution of behaviour change is regarded as one of the primary elements without which global final energy consumption would be around 30% greater in 2030 (IEA, 2021). It is a well-established fact that employee behaviour is an important aspect of energy efficiency and is crucial to consider in all energy auditing practices. Bearing these facts in mind, any undertaking to improve the energy efficiency of a plant's lighting systems comprehensive and consider all possibilities, and approach systematically and holistically to consider all possibilities to untap the full saving potential.

In parallel with increased worries regarding climate change and energy consumption, industrial companies' need for energy management tools such as energy audit methodologies is expanding. On the basis of the importance of lighting systems and the rationale for a holistic approach to lighting energy efficiency as mentioned above, lighting energy audit approaches must be developed to assist industries in identifying energy-saving potentials in their lighting systems.

Despite the above facts, the studies on industrial applications concerning energy-saving in lighting systems are very limited, and the existing studies focus only one aspect of energy-saving measures such as daylighting or energy efficiency retrofitting. For example, Chen et al. (2014) studied the potential of energy-saving through daylighting for an industrial building. A similar study was conducted by (Kousalyadevi and Lavanya, 2019) explored the daylighting potential for a large industrial settling. Regarding the MEMPs, they have rarely been the subject of research, despite the fact that they are an important segment of the shipbuilding industry in terms of environmental emissions and business concerns as mentioned above. Few research has emphasized MEMPs. For example, He et al. (2022) assessed the role of digital technology in terms of the sustainable development of the marine equipment manufacturing industry in China. Zapelloni et al. (2019) analysed a MEMP using a methodology to find sustainable solutions for the manufacture of marine equipment. There seems to be a clear gap in the literature regarding cleaner production and energy management in relation to MEMPs as well as energy efficiency in their lighting systems. To the authors' knowledge, there is no comprehensive work on improving the energy efficiency of MEMPs through energy-efficient lighting solutions.

This study combines two motivational reasons into one background and aims to contribute to the development of cleaner production and energy management cultures in MEMPs through energy-efficient lighting. To achieve this aim, this study presents a lighting energy audit methodology and its application in a MEMP to explore the energy-saving potentials through the holistic consideration of the following key energy-saving measures: energy efficiency retrofitting, daylighting, and behaviour change.

2. Materials and Methods

2.1. Description of case study plant and its existing lighting systems

The plant in our study is an energy intensive MEMP which manufactures various ship and offshore machinery and components such as marine propellers for international and domestic shipyards and shipowners. It is located in the

Marmara Region of Türkiye, which is the most industrialized area and a major hub for the Turkish shipbuilding industry.

The case study MEMP is comprised of a foundry, a machine shop, and offices. The contribution of the case study MEMP's office lightings to the overall lighting energy consumption are negligible because the offices have windows facing south, which maximizes natural light as seen in Figure 1a. In addition, lighting systems in hallways, restrooms, and stairwells with infrequent occupancy are controlled by occupancy sensors to prevent wasteful lighting and conserve energy. Consequently, the energy audit in this study focuses on the foundry sections and machine shop because they are the plant sections that consume the most energy for lighting. The foundry sections are illuminated by HID lamps, whereas the machine shop is lit by fluorescent tubes. The plant also uses LED-based task lighting for various processes such as grinding station (Figure 2C). The specifications of the fluorescent tube, HID bulb, and LED bulb used in the plant are listed in Table 1. As depicted in Figure 2, there is a substantial opportunity for daylighting via the plant roof for the foundry. Nonetheless, this was not exploited during the plant's design phase. The machine shop is in the basement floor under the foundry. The only daylighting application is through the side windows of the plant's foundry as seen in Figure 2b.

Based on the energy audit results conducted in this study, it is estimated that the case study MEMP's existing lighting systems consume approximately 109,169 kWh per year with an electricity unit cost rate (eucr) of €0.2071. This equates to 54,475.3 kg per year of indirect CO_2 emissions based on the grid CO_2 emission-factor (CO_2EF) of 0.499 kg CO_{2e}/kWh (Scarlat et al., 2022).

Table 1: Specifications for the existing electric lighting systems employed in the case study MEMP

	Foundry	Machine Shop	Task Lighting
Type	HID bulb	Fluorescent tube	LED
Rated power	250W	N/A	N/A
Connected Load	285 W	72W	15W
Total number of lamps	72	36	42
Bulb shape	N/A	T8	N/A
Total luminous flux (TLF)	31,600 lm	6,500	2,053lm
Light output ratio (LOR)	86.2%	62.9%	100%
Useful Luminous flux (ULF)	27,241lm	4,087lm	2,053lm
Luminous efficacy	95.6 lm/W	56.8 lm/W	136.9 lm/W
Energy efficiency label	F	G	D
Rated lifetime	14,500hrs	15,750hrs	22,000hrs

Figure 1: A general view of the case study MEMP (a), the plant's roof exploitable for daylighting (b)

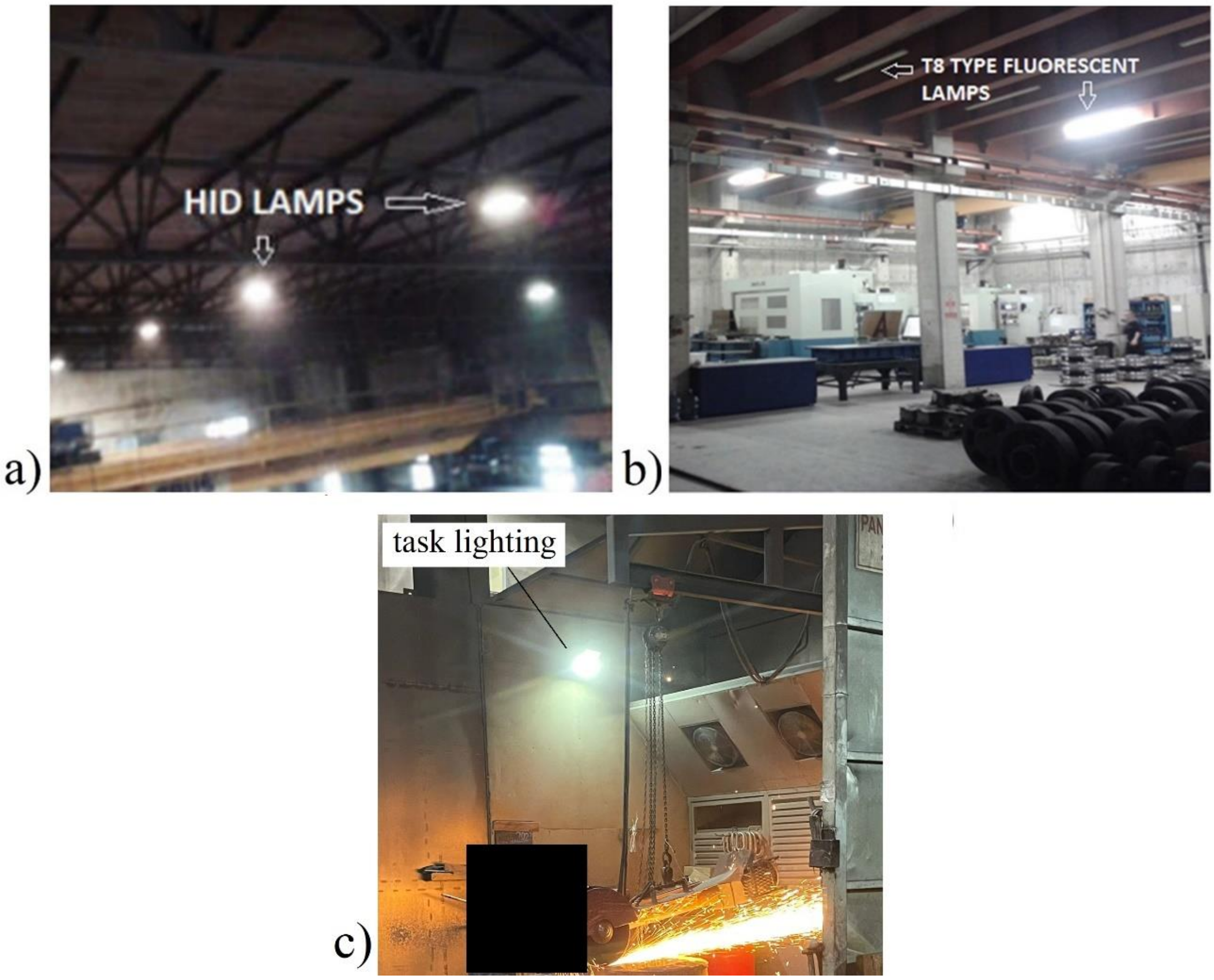

Figure 2: HID lamps in the foundry sections (a), T8 type fluorescent lamps used in the machine shop (b), task lighting (c)

2.2. Lighting Energy Audit Methodology

2.2.1. Lighting assessment

While reducing the energy consumption of a lighting system, an energy-saving measure that provide ESP should satisfy the lighting design requirements (EN 12464, 2011). In this study, the following lighting parameters are considered to conduct lighting assessment for the existing lighting systems and proposed energy-saving measures.

- $\bar{E}$, minimum level of horizontal illumination on a working place established by the Standard EN 12464-1 and lighting requirements (EN 12464, 2011).
- Uo, minimum illuminance uniformity (U) is the ratio between the mean and lowest $\bar{E}$ level on the work plane (EN 12464, 2011).

