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Illumination of barns for dairy cattle: Energy-efficiency and circadian lighting in a Swedish context

S R Ahmmad^{1*}, K A Nordin², P W Zaw², N Gentile², M-C Dubois²

¹ Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Sundsvägen 16, 230 53 Alnarp, Sweden

² Division of Energy and Building Design, Department of Building and Environmental Technology, Lund University, Sölvegatan 24, 221 00 Lund, Sweden

*sheikh.rishad.ahmmad@slu.se

Abstract. Improving energy efficiency in agriculture is key to reducing environmental impact. Lighting in animal buildings is one of the most cost-effective energy saving measures. Lighting retrofit offers a short payback period, enhances animal welfare and production, and aligns with regulations for phasing out fluorescent lighting. The purpose of this study was to investigate the energy-saving potential of daylighting and electric lighting retrofits in dairy barns, focusing on energy efficiency and circadian lighting conditions. The study involved on-site measurements and lighting simulations of a dairy barn located in Southern Sweden. The results show that energy use reductions of 63% can be achieved with LED upgrades. Moreover, installing skylights in the roof would increase daylight autonomy from 12% to 55%, while providing higher melanopic illuminance than electric lighting. In conclusion, implementing LED lighting and daylighting strategies such as skylights can improve energy efficiency and indoor lighting quality in dairy barns.

1. Introduction

Cattle in Sweden spend most of the time indoors except during the pasture season for at least six hours a day for 120, 90, and 60 days in Northern, central and Southern Sweden, respectively [1]. Adequate illumination is crucial to support visual and biological needs of both cattle and human caretakers. Daylight access is particularly valuable in livestock buildings as it contributes to energy savings, economic benefits, lighting quality, and circadian rhythm regulation. The Swedish Board of Agriculture states that daylighting and electric lighting should support the circadian and behavioural needs of the animals [1]. Studies indicate that an extended photoperiod of 16 hours per day contributes to increased milk production [2]. Lighting also influences the physiological processes in cattle through the regulation of circadian rhythms [3], which is especially important since the cows are indoors most of the time. Disruption in circadian rhythms affects milk yield and overall health [3,4]. Electric lighting can represent up to 25% of electricity use in dairy farms, making it one of the largest operational costs [5]. Daylight harvesting can substantially reduce electricity use, while also addressing issues such as lighting uniformity and spectral quality. Achieving uniform illumination is important to prevent behavioural issues in cattle since they may hesitate or stop when moving through areas with non-uniform light levels [6]. Skylights and windows can increase the Daylight Autonomy (DA) or the percentage of time where lighting requirements are met by daylight. However, daylighting



alone is not sufficient for a large part of the year in Sweden to achieve the minimum national lighting recommendation for dairy barns of 150 lux [7,8]. Climatic conditions make supplemental electric lighting essential. Moreover, the visible spectrum for cattle is significantly different from humans [9,10], which is a major consideration for designing lighting in barns to meet the visual or biological needs of cattle. This study aimed to evaluate the current lighting environment of a dairy barn located in Southern Sweden. The goal of the study was to understand whether lighting standards were met while exploring the effectiveness of various retrofit measures to improve lighting quality and energy efficiency. These measures included retrofitting fluorescent lamps with LEDs, introducing skylights, replacing windows, and painting surfaces with lighter colours. Furthermore, the study investigated the circadian lighting conditions focusing on whether the intensity and duration of light exposure adhered to a standard benchmark.

2. Methods

The methodology combined site measurements with lighting simulations, circadian lighting simulations, and energy use calculations (Figure 1). The study involved a dairy barn built in 1990, situated at 55°34' N, in Southern Sweden. The farm consists of three barns and one milking building interconnected by a central corridor. The studied barn is oriented in a North-South direction with an 8° rotation towards the East. A detailed account of the building features is presented in Table 1. The data collection was conducted on February 15, 2024, with near-perfect overcast sky for Daylight Factor (DF) measurements.