The measurement and evaluation of the lighting parameters for the foundry and machine shop were conducted based on the recommendations in EN 12464-1 (EN 12464, 2011). The values of $\bar{E}$ and Uo provided by the existing lighting systems and proposed energy-saving measures were assessed and evaluated using DIALux evo simulation software which is widely validated by many researchers (Bunjongjit and Ngaopitakkul, 2018; Guerry et al., 2019; Hemmerling et al., 2023).

The 3D models of the machine shop and foundry floors were created by using DIALux based on the dimensions, colors, and reflectance values of the plant building envelope (i.e., walls, floors, plant equipment and machinery, and products as shown in Figure 3 and Figure 4). Based on these, DIALux calculated the average values for reflectance of ceiling, walls, and floor as 69.5%, 38.3%, and 42.9% for the ceiling, walls, and floor of the machine shop, respectively, and 37.7%, 36.8%, and 29.8% for the ceiling, walls, and floor of the foundry, respectively. The effect of the daylighting system on heating and cooling loads was not taken into account in this study because the foundry of the plant does not have a heating and cooling system. The plant is equipped with only a central exhaust ventilation system to extract the low-quality indoor air arising from foundry processes.

The studied MEMP performs a diverse range of production activities, whereby there is no certain and constant task or activity area. For those workstations where the size and position of the task or activity area is not certain, EN 12464-1 recommends either considering the entire area as the task area or illuminating the entire area uniformly to the required minimum illuminance levels (EN 12464, 2011). Therefore, the entire plant area has been considered an activity area, and a measurement plane was placed with a height of 0.75 cm on the plant floors. A band of 0.5m from the plant boundary walls is omitted from this computation area unless a task or activity is within or extends into this omitted zone, as recommended by the (EN 12464, 2011).

The grid for measuring points for assessing horizontal illuminance over the defined plane was created using the following equation (EN 12464, 2011):

$$p = 0.2\ x\ 5^{\log_{10}(d)}\ \text{(m)} \qquad (1)$$

Where p is the maximum grid size (m), d is the longer dimension of the area. If the ratio of the longer to the shorter is 2 or more, then d becomes the shorter dimension of the area.

The foundry of the case study MEMP is comprised of various subsections including furnace bay, ladle preheating unit, moulding units, casting zone, shake-out unit, finishing units, welding and repairs unit, heat treatment units, and pattern making shop. The minimum horizontal illuminance (Ē) and Uo values required for these foundry sections and machine shop of the MEMP were established according to the EN 12464-1. The values obtained from the DIALux simulation results were compared against the standard minimum lighting requirement values according to EN 12464-1 in order to determine the lighting performance of the existing lightings and proposed energy-saving measures.

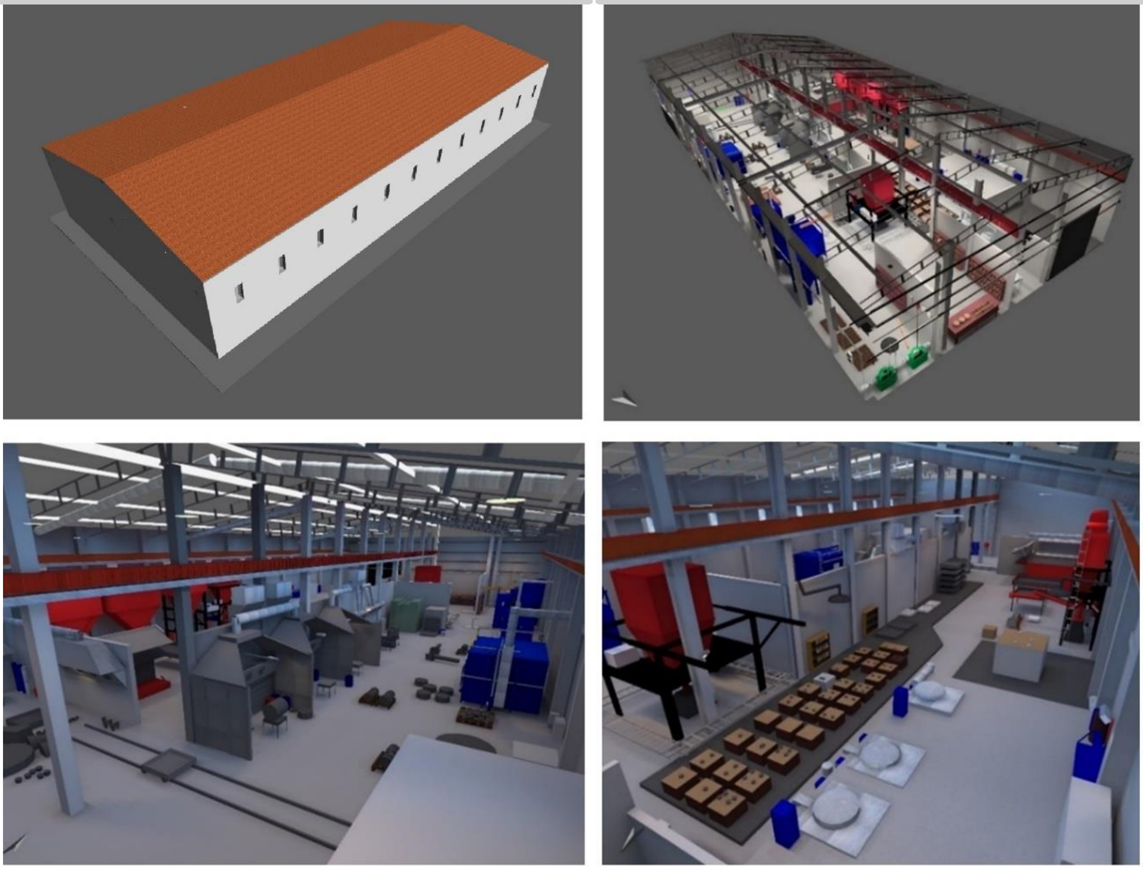

Figure 3: 3D modelling of the foundry of the plant in DIALux

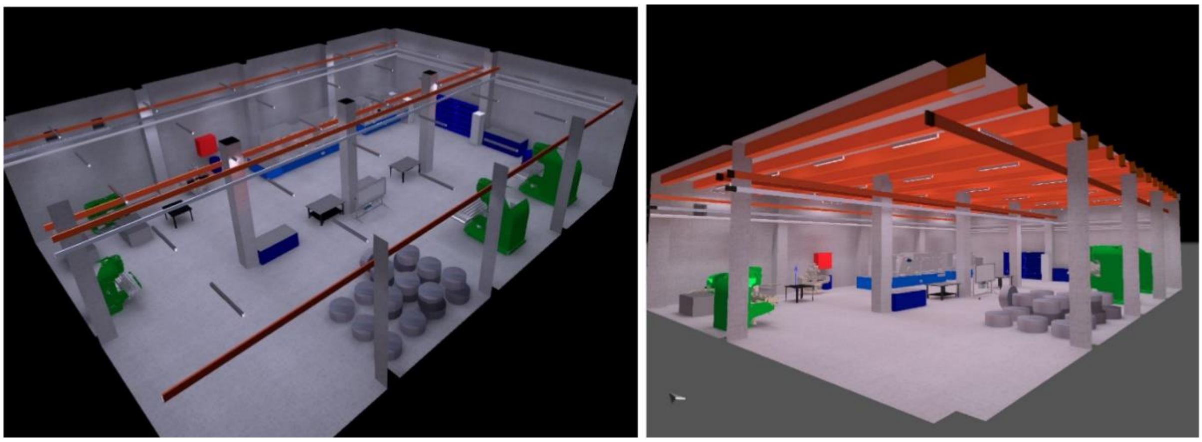

Figure 4: 3D modelling of the machine of the plant in DIALux

2.2.2. Identification of Energy-saving Potentials (ESPs)

2.2.2.1. ESP by Energy Efficiency Retrofitting

In terms of lighting systems, energy efficiency retrofitting can be defined as the replacement of an inefficient lighting system with an energy-efficient one. In this study, energy-efficient LED lighting is proposed as an energy-saving measure to replace the existing lightings of the case study MEMP. The energy efficiency of the existing lighting devices has been evaluated based on the energy label and luminous efficacy, and more energy-efficient alternatives have been sought on the market. The energy efficiency class scheme established by the European Commission's regulation on energy labelling for light sources based on the total mains efficacy is useful as a guide for making informed decisions regarding energy efficiency and energy consumption of lighting products (EC, 2019). According to the most recent label scheme of the European Commission ranging from A (the most efficient) to G (the least efficient) as shown in Table 2, the most energy-efficient lighting products currently available on the market will be labelled C or D (EC, 2021).

Table 2: Energy efficiency classes of lighting bulbs according to total luminous efficacy (EC, 2021)

Energy efficiency class	Total mains efficacy η (lm/W)
A	$210 \leq \eta$
B	$185 \leq \eta < 210$
C	$160 \leq \eta < 185$
D	$135 \leq \eta < 160$
E	$110 \leq \eta < 135$
F	$85 \leq \eta < 110$
G	$\eta < 85$

Based on these, given that the lighting requirements are satisfied, a lighting device with a higher luminous efficacy and more energy-efficient class would be more energy-efficient and provide an ESP. Annual Energy-saving Potential (AESP) by using a more energy-efficient lighting device instead of the existing lightings can be estimated as follows:

$$AESP = AEC_E - AEC_N \ (kWh/year) \qquad (2)$$

where AEC_N and AEC_E are annual energy consumption (AEC) of the new energy-efficient lighting devices and the existing lighting device, respectively. AEC for a lighting device/system can be estimated as follows:

$$AEC = n\ x\ P\ x\ t\ x\ d \quad (kWh) \qquad (3)$$

Where n is number of light bulbs, P is power demand of lighting device (i.e., connected load) (kW), t is working hours in a production day, and d is number of working days in a year. It should be noted that the connected load of the lamps was used to calculate energy consumption in (3) to account for the various losses associated with the lighting technology, such as ballasts, fixtures, parasitic losses, drivers, etc. For example, parasitic losses in LED lighting can be around 19% in some applications (Gentile et al., 2018). The connected loads for the existing and proposed lighting systems are given in Table 1 and Table 4, respectively.

2.2.2.2. ESP by Daylighting

In this study, the proposed daylighting system is based on roof-top skylight, which is a very common approach for introducing daylight into interior spaces and are ideal for sites with an open area between the fenestration point and the space to be lit, such as industrial plants (Dilaura et al., 2011; Sharp et al., 2014). For those times that the daylight is not sufficient to provide the minimum target illuminance, the artificial electric lights are turned on by the system controller to compensate for the lagging illumination and provide constant minimum horizontal illuminance. As long as the share of electric light use is reduced, energy is saved. This requires a photo-sensor-based lighting control system to adjust the electric lighting with respect to the light levels measured by a set of photo-sensors.

AESP by using daylighting system can be calculated based on the time fraction that the daylight satisfies the minimum required horizontal illuminance levels over the work planes. The time period that the artifical electric lightings were on can be estimated based on the Daylighting Autonomy (DA). DA is a daylighting availability metric that shows the fraction of the occupied time during which the target illuminance is met by daylight (Reinhart and Walkenhorst, 2001). DA can be estimated as follows (Chen et al., 2014):

$$DA = \frac{h_{DA}}{h_{total}} \qquad (4)$$

Where h_{DA} is the total hours when the minimum illuminance target is satisfied by the daylight (Chen et al., 2014).

Because the artificial electric lightings will be on during the periods when the daylight cannot meet the required level of illuminance, the AEC by the artificial lighting can be estimated based on the artificial lighting power, DA, and the running hours of the artificial lighting as follows (Chen et al., 2014):

$$AEC_{artifical} = P_{total} x h_{total} x(1 - DA) \ \ (kWh) \qquad (5)$$

Where P_{total} (kW) is the total connected power (i.e., load) of the artificial electric lighting; h_{total} (h) is the total running hours of the artificial lighting. Thus, the AESP by using a daylighting system instead of the existing lightings can be estimated as follows:

$$AESP = AEC_E - AEC_{artifical} \ \ (kWh/year) \qquad (6)$$

The AESP by the daylighting application for the case study MEMP was calculated using (6) based on DA which was calculated for a year by DIALux.

In this study, the energy efficient LED bulb proposed in the energy efficiency retrofitting measure is also considered in the daylighting design so as to improve the system's overall energy efficiency and due to the fact that the existing HID bulbs in the foundry cannot be dimmed. The illuminance distribution over 0.75 m workspaces in the daylighting scenario was simulated under average sky conditions for the summer and winter solstices and equinoxes. Because daylight varies during the day and season, the hours of 9:00 a.m., 12:00 p.m., 3:00 p.m., 6:00 p.m., and 9:00 p.m. during each solstice and equinox were chosen to specify the illuminance distribution throughout the workspaces on the foundry floors and to be compared with the existing HID lighting.

2.2.2.3. ESP by Behaviour Change

A walk-through analysis of the case study MEMP was done, and the plant's premises were audited throughout the energy audit period to find out if any employees left lights on superfluously. In addition, power consumption measurement of the lighting systems of the plant was carried out by using a PEL 103 power and energy data logger so as to identify if any lights were left on during non-operational night hours. The results of these actions will reveal the ESPs linked with employee behaviour.

2.3. Economic and Social Evaluation

2.3.1. Economic evaluation criteria

Three economic indicators have been used to carry out the economic evaluations: NPV (net present value), B/C (benefit to cost), and DPP (discounted payback period) (Eltamaly and Mohamed, 2018; Uyan, 2019). The cost-effectiveness of an energy-saving technique requiring an initial investment must be analysed to determine if the benefits received from its adoption are sufficient to justify the initial expense. Thus, NPV is utilized to conduct an economic analysis of investment-required energy-saving measures. Calculated as follows, the NPV provides an estimate of the net economic benefits of an energy-saving investment:

$$NPV = \sum_{t=1}^{T} \left(\frac{(AECSP, ARCs, SVs, othersavings) - (ICC, RCs, MC)}{(1+i)^t} \right) \quad (€) \qquad (7)$$

Where $AECSP$ is annual energy cost saving potential, ARC is avoided replacement costs (€), RC is replacement cost (€), MC is maintenance cost (€), SV is salvage value (€), ICC is initial capital cost (€), T is project lifetime (year), and i is the real interest rate (%). For an investment to be economically feasible, the NPV should be greater than zero. The lifetime of the energy-saving measure projects was assumed to be 15 years. The real interest rate in Türkiye was estimated to be 0.39% based on the average inflation and interest rate over the past decade (2011-2021) (CBRP, 2023).

The NPV does not demonstrate if one investment is more cost-effective than another. A B/C ratio can be utilized to benchmark the economic performance of investments in energy-saving measures with different IICs (Uyan, 2019). It is calculated by dividing the total present value (PVB) of the benefits by the total present value of the costs (PVC) and is expressed as follows (Uyan, 2019):

$$B/C = \frac{PVB}{PVC} \qquad (8)$$

Another useful parameter to determine the profitability of an investment is the discounted payback period (DPP), which shows how many years it takes for the sum of the present values of benefits and costs to equal the ICC (Eltamaly and Mohamed, 2018).

2.3.1.1. Cost and benefits for daylighting and LED applications

Costs

The cost components include ICCs, RCs, and MCs. The ICC for the daylighting system includes the cost of polycarbonate panels (skylights), LED lamps, aluminium frames and other materials, labour, control system, sensors, fuses, programming, dimmable lamps, wiring, installing, etc. The MC includes the maintenance of the controller and sensors. The RC is assumed to not occur for the daylighting system.

The ICCs of LED lighting include the initial purchase cost, redecorating the electric installation, and labour costs. Based on a report by the UN Environmental Program (UNEP, 2017), the typical lifetime specifications for LEDs range from 15,000 to 30,000 hours. An average of 22,500 hours has been assumed for the LED life cycle in this study. As for the existing lighting devices in the plant, an average of 15,750 hours and 14,500 hours has been assumed for fluorescent lights and HID bulbs, respectively (Turner and Doty, 2013). The LED lamps would be replaced at the end of their useful lives throughout the project period. Thus, the RCs are added to today's ICCs.

Benefits

The benefits include annual energy cost savings, ARC, RC, and SV at the end of the project life, and other possible savings. The annual energy cost saving potential (AESCP) for an energy-saving measure is calculated as follows:

$$AECSP = AESP \ x \ eucr \ (€/year) \qquad (10)$$

The replacement of the existing lightings at the end of their useful lives is avoided when LED lighting or daylighting is applied in the plant. Therefore, the associated ARCs for the existing lighting throughout the project life were subtracted from the ICCs. The total SV for the hybrid daylighting system is the sum of the SVs of the skylights and the controller. The SVs are subtracted from the ICCs. The LCC components, including ICC, RC, and MC, for the energy-saving measures in the case study MEMP were collected through a market survey and are presented in Table 6 for LED lights and in Table 7 for the hybrid daylighting system.

2.4. Environmental and Social Evaluations

2.4.1. Environmental Benefits

The environmental benefit through the implementation of energy-saving measures is the reduction in the plant's carbon footprint. This is expressed as CO_2-equivalent emissions reduction potential annually (CO_{2e}-AERP). It can be calculated based on the CO_{2e} emission factor (EF) of the electricity used in the plant and AESP:

$$CO_{2e}AERP\ = AESP\ x\ CO_{2e}EF\ \ (kg - CO_2/year) \qquad (11)$$

2.4.2. Social Benefits: External health costs savings

Regarding the energy consumption of a MEMP's lighting systems, external expenses include the health costs of air pollution caused by energy consumption. The health costs of electricity usage for a MEMP provided by the utility grid will depend on the utility's power generation. Annual external health cost savings (AEHCS) resulting from energy-saving can be calculated as follows:

$$AEHCS\ = AESP\ x\ ehcur\ \ (€/year) \qquad (12)$$

where *ehcur* denotes the unit cost rate of electricity-related external health costs (€/kWh). In this study, the ehcur for Turkey is estimated to be €1.83/kWh based on the proportion of fuel sources in the country's 2020 power generation capacity (Sönnichsen, 2021) and the external health cost of each power station type by fuel (Dal, 2017).