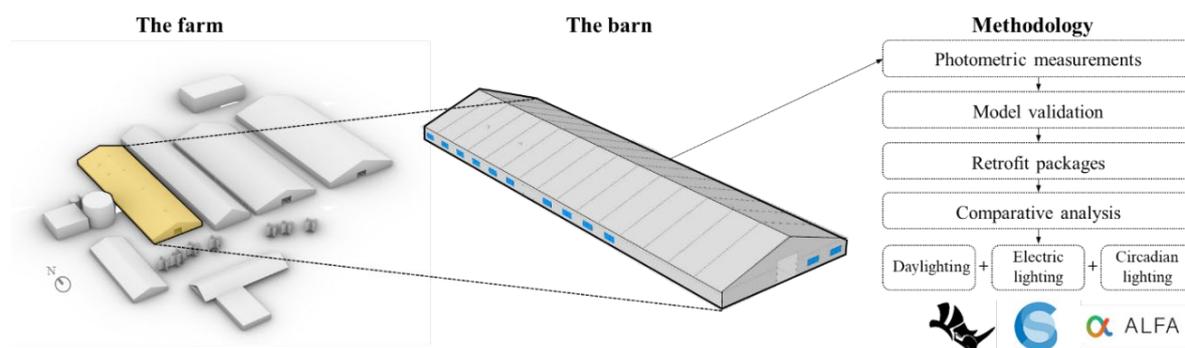


Figure 1. An illustration showing the overall methodology of the study.

Table 1. Overview of the barn properties.

Building properties	
Floor area (sqm)	2037
Capacity	30 cows, 130 heifers, 20 calves
Window-to-wall Ratio (WWR)	14%
Skylight to Floor Ratio (SFR)	Negligible (ca 0.1%). Six small circular skylights.
Supporting structure	Steel frame, light grey.
Floor material	Gravel (feeding alley), concrete (cattle area), straw (resting area).
Wall material	Concrete, red (bottom) and white (top), light grey metal (gable).
Ceiling material	Light grey metal, very dirty.
Windows and doors	Dark green fabric screen over red window frame, grey metal door.

Diffuse surface reflectances were measured with a Hagner S5 spot luminance meter with resolution 0.01 cd/m² and accuracy of $\pm 3\%$ and a reflective reference plate of 95.4% reflectance, using a standard method [11]. For surfaces that were inaccessible for direct measurements, estimates were made based on the surface colour and material properties using a database [12]. The transmittance of windows and translucent surfaces were estimated based on material type and cleanliness using manufacturer data [13]. A transmittance of 14% and reflectance of 10% were used in the simulations, by creating customized *.rad files. The illuminance was measured using a Hagner EC1-X lux meter with a

resolution of 0.1 lux and accuracy of $\pm 3\%$. The device was placed 0.8 m above the floor surface, pointing towards the ceiling. The DF was calculated by simultaneous measurements inside and outside the barn according to standard methods [14]. Measurements were collected along the central axis with a 5-meter interval, up to 25 meters from the entrance. Philips MASTER TL-D Super 80 58W/840 1SL/25 linear fluorescent light sources were used in the barn. A total of 53 light fixtures each having two lamps had an estimated energy use of 68 kWh/1 000 h and 58.5 W power per lamp.

Rhinoceros 3D was used to build a three-dimensional model of the barn while Climate Studio was used for the lighting simulations. A climate file, SWE_SN_Skillinge.026250_TMYx.2004-2018 [15], from the nearby location of Skillinge (55°28' N, 14°16' E) was utilized for the simulations. It should be noted that while DF validation confirms the accuracy of the model's geometry and radiometric behaviour under this TMY dataset, absolute outputs such as DA and illuminance levels remain directly dependent on the chosen weather file and may vary under different or future climate conditions.