3. Application, Results, and Discussion

The ESPs in the lighting systems of the case study MEMP have been investigated through the application of energy efficiency retrofitting, daylighting, and behaviour change measures within the proposed lighting energy auditing framework. According to the simulation of energy consumption in DIALux, the lighting systems' annual energy consumption for the case study MEMP is 109,169 kWh. The HID bulbs in the foundry consume 96,854.4 kWh annually, and the fluorescent tubes in the machine shop consume 12,234.24 kWh annually. LED task lighting was excluded from the energy audit because of its negligible impact on overall energy consumption and higher energy efficiency rating. In total, five ESPs have been identified in the energy audit. The findings of the technical assessments and the economic and social benefits of each measure are described in the following sections.

3.1. Energy efficiency retrofitting

3.1.1. ESP using LED tubes in the machine shop's lighting system (ESP-1)

There were 36 fluorescent fixtures used to illuminate the machine shop. Each lighting fixture contains two fluorescent tubes with a connected load of 72W and a total luminous flux (TLF) of 6500 lm. The lighting output ratio (LOR) for the fluorescent lighting is 62.9%, so the useful luminous flux (ULF) is 4087 lm, and its luminous efficacy is 56.8 lm/W. The total connected load of the fluorescent lighting system in the machine shop is 2.592 kW. The light centre height is 4.6m. The existing fluorescent tubes had an energy efficiency class of G, which is the least efficient class (Table 1).

Consequently, energy can be saved by replacing the existing fluorescent lighting system with a lighting choice that is more energy efficient.

To this end, an LED tube with energy efficiency class D has been proposed as a replacement for the fluorescent tubes. The proposed LED tube's power rating is 30 W, whereas its connected load is 34W. Its LOR is 100%, so its TLF and LLF are 5240 lm, and its luminous efficacy is 154.1 lm/W (Table 4).

Figure 5a illustrates the simulated $\bar{E}$ distribution over the work plane 0.75 meters above the floor of the machine shop, as provided by the existing fluorescent tubes. Table 3 displays the simulation results for $\bar{E}$, $\bar{E}$ min, $\bar{E}$ max, and Uo for the machine shop under the existing fluorescent and proposed LED illumination cases. The simulation results revealed that the average, lowest, and maximum E when the machine shop is illuminated by the existing fluorescent lighting system are 192 lux, 87.7 lux, and 233 lux, while the required (i.e., target) $\bar{E}$ for the machine shop is 200 lx according to EN 12464-1. U, the uniformity of the illumination on the work plane, is 0.46, which is less than the required value of 0.6 according to EN 12464-1. Figure 5a depicts the poor illumination produced by the existing fluorescent system. As seen, while the $\bar{E}$ level in the center of the machine shop is above 200 lux, it ranges from 125 to 175 lux in the areas adjacent to the walls and machine tools, as well as around the building's columns, indicating poor lighting.

In order to save energy and improve illumination, replacing the existing fluorescent tubes with a more energy-efficient LED tube was proposed. The proposed LED tube’s specifications are presented in Table 4. DIALux placed 24 LED tubes vertically along the y-axis, as shown (black bars) in Figure 5b. The mounting height is 5.5m. In order to provide a more uniform illumination, as seen in Figure 5b, 4 additional LED tubes of the same type were placed close to the walls horizontally along the x-axis (red bars).

Figure 5b depicts the arrangement of LED luminaires in the machine shop and the simulated illumination distribution over the work plane 0.75 meters above the machine shop floor. The average, minimum, and maximum horizontal illuminances over the machine shop were determined to be 244 lux, 175 lux, and 309 lux, respectively. Although the minimum E is 175 lux, which is adjacent to a building column, as can be seen in Figure 5b, a significant portion of the calculation surface is above 200 lux. The illumination uniformity is 0.71, while the target value is 0.6. Clearly, the proposed LED tube with the proposed placement arrangement meets the required illuminance level of 200 lux and illuminance uniformity.

The AEC for the proposed LED lighting system was determined to be 5,135.36 kWh, whereas it was 12,234.24 kWh for the existing fluorescent system. Thus, replacing the existing fluorescent lighting system with more energy-efficient LED lighting provides an AESP of 7,099 kWh and an AECSP of €1.470,2. This represents a significant savings of 58% of the machine shop's lighting energy consumption. The CO_{2e}-AERP resulting from the application of the proposed energy-saving measure is 3,542.4 kilograms, while the AEHCS is €12.991.

This measure requires an IIC of €2.688 and offers an AECSP of €1.470,2 per year. The NPV is €13.091, which demonstrates that the investment is economically viable. The B/C and DPP are 2.24 and 10 months (0.83 years), respectively. The CO_{2e}-AERP is 3,542.4 kg annually, whereas the AEHCS is €12.991,1.

Table 3: Simulation results for E, Emin, Emax, and Uo for the machine shop under existing fluorescent tubes and proposed LED illumination

Workstation	Existing 285 W - HID bulb				Proposed 140W - LED bulb				Standard reference level	
	Ē (lx)	Ēmin (lx)	Ēmax (lx)	Uo	Ē (lx)	Ē min (lx)	Ēmax (lx)	Uo	Ēlimit (lx)	Uolimit
Machine Shop	192	87.7	233	0.46	244	175	309	0.71	200	0.6

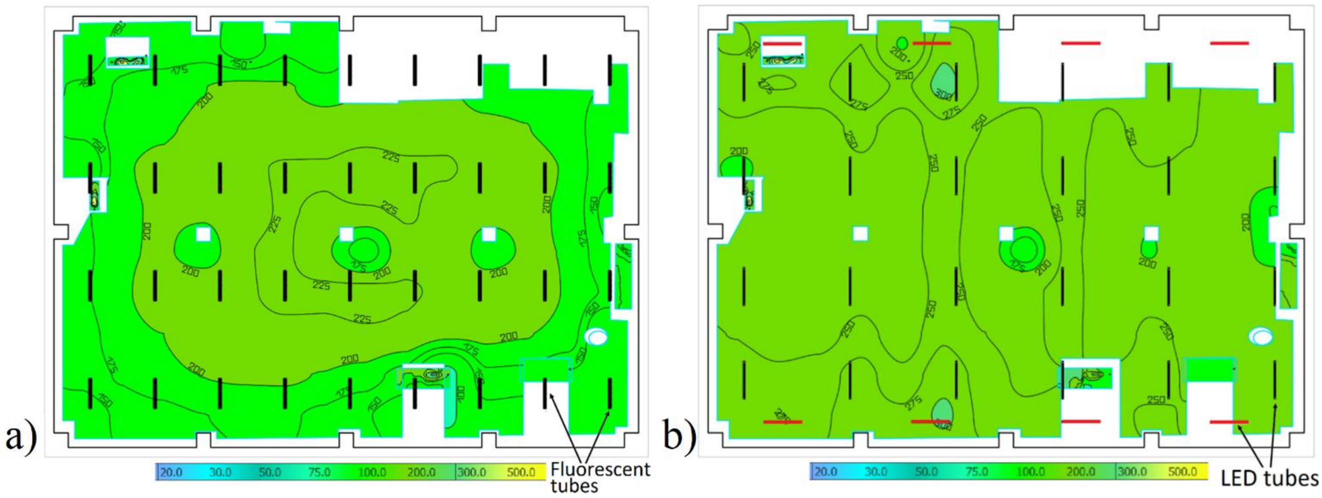

Figure 5: Machine shop lightings layout and horizontal illumination distribution with the existing fluorescent tube (a) and with the new LED tubes (b)

3.1.2. ESP using LED bulbs in the foundry's lighting system (ESP-2)

The foundry's lighting system is comprised of 72 HID bulbs (6x12) (Figure 6a) with a light centre height of 11.65m. The rated power for the HID bulb is 250W whereas its connected load 285W accounting for various losses such as ballast, etc. The total connected load is 20.52 kW. The TLF, LOR, ULF, and luminous efficacy for the existing HID bulb are 31600 lm, 86.2%, 27,241 lm, and 95.6 lm/W, and its energy efficiency class is F (Table 1). An LED bulb of D class suitable for industrial applications was chosen from the DIALux database to replace the existing, inefficient HID bulbs. The proposed LED bulb has a LOR of 100%, so its TLF and ULF are 5240 lm. Its rated power is 140W whereas the connected power load is 190.6W. It has a luminous efficacy of 125.6 lm/W and an energy efficiency class of D (Table 4).

DIALux placed 42 LED bulbs (6x7) as documented in Figure 6b and determined the light center height for the LED bulbs as 10.25m. Figure 6 shows the layout of the bulbs and simulated Ē distribution over the work plane of 0.75m on the foundry workplaces for the existing HID and proposed LED lighting systems. Table 5 displays the simulation results for Ē, Ē min, and Uo for each foundry workstation under HID and LED illumination cases.

The average Ē provided by the existing HID bulbs in the workplaces of the scrap yard, ladle heating unit, and pattern and model making shop was determined to be 195 lx, 177 lx, and 174 lx, respectively, which are lower than the $\bar{E}_{limit}$ value (i.e., 200 lx), despite achieving uniform illumination (greater than the 0.4 U_o limit) in these premises.

The average Ē provided by the proposed LED bulb in each workplace was found to exceed 200 lx, meeting the minimum illumination requirement. In addition, the LED bulb system meets the uniformity requirement in every workspace. According to the illuminance distribution maps in Figure 6, the areas with the lowest E values were those adjacent to the plant walls and the spaces between the walls and equipment, such as the heat treatment furnaces and shot blasting system. Furthermore, the separation walls (around 4-5 meters shorter than the plant's outer walls), which separate the oxyfuel cutting zone from the sand reclamation area, the ladle heating unit from the scrap yard and storage, and the storage from the pattern and model making shop, cause less uniform illuminance in these premises. Nevertheless, both the $\bar{E}$ and U_o criteria are satisfied in the proposed LED lighting system.

The AEC for the existing HID system was determined to be 96,854.4 kWh, while the AEC for the proposed application of energy-efficient LED lighting was calculated to be 37,784.5 kWh. This results in an AESP of 59,070 kWh, which is approximately 61% of the energy use of the existing case. The AECSP provided by the LED light bulb application is €12.233,4 while the IIC is €14.364. The implementation of this measure is economically feasible because it returns an NPV of €140.290 over the course of a 15-year project. The B/C ratio is 3.75, and the DDP period is 14 months (1.17 years). It provides 29,475.9 kg of CO_{2e}-AERP. Moreover, the AEHCS costs €108.098.

Table 4: Specifications of the LED lights proposed for energy efficiency retrofitting

Specification	LED tube for machine shop	LED bulb for foundry
Application	Industrial	Industrial
Power rating	30W	140W
Connected load	34W	190.6W
TLF	5240 lm	23944 lm
LOR	100%	100%
ULF	5240lm	23944 lm
Luminous efficacy	154.1 lm/W	125.6 lm/W
Energy efficiency label	D	D
Rated lifetime	22500hrs	22500hrs

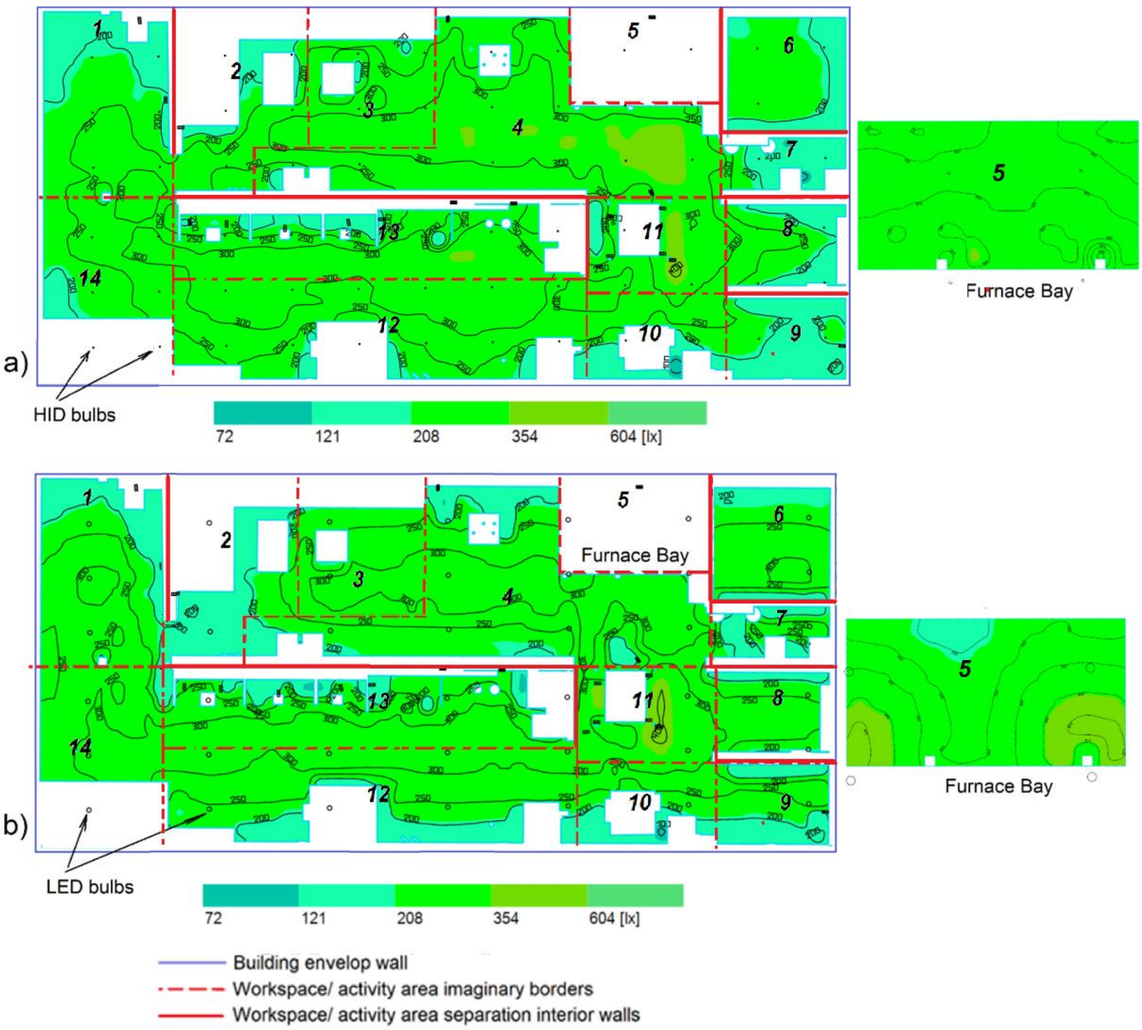

Figure 6: Foundry illumination distribution with the existing HID bulbs (a) and with the new LED bulbs (b) (The numbers of the workstations on the illumination maps are given in Table 5) (The illumination map for Furnace Bay (5) is displayed individually because it is approximately 2 meters higher than the other workstations' common flooring.)

Table 5: Simulation results for E, Emin, and Uo for each foundry workstation under HID and LED illumination cases and comparison with the required minimum levels according EN 12464-1:2019

Workstation (No in layouts in Figure)	Existing 285 W - HID bulb			Proposed 140W - LED bulb			Standard reference level (EN 12464-1:2019)	
	Ē(lx)	Ēmin(lx)	Uo	Ē(lx)	Ēmin(lx)	Uo	Ēmin(lx)	Uolimit
Oxy-fuel cutting (1)	203	79	0.39	241	98	0.41	200	0.4
Sand reclamation (2)	243	142	0.58	250	151	0.6	200	0.4
Moulding unit 1 (3)	284	153	0.54	277	125	0.45	200	0.4
Casting area (4)	278	120	0.43	265	109	0.41	200	0.4
Furnace Bay (5)	312	242	0.78	286	175	0.61	200	0.4
Scrap yard (6)	195	117	0.6	251	172	0.69	200	0.4
Ladle heating (7)	177	99	0.56	205	81	0.4	200	0.4
Storage (8)	217	131	0.6	249	177	0.71	200	0.4
Pattern and model making shop (9)	174	94	0.54	210	113	0.54	200	0.4
Shotblasting (10)	246	105	0.43	263	120	0.46	200	0.4
Moulding unit 2 (11)	209	120	0.57	303	148	0.49	200	0.4
Heat treatment (12)	263	123	0.47	261	111	0.43	200	0.4
Finishing (13)	271	119	0.44	270	128	0.47	200	0.4
Entrance/loading bay (14)	243	169	0.7	271	110	0.41	200	0.4

3.2. Daylighting

3.2.1. ESP by using hybrid daylighting system in the foundry (ESP-3)

The daylighting analysis was performed using DIALux software. The plant's roof is comprised of 2 sections of equal size. The total roof area is about 2624 m^2. The pitch angle for both roof sections is 9º. The orientation of the roof is 63º to the north (Figure 7). The dimensions of a skylight panel are 1mx12m and its transmittance value is 70%, as provided by the designer. The optimal skylight/roof ratio (SRR) in daylighting applications is reported to be between 2.5-15% (Lapisa et al., 2020). In this study, a SRR of about 11% is considered for the daylighting design. In total, 24 skylight panels were uniformly placed on the plant's roof in DIALux (Figure 7). The energy-efficient LED lighting was also considered a component of the proposed daylighting system. Thus, the proposed daylighting system is comprised of roof-top skylights, LED bulbs, LED task lights, and associated control systems.