DF was used to evaluate general light levels and compare simulations with measurements. DA was used to estimate daylight's potential to replace electric lighting, representing the percentage of occupied hours meeting a target illuminance of 150 lux at 0.8 meter. A custom fractional light schedule accounted for pasture time of six hours between May and August, assuming 10 hours of electric lighting. During non-pasture hours, operating hours were 05:00 to 21:00, resulting in 4922 hours annually. The 3F LINDA INOX 2X58 HF (CCT 4000 K) was selected to represent existing fluorescent lighting in the barn, based on site observations. The Pacific LED gen5 Value (WT475C 72S/840 PSD WB TW1 L1200, CCT 4000 K) was proposed as a replacement for fluorescent lights. It was assumed all luminaires are operational and running at full capacity. Energy use for existing electric lighting and improved cases was calculated using Equation 1 based on simulation results.

$$E = t \times (1 - DA) \times P \quad (1)$$

Where: E = Energy use per year [kWh/year], t = 4922 hours per year [hours/year], DA = Full daylight autonomy, [%], and P = Total power for electric lights [kW].

To improve the lighting conditions in the barn, various measures were implemented into the simulation model, tested independently and in combination, see Table 2.

Table 2. Proposed improvement measures.

Improvement	Code	Description
Window	W1	The dark window fabric screen is replaced by a light one, keeping T_{vis} 0.14, raising R_{vis} from 0.10 to 0.61.
	W2	The dark window fabric screen is replaced by a window with a T_{vis} of 0.44.
	W3	The dark window fabric screen is replaced by a window with a T_{vis} of 0.60.
Skylight	S1	A skylight (1.2 x 70 meters) is added along the ridge of the barn, T_{vis} 0.44.
	S2	A skylight (2.4 x 70 meters) is added along the ridge of the barn, T_{vis} 0.44.
Surface reflectances (painted)	P1	Window frames are painted light grey with a R_{vis} of 0.72.
	P2	Ceiling is painted white with R_{vis} of 0.70.
	P3	Columns are painted white with R_{vis} of 0.70.

The circadian lighting simulations were conducted using the ALFA plug-in from Solemma in Rhinoceros 3D. ALFA simulates non-visual effects of daylight and electric lighting on human circadian responses, using the Equivalent Melanopic Lux (EML) as per WELL building guidelines V2 [16]. The simulation results were converted from EML values to Melanopic Equivalent Daylight Illuminance (mEDI) using 0.9058 conversion factor standardized by International Commission on Illumination (CIE) [17]. This is done since mEDI is also included in the WELL building guidelines V2, and mEDI is the only CIE-approved metric [17]. The photopic reflectance values from physical measurements [11] and the database [12] were used to select the closest matching built-in material profiles in ALFA. Small differences in photopic reflectance between the Climate Studio and ALFA models reflect the limited material choices in ALFA. The luminaire's IES file was input into ALFA and a Spectral Power Distribution (SPD) profile matching the luminaire's specifications was selected. A sensor grid was established at 1.5 m above ground to represent cattle eye level. Cattle have a visual

field of about 330° [18]. and each sensor measured melanopic lux using two 180° projections to cover 360°, accounting for their movement. Simulations were conducted hourly from 05:00 to 21:00 during the spring equinox and winter solstice when the cattle are indoors. Studies indicate differences in melanopic irradiance between mammals ranging from 1% to 19% [19,20], which in a recent study resulted in 5% to 19% difference between humans and cattle [21], based on a toolbox [20]. In the absence of specific recommendations for cattle, the lowest human benchmark of mEDI provided by WELL v2 and equal to 136 lux (EML equal to 150 lux) was considered [16].

3. Results

3.1. Daylighting

Firstly, the simulated DF values were compared to results obtained through measurements, see Figure 2. The measured DF were similar to the simulated values, indicating that the model represents the real case in an acceptable way. The measurement was slightly higher in the first point (5m) and lower in the other points. On average, the difference in DF was 0.11% with a standard deviation of 0.04%.

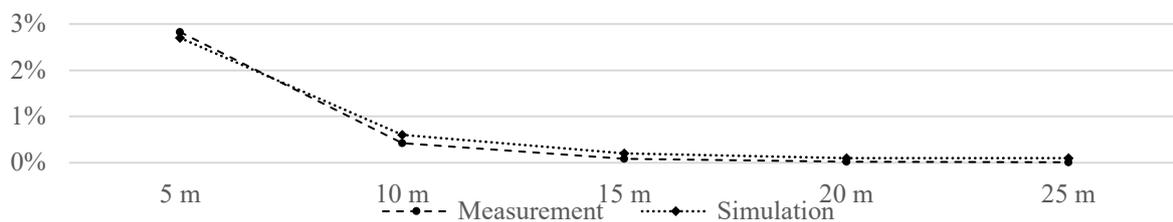


Figure 2. Comparison between the measured and simulated DF along the central axis of the barn.

A preliminary analysis [21] indicated that the largest potential for DA and lowest LD (Light Dependency) occurred between 11:00 and 13:00 and during the summer months. The simulation results after implementing different proposed improvements are depicted in Figure 3. The barn showed a high potential for DA improvement, rising from around 10% in the base case to 60% in the final improved case.

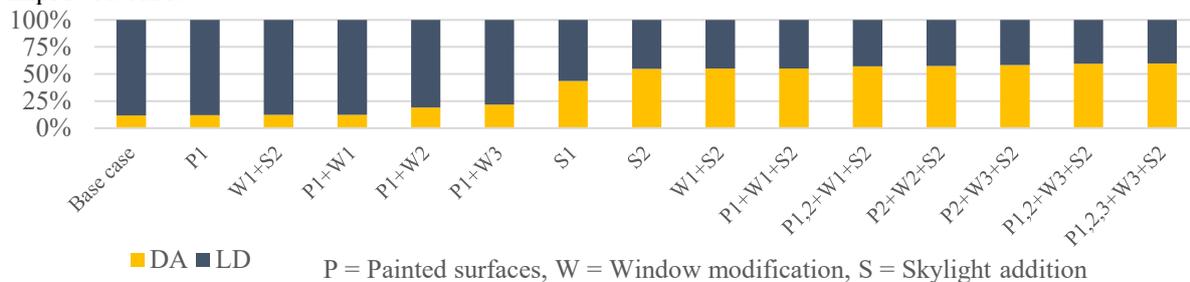


Figure 3. Impact of improvement measures on DA and LD in the barn.

3.2. Electric lighting with different lamps and daylight harvesting systems

The comparison between the base case and improved case is shown in Table 3. The 55 W LED luminaires provided a higher illuminance compared to the fluorescent luminaires while using only 37% of the power, i.e. reducing the LPD from 4.0 to 1.5 W/m². The energy use per year is shown in Figure 4. The total energy use was 35 500 kWh/year for the base case and 13 000 kWh/year with the LED solution, which corresponds to a reduction of approximately 63%. If the smaller skylight is introduced as a single measure, the energy use was reduced to 20 000 kWh/year using fluorescent lighting and 7 300 kWh/year using LED. Doubling the skylight size led to a reduction of energy use to 16 000 kWh/year with fluorescent lighting and 5 900 kWh/year with LED. Implementing all measures resulted in an energy use of 14 200 kWh/year with fluorescent lighting and 5200 kWh/year with LED. However, the uniformity of illuminance decreased after replacing fluorescent lights with LEDs. The

higher illuminance and narrower light distribution of LEDs intensified the contrast between brightly and poorly lit areas. The Uniformity Ratio (UR), which is defined by the minimum illuminance divided by the average illuminance, decreased from 0.25 with fluorescent to 0.19 with LED.

Table 3. Electric lighting in Base Case and Improved case.