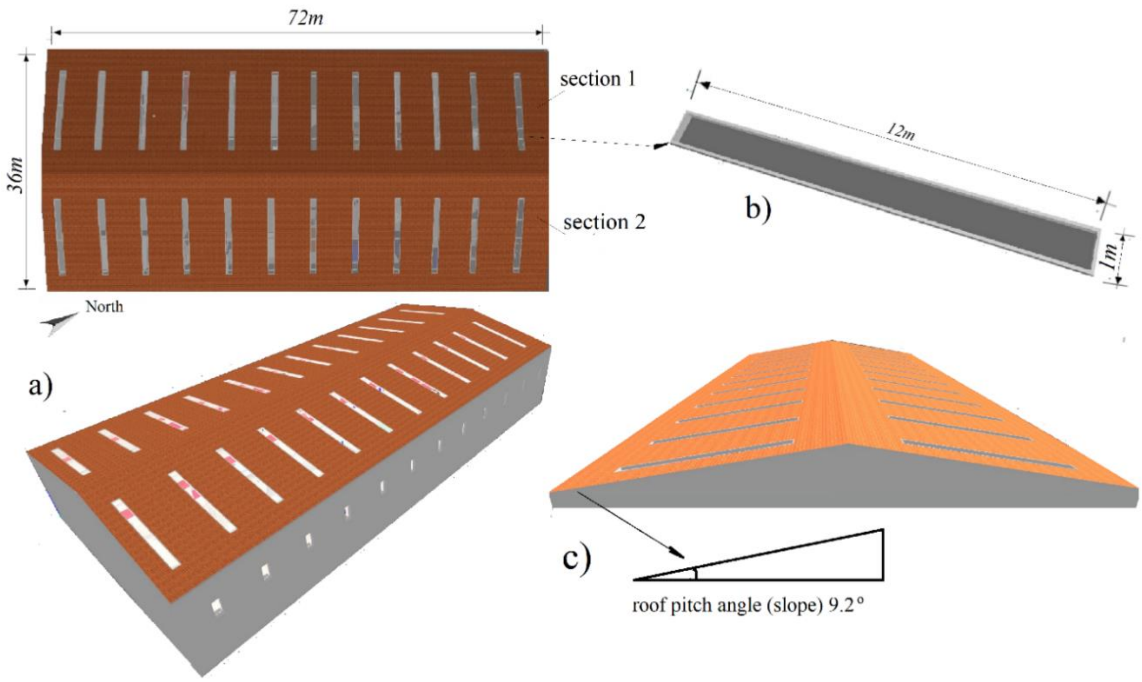

Figure 7: Placement of skylights on the plant's roof (a), skylight dimensions (b), and pitch angle of the roof (c)

Figure 8 shows the annual course of the daylight input (i.e., luminous exposure) (lx*h/day) and the lighting system's energy demand. As expected, the luminous exposure is highest around the summer solstice, while it is lowest around the winter solstice. In parallel, the energy demand for electric lights (i.e., LED tasks + LED bulbs) was lowest during the summer, and vice versa.

The simulation results revealed that the DA for the daylighting system application is 58%. This means that daylight was sufficient to satisfy the 200-lux target for the foundry work spaces for 58% of the working hours (i.e., 4720 hours) in a year, hence saving energy. The AEC for the existing lighting system (i.e., HID bulbs + LED task lighting) was 99,216 kWh, while the AEC for the proposed daylighting system (i.e., daylight controlled + LED bulbs + LED task lights), in which the electric lighting luminaries were controlled and dimmed by the controller according to the illuminance levels over the workspaces, was found to be 19,187 kWh. Thus, the AESP of the proposed daylighting application is 79,372 kWh, which is 80% of the annual energy consumption of the foundry lighting system. Annually, the AECSP is €16.438, whereas the AEHCSP is €145.250,7. The CO_{2e}-AERP is 39,606.6 kg-CO_{2e}.

The IIC to implement the daylighting system is €35.480. The economic analysis shows that the NPV is €184.322,6, which implies that it is economically feasible. The B/C ratio is 3.7, whereas the DPP is 2.1 years. If the plant uses daylighting, the annual carbon emissions will be reduced by 39,606 kg. Also, there will be a reduction of €145.250,7 in AEHCS.

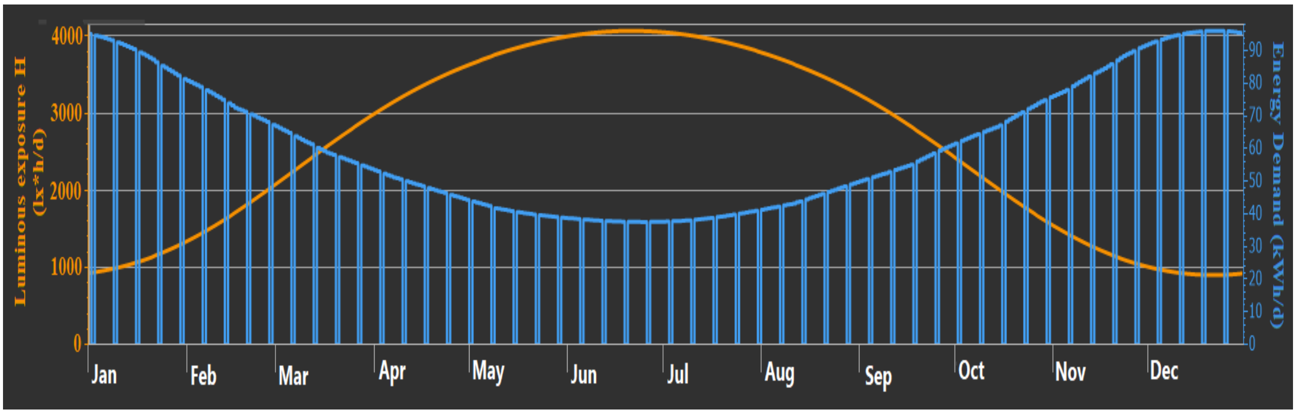

Figure 8: Daily luminous exposure (lx*h/day) and foundry lighting system energy demand the daylighting application.

Table 6: Cost components for ESP-1 and ESP-2 (LED applications)

ESP No:	Cost component	Elements	Unit Cost	Quantity	Total Cost
ESP-1	IIC	Purchasing price, redecoration of electric installation, and associated labour cost for LED lamps	€96	28	€2.688
	RC	Cost of replacing LED lamps at the end of their useful life during the project life	€76	28	2128/every 5 years
	ARC	Avoided cost of replacing the existing fluorescent tubes during the project life	€20	36	€720/every 4 years
ESP-2	IIC	Purchasing price, redecoration of electric installation, and associated labour cost for LED lamps	€342	42	€14.364
	RC	Cost of replacing LED bulbs at the end of their useful life during the project life	€300	42	€12600/every 5 years
	ARC	Avoided cost of replacing the existing HID bulbs during the project life	€60	72	€4.320/every 4 years

Table 7: Cost components for ESP-3 (daylighting application)

Cost component	Elements	Unit Cost	Quantity	Total Cost
IIC for skylights	Polycarbonate panels	€30/m^2	288	€ 8.640
	Aluminium frames including cap profile, base profile, U profile end caps, base profile, U profile end caps, anti-dust edged tape, H profiles	€30/m	624m	€18.720
	Workmanship	€100/day	10 days	€1.000
IIC for control system/electric works	Controller	€2.000	1	€2.000
	Sensors	€100/pcs	6	€600
	Fuses, control board, programming, wiring, etc	€2.400	1	€2.400
	LED bulb + electric works	€342	42	€14.364
	Engineering and workmanship	€2.100	1	€2.100
Total IICs				€49.824
Total SVs for control system + skylights				€550
Total MCs for sensors and control system				€435/year
Total ARCs	Avoided cost of replacing the existing HID bulbs during the project life	€60	72	€4.320/every 4 years

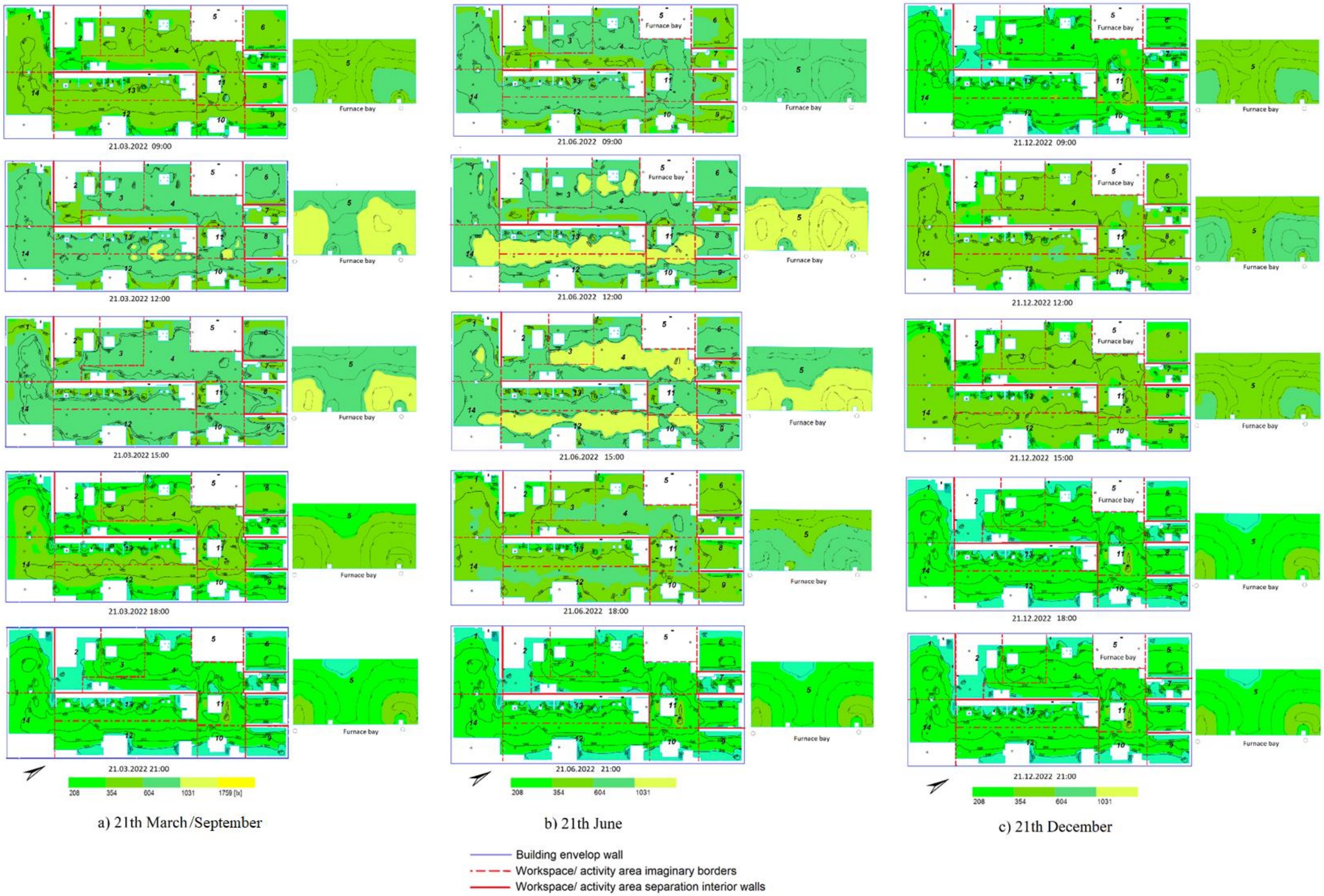

Figure 9: Simulated Ē distributions over the 0.75-m task and activity areas in the foundry for the proposed daylighting application under average sky conditions on the solstices (June 21 and December 21) and equinoxes (March 21 / September 21) at 9:00 a.m., 12:00 p.m., 3:00 p.m., 6:00 p.m., and 9:00 p.m.