Case	Solution	Total power	Mean Illuminance	Median Illuminance
Base Case	Fluorescent	7 208 W	173 lux	182 lux
Improved Case	LED 55 W	2 640 W	184 lux	201 lux

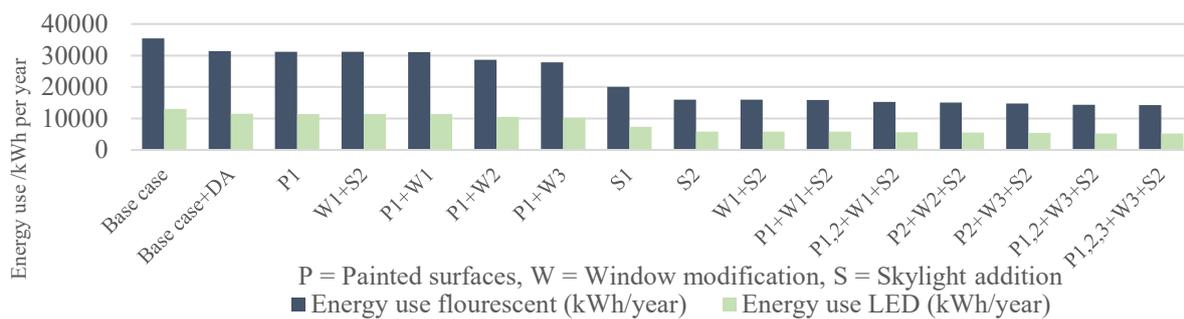


Figure 4. Energy use per year for the base case and improved cases.

3.3. Circadian lighting

The result of ALFA simulations adjusted to mEDI for the base case and improved case (LED lighting and addition of S2 skylight) are shown in Figure 5. The illuminance levels for the base case peak at mEDI equal to 382 and 185 lux at 12:00 hours during the Spring equinox under sunny and overcast skies, respectively. The M/P ratio consistently remains below 0.8 except Spring equinox under sunny sky, resulting in lower mEDI values compared to photopic lux. During the Winter solstice, neither electric lighting nor daylighting is sufficient to meet the threshold of mEDI equal to 136 lux, except for a few hours when the sun is near the horizon and light enters through the main entrance.

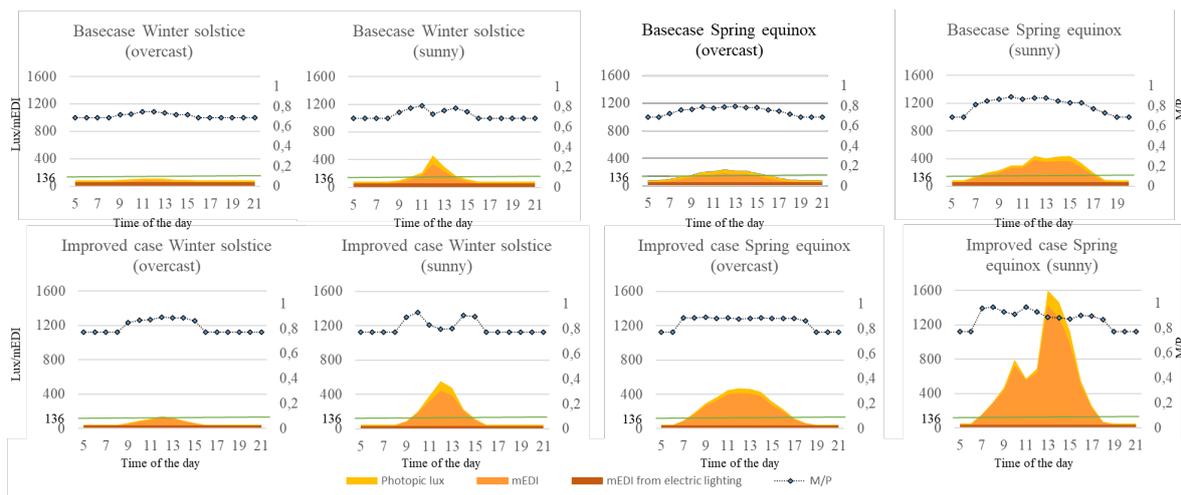


Figure 5. Average photopic lux, average mEDI, mEDI from electric lighting, and M/P (melanopic/photopic) ratio at different times for the base case and improved case.

In the improved case, fluorescent electric lighting is replaced with LED lighting, and a skylight (S2) was added. The peak is mEDI equal to 1422 lux at 13:00 hours during the Spring equinox under clear skies. The cattle areas received more direct sunlight in the afternoon. Winter solstice did not meet the mEDI threshold for all the 16 hours on an overcast day. Despite having a higher mean

illuminance on the horizontal plane and a higher M/P ratio, the contribution to mEDI from electric lighting is lower in the improved case compared to the base case (mEDI equal to 37 compared to 56 lux), which is due the narrower beam of light from the LED luminaires. Therefore, in both base and improved case, the mEDI criterion was not met when using only electric lighting.

4. Discussion and conclusions

The aim of this study was to investigate the energy-saving potential of electric lighting and daylighting in dairy barns, with a secondary goal of evaluating circadian lighting conditions. The study provided evidence supporting LED upgrades combined with daylight measures in dairy barns. This study highlights the opportunities for improving daylighting and electric lighting in dairy barns.

Introducing more light through a skylight could potentially introduce more solar heat gains, but it could also improve the ventilation in the barn. With the 16-hour days and 150 lux thresholds used in this study, reaching a DA of approximately 60% was possible using several measures including maintaining a high reflectance of surfaces and transmission of windows. However, such values may be hard to achieve and maintain due to the higher dirt and manure accumulation inside the barn. The energy savings potential from replacing the fluorescent lighting to LEDs in this study was found to be 63%, which is substantial saving corresponding to significant energy cost reduction. A partial reason for the larger saving was that the luminaires were initially unevenly distributed, while replaced luminaires in the barn were evenly spread. When replacing the lighting system, the illuminance of the barn increased even though the total luminous flux provided by the luminaires decreased. In the improved case, a greater part of the light from the luminaires was directly illuminating the measurement plane while the base case luminaires reflected some light off ceiling and wall surfaces, where light was absorbed. Using both daylighting strategies as well as electric light replacement, the energy use for electric lighting could be reduced by 83%.

In this study the Melanopic Equivalent Daylight Illuminance (mEDI) benchmark equal to 136 lux for 4 hours was not reached during Winter solstice with an overcast sky, but it was reached for all the other times studied. There is a large difference between clear and overcast days, however, overcast days on Spring equinox still resulted in a high average mEDI in the improved case with added skylight. The electric lighting did not achieve the benchmark at any of the times studied. The proposed implementation of the new LED lighting led to a reduction in mEDI which was largely attributed to the narrow luminous distribution of the selected LED luminaire. The lower M/P values can be attributed to two factors: the use of mEDI for calculation, which is approximately 10% lower than EML; and the influence of surface reflectances that alter the spectral composition of reflected light.

Further study on the thermal effects of lighting retrofit measures; particularly solar heat gains and losses through skylights can provide a more comprehensive understanding of its impact on overall building energy consumption, which warrants integrated lighting and thermal simulations. A major limitation of this study is that the illuminance uniformity was not fully addressed, which plays a crucial role in cattle wellbeing.

Credit-author statement

S R Ahmmad, K A Nordin, and P W Zaw contributed equally to the conceptualization, analysis, investigation, methodology, validation, visualization, and writing. N Gentile and M-C Dubois supervised the project, contributed with the conceptualization, methodology, reviewing, and editing the manuscript, as well as to the funding acquisition and project administration.

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