3.3. Behaviour Change

3.3.1. ESP through avoiding the unnecessary lighting in the machine shop (ESP-4)

In the machine shop, an evident and unnecessary use of lights was observed. As Figure 10 shows, three fluorescent fixtures over three machines were left on for the duration of the entire production shifts during the energy auditing days. According to the plant management, these machines are estimated to be used for around 30% of a 17.5-hour production shift (i.e., day + evening shift). These lights must be switched off during the remaining 12.25 hours of the production shift. The AEC for three fluorescent fixtures was calculated to be 780 kWh. This implies that, if the employees change their inefficient behaviour and switch off the unnecessary working fluorescent lights, the AESP is 780 kWh, which is 6.3% of the machine shop lighting system's energy use. The associated AECS and CO_{2e}-AERP are €161,5 and 38,922 kg-CO_2e respectively. The AEHCS is €1.427,4. If the employees do not change their inefficient behaviour and do not turn off 3 LED tubes (i.e., assumed to be the equivalent of 3 fluorescent fixtures) in a scenario where LED tubes would be applied in the plant in the future (i.e., ESP-1), the annual energy waste would be around 246 kWh annually, with associated environmental and financial losses. In turning off superfluous lights, it must be ensured that the adjacent workspaces do not experience a decrease in illumination. As depicted in Figure 11, this was verified for the LED tubes by conducting a simulation in DIALux, which revealed that turning off the unneeded lights had no effect on the illumination of the surrounding workplaces.

Figure 10: Unnecessary use of lighting in the machine shop of the case plant

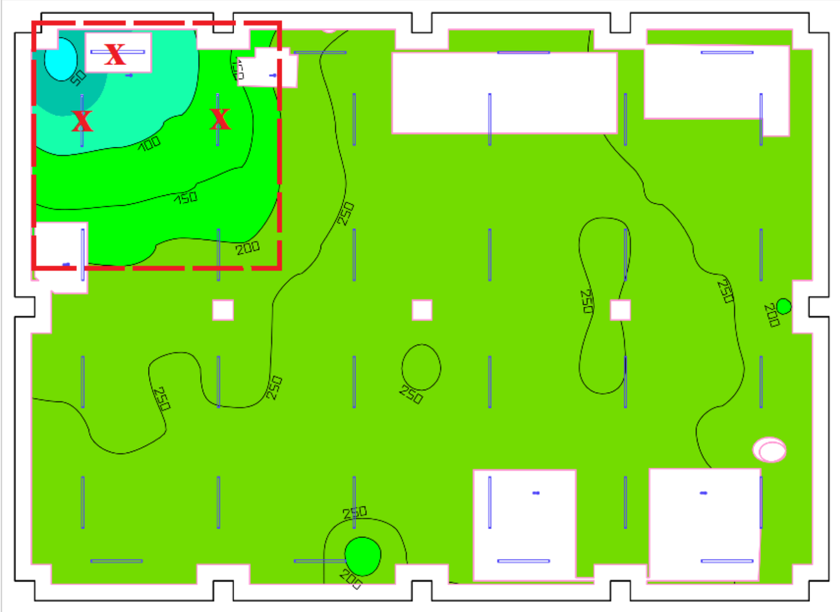

Figure 11: Illuminance distribution on the machine shop when the unnecessary working LED tubes are turned off.

3.3.2. ESP through avoiding the unnecessary lighting in the foundry (ESP-5)

The power consumption of the lights in the plant premises was recorded for a typical 24-hour period to investigate any unnecessary lighting usage. An unnecessary light use was identified for the plant's foundry. Figure 12 shows the power demand profile of the lighting system in Section 2 for a 24-hour period. As seen in Figure 12, the power demand of the lighting system was around 3.8 kW throughout the day and evening shift, and the lights were turned off during the lunch break. However, around 5 HID bulbs were left on beyond the end of the evening shifts, resulting in an unnecessary power demand of around 1.4 kW during non-production hours, between 1:30 a.m. and 8:15 a.m. (6.75 hours), as indicated in Figure 12. This was verified by the plant management as an employee mistake. Assuming such a mistake occurs every production day, it will result in an annual waste of 2,788 kWh of energy. Therefore, avoiding unnecessary lighting in the plant's foundry will result in an AESP of 2,788 kWh, which is around 3% of the foundry's lighting system. The associated AECS, CO_2-AERP, and AEHCS are €577,4, 1,391.2 kg-CO_{2e}, and €5.102, respectively. This ESP-5 was estimated based on the existing HID bulbs. If five LED lights are left on for the same period in the ESP-2 scenario, the corresponding AESP would be 1,897.6 kWh, while the resulting AECS, CO_2-AERP, and AEHCS are €393.947 kg-CO_{2e}, and €3.472,7, respectively.

Combined with the identified behaviour-related ESP (ESP–4) in the machine shop, employee behaviour is responsible for an unnecessary annual energy consumption of 3,568 kWh, that is 3.2% of the plant's total lighting energy consumption. As these ESPs do not require any expenditure, no cost-benefit analysis is required.

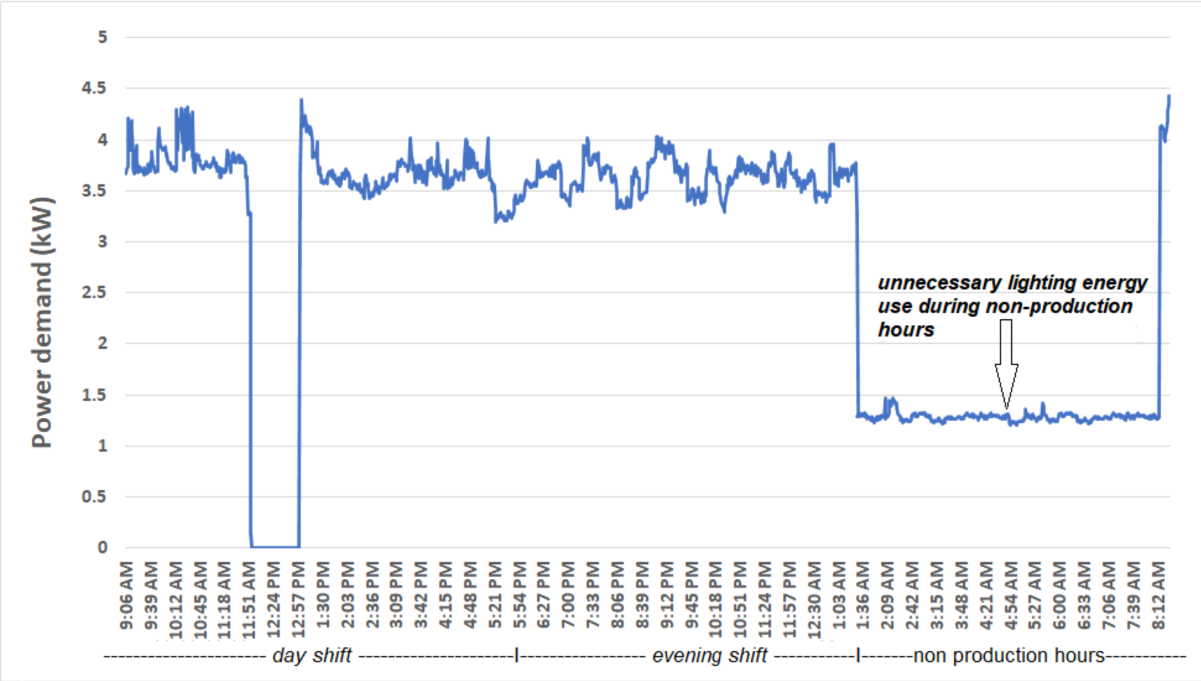

Figure 12: Power consumption profile for the lightings of foundry

Table 8: ESP identified in the lighting energy audit.

ESP No.	Measure	ESP %	AESP (kWh/year)	AECSP (€/year)	CO_2-AERP (kg-CO_2)	AEHCS (€/year)
ESP-1	Energy Ef. Retrofitting	58	7,099	1.470,2	3,542.4	12.991,1
ESP-2	Energy Ef. Retrofitting	61	59,070	12.233,4	29,475.9	108.098,1
ESP-3	Daylighting	80	79,372	16.438	39,606	145.250,7
ESP-4	Behaviour Change	6.3	780	161,5	389.2	1.427,4
ESP-5	Behaviour Change	3	2,788	577,4	1,391.2	5.102

Table 9: Economic performances of ESPs requiring investment.

ESP No.	Measure	AECSP (€/year)	IIC (€)	NPV (€)	B/C	DPP (year)
ESP-1	Energy Ef. Retrofitting	1.470,2	2.688	13.091	2.24	0.83
ESP-2	Energy Ef. Retrofitting	12.233,4	14.364	140.290	3.75	1.17
ESP-3	Daylighting	16.438	35.480	184.322,6	3.70	2.1

3.4. Discussion

As the results demonstrate, there is a considerable potential to save energy in the lighting systems of the case study MEMP through retrofitting, daylighting, and behaviour change.

The lighting performance assessment revealed that the existing fluorescent lighting system in the machine shop fails to provide a uniform and sufficient level of illuminance, whereas the proposed LED tube showed superior lighting performance and satisfied the illuminance and uniformity requirements according to the EN 12464-1 standard. While the existing system consisted of 36 fluorescent tubes, it was determined that 28 LED tubes would be sufficient to achieve the required lighting performance. Clearly, despite the fact that the existing fluorescent tubes have a higher luminous flux and their quantity is greater, the suggested LED tubes provide greater illuminance owing to their 100% LOR compared to the fluorescent tubes' 62.9% LOR.

The existing lighting in the foundry, comprised of 72 HID bulbs, provided uniform illumination on the work planes, but it was slightly below the required illuminance (i.e., 200 lx) for the scrap yard, ladle heating unit, and pattern and model making shop. The number of the proposed LED bulbs to satisfy the required lighting performance over the entire workstations of the foundry was found to be 42. While the light centre height for the existing HID bulbs was 11.65m, the optimized light height centre for the proposed LED bulbs was found to be 10.25m. In addition, the LED bulbs' LOR was 100%, quite higher than the HID's 86.2% LOR. Due to these, the proposed LED lighting system outperformed the current HID system in terms of illumination performance while using fewer bulbs.

Regarding the proposed daylighting system, it meets the minimum illuminance requirements in all seasons. It was determined that daylight provided 58% of the required illuminance annually. Also, it provides very uniform illuminance on the workspaces throughout the day in the winter season, as one can see for the winter solstice in Figure **9**Table **9**c. However, the proposed design does not provide illuminance with adequate uniformity during summer days, particularly around the noon hour when the sun is far higher in the sky, as seen in Figure 9b. The illuminance levels over some areas of the foundry are above 1000 lx, as seen in Figure 9b. As seen in Figure 9a, the illumination during the spring and autumn equinoxes is also acceptable, except for the furnace bay, where the illuminance is over 1000 lx during noon.

Regarding energy savings, the proposed application of LED tubes in the machine shop can reduce lighting energy consumption by 58% (ESP-1), resulting in an annual energy savings of 7,099 kWh with associated annual energy cost savings, carbon emissions savings, and external health cost savings of €1.470,2, 3,542.4 kg-CO_{2e}, and €12.991,1, respectively. The foundry is the major energy consumer in terms of the overall plant lighting energy consumption, being responsible for 99,216 kWh annually. The LED bulb application can cut the foundry's lighting annual energy use by 61% (ESP-2). This translates into 59,070 kWh of yearly energy savings and an annual energy cost savings of €12.233,4. Also, it is possible to cut the plant's carbon emissions by 29,475.9 kg annually and the expenditures associated with external health by €108.098.1. The proposed daylighting design can cut the foundry's lighting energy use by 80% (ESP-3). 79,372 kWh and €16.438 in yearly energy and energy cost savings would result, while 39,606.6 kg of carbon emissions and €145.250,7 in annual public health expenses may be avoided.

The investment cost for ESP-1 is €2.688. It will amortize its implementation cost in about 0.83 years (10 months) thanks to the annual savings of €1.470,2. The investment in ESP-1 is economically feasible, as it provides a NPV of €13.091 over 15 years and a B/C ratio of 2.24. Similarly, ESP-2 and ESP-3, which are alternatives to one another, are found to be economically viable because of their NPVs of €140.290 and €184.322,6, respectively. Their B/C ratios are 3.75 for ESP-2 and 3.70 for ESP-3. The investment cost for ESP-2 is €14.364, but it provides annual cost savings of €12.233,4 and redeems itself in about 1.17 years (14 months). ESP-3 has an investment cost of €35.480, while annual cost savings are €16.438, and the payback period is approximately 2.1 years (25 months).

ESP-3 (daylighting) is more attractive than ESP-2 (LED bulb) in terms of ESP, NPV, and B/C. However, its investment cost is about 2.5 times that of ESP-2, and its DPP time around 2 times of ESP-2's. The deployment of the daylighting system in the foundry alone can result in a dramatic reduction of 71.2% in the entire plant's lighting system energy use and associated energy costs, carbon emissions, and social external health costs. However, considering the concerns of excessive illumination and non-uniformity during summer days with daylighting, LED lighting for the foundry is a better alternative to daylighting. As ESP-1 (LED tube) requires a lower investment cost, it can be combined with ESP-2 (LED tube) to provide additional benefits. This would provide a 60.6% savings in the entire plant's lighting energy use, with an IIC of around €17.052, a NPV of €153.375, a B/C of 3.5, and a DPP of 1.25 years.

The foundry and machine shop's lighting energy consumptions can be further reduced by more energy-efficient employee behaviour. Avoiding superfluous illumination through increased employee awareness can provide 6.3% and 3% energy savings and associated benefits in the machine shop (ESP-4) and foundry (ESP-5), respectively. Energy-saving through behaviour change necessitates no investment. In total, employee behaviour accounts for approximately 3.2% of the plant's total lighting energy consumption. Given that this study's investigation into energy savings related to employee behaviour is demonstrative and limited, the actual energy losses associated with employee behaviour at the case study MEMP plant may exceed those identified. The employees should be trained to develop an awareness of energy efficiency. For instance, the results of this analysis can be utilized to enhance employee comprehension and perception of energy efficiency.

If ESP-1, ESP-2, ESP-5, and ESP-6 are applied together, the lighting energy consumption of the case study MEMP can be reduced by around 64%, resulting in monetary, environmental, and social benefits.

The lighting assessment in this study was based on the horizontal illuminance and illuminance uniformity. Other lighting parameters such as glare and unified glare rate can be included in the proposed framework as a future study. Also, the SRR for the designed daylighting system was about 11%, and 12x1-meter skylights with 70% transmittance were installed uniformly on the plant's roof. The proposed daylighting system can be further optimized to achieve a more uniform illuminance in all seasons. For instance, a skylight material with a lower transmittance can be employed in a daylighting system design, and the SRR ratio can be reduced to allow less daylight to diffuse inside the plant.

4. Conclusions

This paper presents a systematic evaluation of the implementation of three major energy-saving measures within a holistic energy audit framework for the lighting systems of a MEMP in Turkey, which is comprised of foundry sections and a machine shop. The energy audit included the following major energy-saving measures: energy efficiency retrofitting, daylighting, and behaviour change. Through lighting assessment and identification of ESPs, the technical analyses were conducted to investigate each energy-saving measure. The economic evaluations were conducted based on IIC, NPV, B/C, and DPP to identify the cost-effectiveness of ESPs. The benefits to society were measured by the amount of CO_2 reduction and money saved on external health costs. The results of this study demonstrate that there is a great potential to save energy in the lighting systems of industrial plants through different measures. The importance of adopting a holistic approach to identify energy savings potentials have also been demonstrated. It was found that about 64% savings can be achieved in the lighting systems energy consumption for the case study MEMP.

Energy-efficient lighting through energy efficiency retrofitting, daylighting, and behaviour change can assist MEMPs in adopting cleaner production and energy management cultures and accelerating their low-carbon transformation. This study is the first attempt in terms of energy efficiency, management, and clean production in MEMPs. The methodology proposed in this study is generic in nature and can be tailored to the needs of other MEMPs to improve their lighting systems energy efficiency. The proposed methodology can be used by the MEMPs as well as other industrial sectors in their energy planning activities to identify energy savings potentials in their lighting systems. Our future research will focus on the other energy-consuming systems in MEMPs to improve their energy efficiency and the techno-economic feasibility of incorporating renewable and clean energy into MEMPs.

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MEMP: Marine equipment manufacturing plant
GHG : greenhouse gas emissions
NDC : Nationally determined contributions
ESP : energy-saving potential
LED : light emitted diode
HID : High intensity discharge
AESP : Annual energy-saving potential
AEC : annual energy consumption
NPV : net present value
B/C : benefit to cost
ARC : avoided replacement cost
SV : salvage value
ICC : initial capital cost
RC : replacement cost
PVB : present value of benefits
PVC : present value of costs
DPP : discounted payback period
AEHCS: annual external health cost saving
SRR : Skylight roof ratio
LOR : light output ratio
TLF : total luminous flux
ULF : useful luminous flux

HIGHLIGHTS

- Improving energy efficiency through lighting energy auditing framework.
- Holistic consideration of energy efficiency retrofitting, daylighting, and behaviour change.
- Promotion of clean production and energy management in marine equipment manufacturing plants.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: