buildings

Article

Daylight Performance of a Translucent Textile Membrane Roof with Thermal Insulation

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Abstract: Daylight usage in buildings improves visual comfort and lowers the final energy demand for artificial lighting. The question that always occurs is how much conservation can be achieved? New or rare materials and constructions have a lack of information about their application. Therefore, the current investigation quantifies the daylight and energy performance of a rare multi-layer textile membrane roof. A translucent, thermal insulation with a glass fibre fleece between the two roof membranes combines daylight usage and heating demand reduction. A sports hall built in 2017 is used as a case study building with 2300 m² membrane roof surface. The optical properties of the roof construction were measured with a total visual light transmittance τ_v of 0.72% for a clean surface. A climate-based annual daylight modelling delivers daylight indicators for different construction scenarios. The results show that, in comparison to only one glass façade, the additional translucent and thermally insulated membrane roof construction increases the annual daylight autonomy (DA_{700}) from 0% to 1.5% and the continuous DA_{700} from 15% to 38%. In the roof-covered areas of the sport field, this results in a 30% reduction of the electricity demand for artificial lighting from 19.7 $kWh_{el}/m^2/a$ to 13.8 $kWh_{el}/m^2/a$, when a dimming control is used. The study also found that the influence of the soiling of one layer decreases its light transmittance by a factor 0.81. Two soiled layers lower τ_v by a factor of 0.66 to 0.47%. This increases the electricity demand for lighting by only 12%. The results should be very valuable as a comparison and benchmark for planners and future buildings of a similar type.

Keywords: translucent textile membrane roof; climate-based daylight modelling; daylight performance; energy conservation; translucent thermal insulation; multi-layer membrane

1. Introduction

The construction and materials of a building have a huge influence on its physical interaction with the environment and the required technical effort to reach the required indoor acoustics, air quality, visual and thermal comfort states. Passive functional components show less life cycle financial and environmental cost and need less maintenance than active systems. The drawback of less control of passive components can be compensated with adequate planning, sizing and backup systems.

In this context, passive daylight usage in buildings improves visual comfort and lowers the energy demand for artificial lighting. However, how much conservation can actually be achieved? New or rare materials and constructions often lack information about their application. Therefore, the current work investigated the daylight performance of a multi-layer textile membrane roof with a size of 2300 m² on top of a sports hall (Figure 1).

(**a**) glass façade on the north-east side (**b**) attachment with wooden façade

Figure 1. Photographs of the case study building from: (**a**) north; and (**b**) west.

As the authors of this study found few articles about energy data related to sport buildings in general and especially none on the visual influence of membrane constructions, the literature review mainly refers to office buildings and other translucent materials. Other researchers, e.g., Haase et al. (2011) [1], made the same observation about membrane constructions. With the term "membranes", we refer to textile membranes with a woven fabric in distinction to foils. Some sport buildings with multi-layer membrane roofs have been built in the last years, but with very little available public information. There are for example the "Odate Jukai Dome Park" in Japan, the "Kurklinik Masserberg" in Germany (no translucency) and the "Dedmon Athletic Center in Radford" in USA (see Table 1).

Table 1. Optical properties of other multilayer membrane roofs.

Site	Light Transmittance τ_v	U-Value [W/m²/K]
Odate Jukai Dome Park [2]	8%	no insulation
ZAE Würzburg Technikum [3]	3%	1
University Sport centre Radford [4]	3.5%	0.47
Olympia swimming hall Munich [4]	1.5%	0.42

Concerning energy performance, the electricity consumption to supply indoor illuminance needs has a relevant part in the total energy consumption of buildings. A report [5] based on simulations from the institute for housing and environment in Germany relates 34% of the primary energy (PE) demand Q_{PE} in a standard office building to artificial lighting (al). This corresponds to an electricity demand for artificial lighting ($Q_{el,al}$) of 27.6 kWh_{el}/m^2_{tfa} for low efficiency lamps (5.4 $W_{el}/m^2/100$ lx) or 35% of the total electrical energy demand $Q_{el,tot}$. The target indoor illuminance in that report is assumed to be 300 lx. This amount can be decreased by 87% to 3.4 kWh_{el}/m^2_{tfa} using high-efficient fluorescent lamps (2.5 $W_{el}/m^2/100$ lx), a daylight sensitive lighting control and a strategy allowing different illuminance levels in the room and individual working space lights. Then, the workstations are illuminated with 500 lx and all other areas with 220 lx. The PE/Q_{el} demand for artificial lighting in such a high efficiency building is then 15%/23% of the annual energy demand. In the commercial building sector of the U.S.A., in 2003/2012, artificial lighting accounts for 21%/10% of the measured total site energy consumption and 38%/17% of the $Q_{el,tot}$ consumption [6]. A Swiss monitoring study in 128 office buildings reports a 25% share in the $Q_{el,tot}$ consumption during 2005–2007. The report confirms the U.S.A. trend of the high exploitation of efficiency potentials in lighting technology.

1.1. Energy Consumption in Sport Buildings

The authors of the current article found very little information about the detailed composition of the energy consumption of sport buildings. As lighting is the focus of this article, heating energy, e.g., from Beusker et al. [7], is not of interest. Two studies from 2009 and 2005 report monitoring values of the arithmetic mean for the total electricity consumption $Q_{el,tot}$ in German "dry" sport halls of 32 $kWh_{el}/m^2/a$ (sample size 1365 [8]) and 50 $kWh_{el}/m^2/a$ (sample size 90 [9]). A UK report from 2001 [10] states as typical mean $Q_{el,tot}$ for a local dry sports centre 105 $kWh_{el}/m^2/a$.

1.2. Lighting Systems and Conservations

When speaking about "savings" or "conservations", a crucial but often ambiguously mentioned issue is the reference or base case that any scenario relates to. In addition, the real consumption is highly sensitive to boundary conditions such as neighbouring buildings, availability of solar radiation, target illuminance, geometries, user behaviour, equipment specifications or correct sizing. Hence, there is a high variation between different buildings and comparisons should be taken with care. Consequently, electric energy savings for lighting determined via measurements or calculation show a very large range of variation between 11% and 94% [11]. Some correlations try to cover all relevant influences and offer methods to estimate energy savings (e.g., Krarti et al. [12] and Ihm et al. [13]). Lowry [11] criticized that savings caused by automatic controls are overestimated in many cases because of choosing a non-adequate reference scenario with an insufficient user behaviour profile for manual on/off control. He also suggested as a key performance indicator to focus on absolute energy metrics instead of percentage savings. The authors of the current article strongly support these suggested methods and try to give absolute energy values and clear reference scenarios.

Besides the environmental and financial costs of the energy demand for artificial lighting, visual comfort and health aspects are also in favour of natural daylight [14,15]. In sunlit situations, the natural daylight often has to be blocked to prohibit glare and overheating. Beside transparent windows with shelves and reflecting blinds [16], other constructions exist such as translucent wall materials or waveguide systems especially to transport daylight also to façade distant spaces.

1.2.1. Materials

Translucent materials can help to reduce glare risk with an increased indoor daylight availability. However, glare remains a relevant risk. Matusiak [17] investigated the human glare sensing in the high latitudes of Norway with experiments. Her results are that a completely translucent aerogel façade in direct sunlight orientation with a light transmittance τ_v of 29% still causes intolerable glare in sunlit periods.

A numerical study from Pagliolico et al. [18] in Turin applied partly translucent interior walls with glass splinters in the concrete (τ_v 29%). The target of the photosensitive dimming control was 500 lx. Compared to opaque interior walls, the $Q_{el,al}$ decreases from 11.3 to 10.0 $kWh_{el}/m^2/a$ in rooms with adjacent south oriented outside wall (with movable blinds) and from 6.3 to 5.0 $kWh_{el}/m^2/a$ for north orientation.

In New York, a multipurpose, seven-storey building with a translucent marble envelope was investigated by Rosso et al. [19]. A Colour Rendering Index (CRI) of 86 is measured. Simulations under an indefinite control reveal a decrease in the $Q_{el,al}$ from 18 to 16 $kWh_{el}/m^2/a$ (11% savings) for a translucent marble façade (τ_v 7%) compared to an opaque one. Furthermore, the high solar reflectance of 58% for the marble reduces the demand of energy for cooling by 10%, when compared to more traditional cement-based façades with solar reflectance of 30%. The target illuminances ranged from 150 to 300 lx.

A translucent wall with silica aerogel and PCM material has been investigated experimentally and numerically in a laboratory by Souayfane et al. [20]. They focus on the thermal behaviour.

Ahuja et al. [21] evaluated the monetary savings in energy consumption for heating, cooling and lighting of an interesting translucent concrete wall system in Berkeley. Unfortunately, the reference was not a realistic scenario with a standard window wall but a completely opaque room. The insulated concrete panels were fabricated with embedded optical fibres with different fibre ratios for light transmission. The fibres penetrated all wall layers, namely concrete, Extruded Polystyrene (XPS) insulation and the final drywall. With a probabilistic manual on/off switching behaviour of the occupants, they found an optimum financial cost reduction of 18% related to a completely opaque room.

Optical fibres can also be combined with solar concentrators for a building daylighting system (waveguides). They can deliver sunlight deep into the interior rooms of a building [22,23]. This technology allows supplying rooms without outside connection with natural daylight. To distribute the collected light, conventional light fittings can be used. However, the operating distance of such systems is limited. With increasing length of the optical fibres, the wavelength between 720 and 780 nm in the visible wavelength range will be lost. That causes a blue shift which leads to optically uncomfortableness [24].

1.2.2. Lighting Control

As with all automation systems, for the lighting control system, the control strategy and control parameters influence the result tremendously. Different control types are:

- Manually operated on/off (not automatized).
- Time scheduled on/off.
- Occupancy sensitive on/off.
- Daylight sensitive with: (i) dimming; or (ii) stepped.

Hybrids between these types are possible. A daylight sensitive control can reduce the $Q_{el,al}$ by 75% with a simple time schedule as a reference [25]. Comparing dimming and stepped daylight sensitive controls, dimming is only advantageous from an energetic point of view for low sunlit locations or room geometries [25,26]. Then, the part load can be effectively used and only few time periods with the (unwanted) minimum residual load of dimming lightings occur. On the other hand, dimming appears more appealing for human sensation because of the more continuous changings.

Field experiments measuring illuminance in an atrium office building in Hong Kong indicate electricity savings for dimming control compared to opaque walls of 59–75% [27]. Roisin et al. [28] investigated the potential energy savings in a virtual office room with occupancy or daylight sensitive control in three European cities (Stockholm, Brussels and Athens). The reference has the same geometry but a different control with time scheduled on/off: 45–61% of the electric energy can be saved with dimming and 11% with occupancy on/off control. The façade orientation played a minor role in the order of 4% in the worst case of Stockholm. A field study [29] in a 51-storey office building in New York revealed a 20% reduction of $Q_{el,al}$ for dimming control relative to an occupancy based control.

Going into more detail is out of the scope of the current article. In the case study, building a dimming control is realized as described in Section 2.1.

1.3. Membrane Roofs

The advantages of textile membrane roofs are their low weight and long covering ranges. Furthermore, they appear very aesthetic with their unusual and soft shapes. A sophisticated collection of realized membrane buildings can be found in a report by Haase et al. [1] in German language. Many aspects of these special tensile roof constructions are of importance, for example the wind loadings on their unusual shapes [30] or the acoustic behaviour [30,31]. However, this is out of the scope of the current article. Concerning the optical properties, Haase et al. [1] measured a light transmittance τ of 3.7% for a single layer of a PVC coated Polyester (PES) tensile membrane and 1.1% for a double layer with air gap. An overview of some example buildings with membrane roofs and their properties is given in Table 1. The multipurpose hall "Odate Jukai Dome Park" (Japan) with two layers of PTFE coated glass fibre textile shows a light transmittance of 8% [2]. Insulated and translucent multilayer constructions are also realised: The "ZAE Würzburg Technikum" building (Würzburg, Germany) with 10 cm translucent glass fibre insulation shows a U-value of 1 W/m^2K and a τ of 3% [3]. The University Sport centre Radford (VA, USA) with an aerogel insulation and glass fibre membrane shows a τ of 3.5% and a U-value of 0.47 $W/m^2/K$ [4]. The Olympia swimming hall Munich (Germany) with a 7 cm PES fleece insulation has a U-value of 0.42 $W/m^2/K$ and a τ of 1.5% [4].

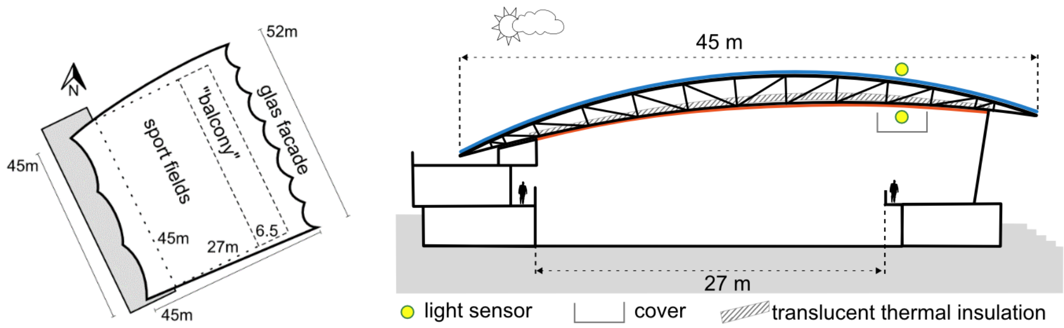
2. Materials and Methods

In this section, we present first the case study building's properties and geometry and then optical measurements. The annual daylight simulations with the different scenarios are described last. They yield the key performance indicators of daylight use and electricity consumption.

2.1. Case Study Building

The community gym "Julius-Hirsch-Sportzentrum" is located 288 m above sea level at 49.482 latitude and 10.988 longitude in the German municipality of Fürth [32]. The sport arena is intended to host one indoor soccer/hand ball/basketball match or three small spaces for school sports.

The building has a glass façade on the northeast side with the so-called indoor "balcony", a 45 m × 27 m indoor field, changing rooms below the balcony and in the integrated attachment with the wooden façade. Figure 1 shows photos from the outside and a schematic top view is presented in Figure 2a. The rooms are arranged throughout the basement and ground floor while the sport field is located at the subterranean level of the basement, as shown in Figure 2b. The membrane roof spans the field and partly the secondary rooms. From an architectural point of view, the shape of the roof reminds of a sprinter on the starting block while the white membrane represents sportswear [33]. The light weight impression of the building appears adequate to the dynamic activities inside [33].



(**a**) Top view scheme (**b**) Elevation from south direction

Figure 2. (**a**) Scheme of the top view; and (**b**) elevation from south direction of the complete building. The sensor positions of the short time measurements of the illuminance are indicated.

The overall heat transfer coefficient (U-value) is 0.23 W/m²/K for the opaque and 1.6 W/m²/K for transparent envelope components (from the certificate EnEV 2007, more details in Table A1). The total primary energy demand according to EnEV 2009 is calculated as 129 kWh/m². Further description about hygrothermal simulations of the roof construction and general information about the project can be found in Cremers et al. (2016) [34]. Details about the roof construction follow in the next subsection.

2.1.1. Roof Construction

The scheme of the layer construction of the roof can be found in Figure 3a. It consists of an outer membrane (OM) as weather protection, a 0.5–2.5 m air space, a thin cover foil as humidity barrier, a thermal insulation, a small 4 cm air gap and the inner membrane (IM). The OM is walkable. A photography of the membrane interspace is shown in Figure 3b. A maintenance gangplank on the right side, the underside of the outer membrane at the top part of the image and the cover foil at the bottom part can be seen. The relevant properties of the roof construction and the glass of the façade are presented in Table 2. Most information was taken from the company datasheets. The total transmittance was measured as described in Section 2.2.

(**a**) scheme is not proportional (**b**)

Figure 3. (**a**) Side view scheme of the roof layer construction; and (**b**) photograph of the membrane interspace. A monitoring platform for other measurements is visible on the two ropes on the right-hand side of the image.

Table 2. Material properties of the building's non-opaque components.

Component	Product	Property	Value
Glass façade	Insulated triple glazing	Light transmittance τ_v	60%
Outer membrane	Précontraint 1202 T2 2399 high translucency type, Serge Ferrari S.A.S	Fabric material/Top bottom coating	Polyester/PVC
		Top/bottom varnish	Polyvinylidenfluorid (PVDF)
		Light transmittance [1] τ_v	18%
		Light transmittance [2] τ_v	16%
		Light transmittance [3] τ_v	25%
Cover foil	Hostaphan® RUF, Mitsubishi polyester film GmbH	Material	Polyethylenterephthalat (PET)
Thermal insulation roof	TIMax GL-PlusF Wacotech GmbH & Co.KG	Material	Glass wool
		Thermal conductivity	ca. 0, 1 W/m/K
		Thickness	40 cm
		U-value	0.25 W/m²/K
Inner membrane	Précontraint 1002 S2 3399, high translucency type, Serge Ferrari S.A.S	Fabric material/Top bottom coating	Polyester/PVC
		Top/bottom varnish	PVDF
		Solar transmittance [2] T_S	19%
		Light transmittance [2] τ_v	16%
Total roof construction		Light transmittance [1] τ_v	ca. 0.72% [4] clean, 0.47% [1] soiled

[1] Measured value; [2] EN 410; [3] NFP 38,511 (French standard with partly diffuse incident light); [4] extrapolation.

2.1.2. Lighting System

The lighting installations in the main hall have a total electrical power of 10.4 kW and a luminous flux of 1830 k lm. This refers to Light Groups 1–4 in the simulation. They are listed in Table 3. The dynamic dimming control design aims to an illuminance on the ground of 700 lx. Three levels of 300, 500 and 700 lx can be set manually to override the automatic.

Table 3. Technical data of the realized lighting inside the main hall.

	Properties of one light element	A_{hall}: area of the sport fields and platform
94	W electricity consumption apiece	refers to the foot print area of the main hall
16,500	lm luminous flux apiece	1507 m²
1.6	m length apiece	Design illuminance on the floor: 700 lx
111	pieces in total	
6.9	W/m² electrical power/A_{hall}	(10.4 kW total)
1215	lm/m² luminous flux/A_{hall}	(1832 klm total)

2.2. Optical Measurements

To calculate the (visual) light transmittance τ_v (DIN EN 410:2011-04), measurements of the (visual) illuminance E_v based on EN 14500:2008 were carried out. A spectrometer "GL Spectis 1.0 Touch" from "GL Optic Lichtmesstechnik GmbH" was used as measuring equipment. The spatial positions of the sensor were 5 cm under the inner membrane ($E_{v,IM}$) and vertically directly above the position on top of the outer membrane. $E_{v,OM}$ equals the ambient conditions in the membrane plane (Figure 2b). A cover protects the bottom measurement under the IM from insolation through the glass façade. Multiple measurements were recorded (Table 4) and led to a (visual) light transmittance τ_v of 0.47% with soiling on top of the OM as well as on the cover foil. The roof construction was at the time of the measurement two years old.

Table 4. Measurement of the illuminance for the (visual) light transmittance τ_v.

Year 2018	$G_{glob,OM}$	$G_{glob,IM}$	$E_{v,OM}$	$E_{v,IM}$	τ_{tot}	τ_v	$CCT_{v,OM}$	$CCT_{v,IM}$
	[W/m²]	[W/m²]	[lx]	[lx]	[%]	[%]	[K]	[K]
8 May 10:38	431	2.52	89 100	416	0.58	0.47	5720	7560
8 May 10:39	432	2.55	89 300	420	0.59	0.47	5730	7570
8 May 10:39	432	2.57	89 100	425	0.60	0.48	5730	7550
8 May 10:40	432	2.56	89 100	422	0.59	0.47	5720	7560
average					0.59	0.47	5725	7560

With the same measuring device, the illuminance above and below the OM was recorded at two different positions: around a cleaned area of 1 m^2 and around a soiled area untouched for two years. Therewith, the transmittance τ_v of only the clean OM was calculated to 18% and the soiled OM to 14.6%. Hence, a decrease of the transmittance through one layer by a factor 0.81 was caused by the soiling. As the layer in between the cover foils also gets soiled by dust and pollen, we estimated the clean transmittance from the complete roof construction as 0.72% (0.47% divided by $0.81^2 = 0.656$). Additionally, the daylight factor was measured as 0.83%. The daylight factor represents the percentage of the outdoor light (illuminance in lx) under overcast skies that is available indoors on the horizontal plane in the occupant area.

2.3. Simulation

2.3.1. 3D Model

The geometry of the sports hall was simplified for the simulation and built in SketchUp Pro 2018. The hall itself was shown as a hall floor and a platform behind a single glass front, which consists of joined single windows. Adjacent rooms and the supporting structure were not mapped for the light simulation process. The roof was designed as a translucent membrane roof. Table A3 in Appendix A presents the material definition file of DIVA for the translucent component.

To define other material properties, the following parameters were assumed or taken from datasheets and experiments:

- Floor: Sports hall flooring with a reflection of 20%.
- Wall: Interior wall with a reflection of 50%.
- Ceiling: High reflectance ceiling with a reflection of 70%.
- Window: Two-window insulating glass with a transmission of 70%.
- Membrane: The layer structure of the real object was modelled in the software as one component. A diffuse reflection of 69% and a total diffuse transmission of τ_v Roof in Table 5 were assumed. Direct reflection and transmission were set to 0. See Table A3 in Appendix A for the material config file.

2.3.2. Daylight and Artificial Lighting

The geometric model was built as a 3D model in SketchUp Pro 2018 and exported to Rhino 5. A screenshot of the 3D model can be found in Figure 4a. The simulations were performed in Diva 4.0.2.24, which is a plugin for Rhino to simulate daylighting and artificial lighting.

The material properties of the roof construction for the simulations were determined via experiments (see Section 2.2). An annual daylight simulation in Rhino 5 with Diva calculated the lighting parameters Daylight Availability (DA), Continuous Daylight Autonomy (CDA) and Useful Daylight Illuminance (UDI) as well as the electricity consumption of the artificial lighting. It ran in one-hour time step resolution.

The approach of the varied parameters for the different scenarios is shown in Table 5. Properties of the building envelope, the target indoor illuminance, the lighting control and the transmittance of the roof component were varied. The 18 investigated variants are shown with all varied parameters in Table 6. There were two main groups of similar scenarios with target illuminance values of 300 (Nos. 1–7) and 700 lx (Nos. 8–14). As a step in between, two 500 lx variants were also calculated (Nos. 17 and 18). In addition, two scenarios with increased and decreased transmittance were considered (Nos. 15 and 16). According to the German standard DIN V 18599-10:2016-10, a sports hall should have a minimum target illuminance of 300 lx. In reality, artificial light is often used with higher target values so that scenarios with 500 and 700 lx are also tested. Overall, 700 lx is the realized situation in the case study building. Except scenario Nos. 15 and 16, the transmittance of the roof represents the clean surface case. No. 15 corresponds to the soiled surfaces and No. 16 to other materials with higher transmission. The user in lighting control mode "on/off" (o/o) switches the light statistically off when an indoor illuminance of 300 lx is exceeded. It is more than a time fixed schedule. This mimics a human operated situation. Dimming adapts the light power daylight sensitive to the target value. The target values also determine the installed lighting power (Table 5).

Table 5. Overview of the values of the varied scenario parameters for Light Groups 2–4. Not all of the possible combinations were simulated.

Parameter:	Envelope	Target Illuminance [lx]	Control	τ_v Roof [%]
	• Opaque • Façade only • Roof only • Façade + roof	• 300 (3.4 kW_{el}) • 500 (5.6 kW_{el}) • 700 (7.9 kW_{el})	• Manual On/off • dimming	• 0.48 • 0.74 • 3

Table 6. All used parameters of the 18 simulation scenarios in detail.

No.	Name	τ_v Roof [%]	Target Illuminance [lx]	Control	Envelope	Comment
1	Opaque 300	0.72	300	o/o = dim. [1]	Opaque	Opaque building
2	Reference 300	0.72	300	On/off	Façade	Conventional building
3	-	0.72	300	On/off	Roof	
4	-	0.72	300	On/off	Façade + roof	Control mode comparison
5	-	0.72	300	Dimming	Façade	-
6	-	0.72	300	Dimming	Roof	-
7	-	0.72	300	Dimming	Façade + roof	Real built geometry
8	Opaque 700	0.72	700	o/o = dim. [1]	Opaque	Opaque building
9	Reference 700	0.72	700	On/off	Façade	Conventional building
10	-	0.72	700	On/off	Roof	-
11	-	0.72	700	On/off	Façade + Roof	Control mode comparison
12	-	0.72	700	Dimming	Façade	-
13	-	0.72	700	Dimming	Roof	-
14	Real Building	0.72	700	Dimming	Façade + Roof	Real built situation, clean

15	Lower τ_v Roof	0.47	700	Dimming	Façade + Roof	Real built situation, soiled
16	Higher τ_v Roof	3	700	Dimming	Façade + Roof	Sensitivity case high τ_v
17	Reference 500	0.72	500	On/off	Façade	Medium lx set point
18	-	0.72	500	Dimming	Façade + Roof	Medium lx set point

[1] In an interior space without daylight, dimming and on/off control behave the same.

The lighting controls were defined in a grid of 1 m × 1 m and illuminance was evaluated at 1 m height. The sports hall was divided into four light groups for the control, as shown in Figure 4b. The balcony at the glass façade was defined as Group 1 with an installed lighting power of 2538 W for the 700 lx target. The sections of the sports hall were defined as Groups 2–4 with a lighting power of 2632 W each. In total, there is an installed lighting power of 10,434 W. For the simulation, a ballast lost factor of 28% and a standby-power of 8.4 W per LG meaning in total 25.2 W were assumed. The occupancy profile is 08:00–18:00 every day of the year (Figure A1). The weather file is located in the city Stuttgart in central Europe (Coordinates 48°47′ N 9°11′ E) with an annual global horizontal irradiation of 1093 kWh/m²/a.

(**a**) (**b**) light groups (LG) for the control

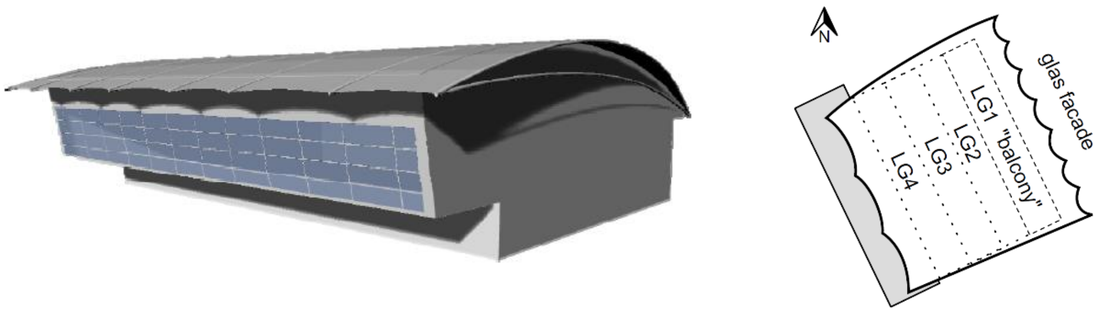


Figure 4. (**a**) 3D model in SketchUp, view from north; and (**b**) group definition of lighting sections.

2.4. Daylight Metrics

The Daylight Factor first proposed in the UK in the early 1900s is the ratio of internal illuminance to external horizontal illuminance under an overcast sky defined by the CIE luminance distribution [35].

In 1989, the Daylight Autonomy (DA) parameter was proposed by the "Association Suisse des Electriciens" and further developed by Reinhart from 2001 to 2004 [36]. It was the first dynamic approach for daylighting indoor evaluation. The DA_{xyz} represents the percentage of hours during a period (i.e., year or the occupation times over one year) when the natural indoor illuminance value in an area overcomes a predefined threshold xyz indicated in the indices. It does not provide information about illuminance values below the defined threshold.

Rogers et al. (2006) [37] developed a modification of the DA called the continuous Daylight Autonomy (cDA_{xyz}). With respect to the DA definition, it additionally counts partial values below the specified illumination level threshold xyz. A timely situation with CDA of 50% is not unique. It could mean that half of the time the illuminance threshold was completely reached and the other half of the time it was completely dark. It could also mean that all the time the threshold was only half reached.

The Useful Daylight Illuminances (UDI), proposed by Mardaljevic and Nabil in 2005, is also a dynamic daylight performance measure that is based on work plane illuminances [36]. It also represents the percentage of hours during a period when the natural indoor illuminance values lie in certain borders, namely <100 lx, within 100–2000 and above 2000 lx ($UDI_{<100}$, $UDI_{100–2000}$ and $UDI_{>2000}$). As its name suggests, it aims to determine when daylight levels are "useful" for the occupant, that is, neither too dark (<100 lx) nor too bright (>2000 lx) [36]. The upper threshold is meant to detect times when an oversupply of daylight might lead to visual and/or thermal discomfort [36]. The $UDI_{>2000}$ is equivalent to a DA_{2000}.

3. Results

The results of the simulations are presented using daylight indicators and energy demand analysis. The results hold for the case study building geometry investigated in this study which has a speciality with an indoor "balcony" at the side of the glass façade (Light Group 1). The presented results concerning energy are related to Light Groups 2–4 located at the sport field. They are shaded from the "balcony" and further away from the glass façade than fields in other buildings directly adjacent to a transparent façade.

3.1. Daylight

Daylight indicators in the current study are the daylight autonomy (DA), the continuous daylight autonomy (CDA) and the useful daylight illuminance (UDI) with certain thresholds. The results of their spatial distribution are shown in Figure 5a–c. Light Group 1 (LG1, Figure 4b) adjacent to the window on the so-called "indoor balcony" was also included here. LG 1 was excluded for the energy demand analyses of lightening the field in the following section. Only the sport field was placed in focus to be more comparable to other sport buildings. The DA was calculated with a hard threshold and therefore applicable for switch on/off situations. The CDA was applied for dimming systems, as it weights the differences to the threshold.

The DA_{xxx} with the respective thresholds 300, 500 and 700 lx increases of course with more light transmitting components. The single translucent roof shows a higher daylight usage (DA_{300} 17%, CDA_{300} 48%) compared to the single transparent façade (DA_{300} 2%, CDA_{300} 34%), see Table 7. The spatial distribution in the façade-only cases is highly asymmetrical towards the transparent façade (Figure 5a). Especially, the shaded edge under the "balcony" exhibits very dark areas. The Façade + roof cases deliver a more homogeneous daylight supply over the field especially concerning the CDA. The corner below the balcony remains the darkest area. Very homogeneous illuminance distributions achieve the roof-only envelope scenarios. However, the DA_{700} and CDA_{700} of 0% and 23% are smaller than the "facade + roof" cases with 1.5% and 38% (Figure 5b).

Increasing/decreasing the roof transmittance from 0.72% to 3%/0.47% changes the CDA in the 700 lx cases from the mentioned 38% to 70%/30% (Figure 5c and Table 7). The DA considerably changes from 1.5% to 47%/0%. The large transmittance of 3% (scenario No. 16) gives tremendous benefit for the daylight performance as also seen later in the electricity demand.

The balcony area has the highest daylight performance in the cases with glass façade as it is adjacent to the window. The UDI > 2000 indicates the risk of glare. This is harmless for all scenarios except No. 16. A shading system for the façade would be recommendable in that case. Even in the centre regions of the field, some signs of glare risk can be seen in Figure 5c. Going to such large transmittance values in a roof would require a closer investigation of glare and shading measures.

Table 7. Summary of annual daylight indicators for all scenarios.

	DA_{xxx}/CDA_{xxx} [%]		
	300 lx	**500 lx**	**700 lx**
Opaque, τ_v 0.72%	0.00/0.00		0.00/0.00
Façade-only	2.12/33.93	0.07/20.57	0.00/14.71
Roof-only	16.74/48.12		0.00/23.04
Facade + Roof	39.49/66.56	13.60/50.12	1.47/37.63
Facade + Roof, τ_v 0.47%			0.02/29.93
Facade + Roof, τ_v 3%			46.86/70.19

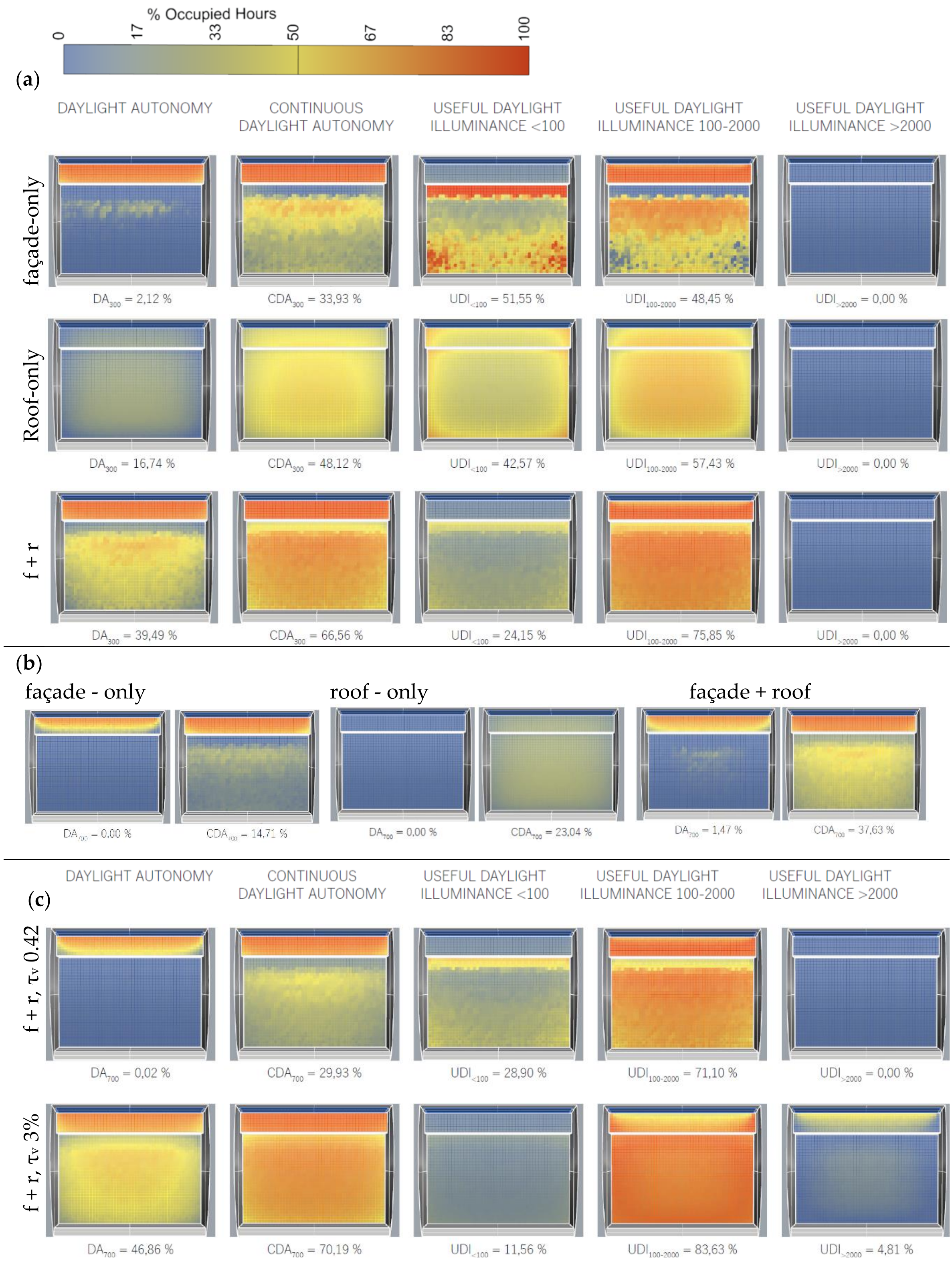
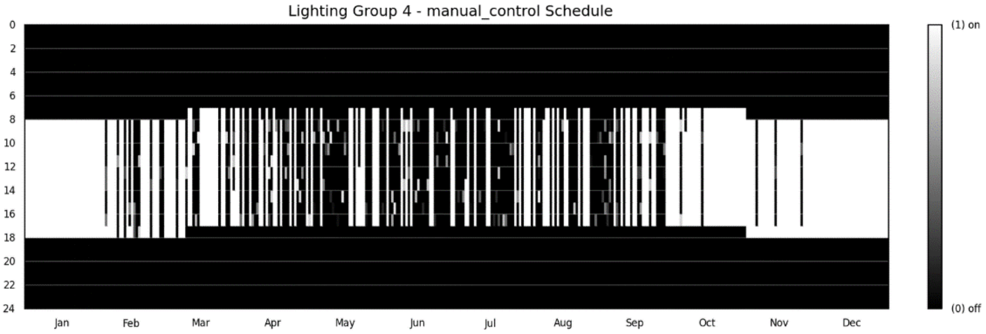


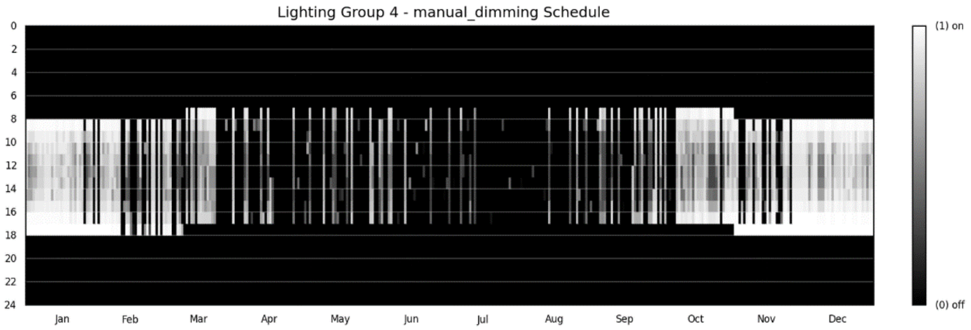
Figure 5. Spatial distribution of annual daylight indicators for scenarios with target illuminance: (**a**) 300 lx, Nos. 1–7; (**b**) 700 lx, Nos. 8–14; and (**c**) varied transmittance τ_v, Nos. 15 and 16. Scenarios Nos. 17 and 18 can be found in Figure A2.

3.2. Electricity Consumption

For the energy consumption of any automated system, the control behaviour is crucial. To interpret and transfer the results in this work to other situations, an understanding of the two used control modes is essential. As an example, for the operation of the control modes, two visualisations of the transient behaviour are shown in Figure 6. The users in "o/o" mode switch off the lighting with a certain probability if illuminance values above 300 lx occur. The dimming always dims the lighting following a photo sensor and the target illuminance value. Hence, the dimming mode in Figure 6b shows many times with partly operated light in grey colour.



(**a**)



(**b**)

Figure 6. Operation of the control modes as an example: (**a**) on/off (o/o) in No. 4; and (**b**) dimming in No. 16.

The results of the absolute electricity demand for artificial lighting ($Q_{el,al}$) in all scenarios are presented in Figure 7. All absolute values of $Q_{el,al}$ including the LG1 at the balcony can be found in Table A2. The relative savings are shown in Table 8 and in absolute values in Table A4. The table contains much information. The column scenario No. is related to the scenario No. in the rows. The Unit is per cent. Negative values are savings. For the detailed scenario No. parameter settings, see Table 6. The header here in Table 8 indicates a short description of the scenario settings. Relations of a scenario with itself are highlighted with grey. Blue cells are referred to in the text. As an example for the reading of the table, the blue cell in the very bottom of the column with the scenario No. 14 means that variant No. 14 saves 10% electrical energy for AL compared to the case No. 11 indicated at the very left of the row. Going in that row to the left until column with No. 4 means that No. 4 compared to No. 11 saves 57%.

First, the absolute energy demand in the same geometry (i.e., "façade") increases with increasing the target illuminance values from 300 over 500 to 700 lx. Comparing the different control modes "dimming" and "on/off", "dimming" reduces the demand in all daylight variants. In the scenarios "Façade + roof" which equal the case study building's geometry, this sums up to −24/−10% for a target illuminance of 300 lx/700 lx (Table 8 line "No. 4/11" blue cells). Higher target illuminances in this setting lead to less relative savings. This is because of the higher demand combined with only little higher natural daylight using potential. The absolute savings increase slightly from 1.9 to 2.0 MWh/a. It becomes obvious in Figure 7 that the highest daylight impact on lowering the $Q_{el,al}$ over all different target illuminances can be generated by using a translucent membrane roof in combination with a transparent façade. In the cases of 300 lx/700 lx, the membrane added to the transparent façade cases reduces the $Q_{el,al}$ drastically by 42%/32% when relating the dimming control cases to the conventional building reference cases "façade-only" with on/off control (Table 8 line "No. 2/9" blue cells). This comparison holds for a modern new building compared to a conventional one. The influence of only the translucent roof reveals when comparing No. 7 to No. 5 (300 lx) and No. 14 to No. 12 (700 lx). Then, 38% (3.8 MWh/a) and 30% (7.2 MWh/a) can be saved, respectively. The 30% savings are the main result of the article and highlighted with the blue cell and white text in Table 8.

The influence of lowering (soiling) and increasing the transmittance of the roof is investigated with Nos. 15 and 16 compared to No. 14. The soiling of the OM after two years (No. 15) which reduces the light transmittance τ_v from 0.72% to 0.47% increases the $Q_{el,al}$ by 12%. A roof with τ_v = 3% lowers it by 41% (Table 8, line "No. 14", blue cells). By chance, the $Q_{el,al}$ in case No. 15 with low τ_v ("700 dim 0.47" in Figure 7) almost equals No. 11 with o/o control and clean τ_v of 0.72% ("700 dim" Façade + roof in Figure 7).

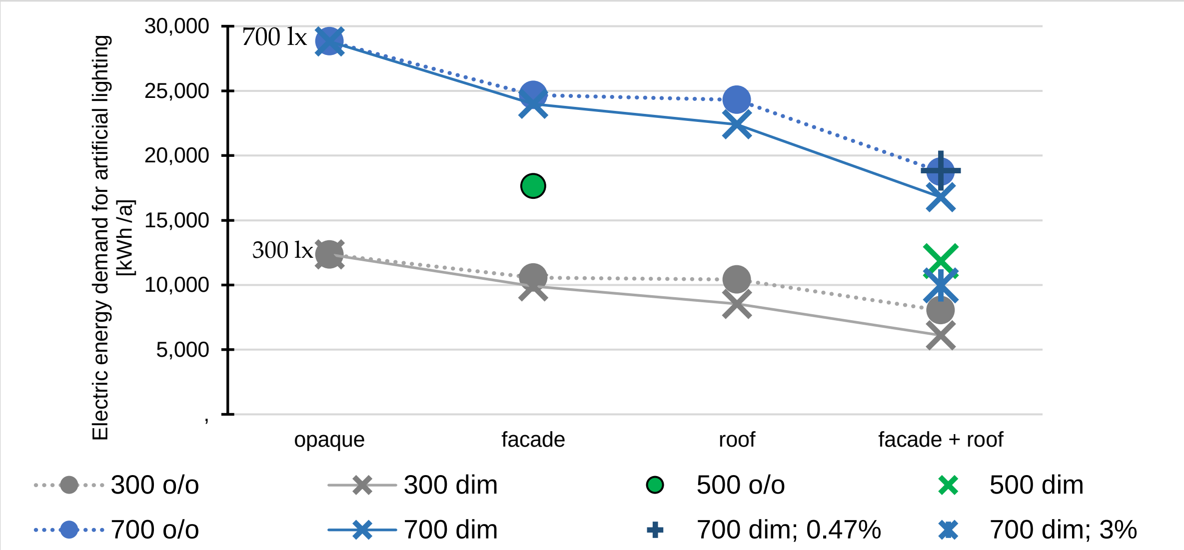


Figure 7. Electrical energy demand for artificial lighting.

Table 8. Relative electrical energy savings for AL: The column scenario No. is related to the scenario No. in the rows. The Unit is per cent. Negative values are savings. For detailed scenario No. parameter settings, see Table 6. The header here indicates a short description of the scenario settings. For example, the blue cell in the very bottom of the column with the scenario No. 14 means that variant No. 14 saves 10% electrical energy for AL compared to the case No. 11 indicated at the very left of the row. For another example, going in that row from the blue cell to the left until column with No. 4 on the top means that No. 4 compared to No. 11 saves 57%. Grey cells are relations of a scenario with itself and hence contain a 0 representing no savings.

[%]	300 lx							700 lx							τ Low	High	500 lx	
		O/O			Dim				O/O			Dim			Dim		O/O	Dim
	op.	f.	r.	f + r	f.	r.	f + r	op.	f.	r.	f + r	f.	r.	f + r	f + r	f + r	f.	f + r
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	−14	−16	−35	−20	−31	−51	133	100	97	52	94	81	36	52	−19	43	−4
8	−57	−63	−64	−72	−66	−70	−79	0	−14	−16	−35	−17	−22	−42	−35	−65	−39	−59
2	17	0	−2	−24	−6	−19	−42	172	133	130	77	127	112	59	78	−6	67	12
9	−50	−57	−58	−67	−60	−65	−75	17	0	−2	−24	−3	−9	−32	−24	−60	−29	−52
5	25	7	5	−19	0	−14	−38	191	150	146	89	143	127	70	90	1	78	20
12	−49	−56	−57	−67	−59	−64	−75	20	3	1	−22	0	−7	−30	−22	−59	−27	−51
14	−26	−37	−38	−52	−41	−49	−64	72	47	45	12	43	34	0	12	−41	5	−30
17	−30	−40	−41	−54	−44	−52	−65	63	40	38	6	36	27	−5	7	−44	0	−33
4	54	32	30	0	23	6	−24	259	207	203	133	199	179	109	134	24	119	47
11	−34	−44	−44	−57	−47	−54	−67	54	32	30	0	28	20	−10	0	−47	−6	−37

The area of the sport field supplied by Light Groups 2–4 adds up to 1215 m^2. This results in an annual area specific demand of 13.8 $kWh_{el}/m^2/a$ for scenario No. 14 (the realised membrane case study building) compared to the reference conventional building case No. 9 with 20.3 $kWh_{el}/m^2/a$ (only transparent façade, manual on/off control). That envelope case with the dimming control (No. 12) demands 19.7 $kWh_{el}/m^2/a$. The realized envelope situation with o/o control (No. 11) causes 15.4 $kWh_{el}/m^2/a$.

4. Discussion and Conclusions

A limitation of the current work is the occupancy profile used. It was assumed as 08:00–18:00, 365 days a year. The transfer of the saving potential in relative numbers on other buildings with more night-time use may be critical. The absolute numbers scaled with the illuminated field area and occupancy days over the whole year could be more accurate.

The so-called "indoor balcony" decreases the daylight usage of the analysed sport field in the current situation. Other fields adjacent to a glass façade would perform more promising. In that sense, the geometrical situation of the current study is conservative for the daylight performance. As opposed to this, the assumed occupancy schedule (08:00–18:00) lies strongly inside the daylight times. Hence, this boundary condition is favourable for the daylight performance.

Keep in mind that the (absolute or area specific) energy values indicated in the text always refer only to the sport field and not to the total building area or the indoor balcony.

Transferable findings are:

- Combining a translucent roof with a transparent north façade performs best for lighting the field with a low electricity demand for artificial lighting of 13.8 $kWh_{el}/m^2/a$ under 700 lx target illuminance. Comparing this value to reported total building electricity consumptions of 32 [8], 50 [9] and 105 $kWh_{el}/m^2/a$ [10] for dry sports centres, it appears to be very low, especially for the field area where the highest lighting load occurs.
- Adding this membrane roof even with the relatively low τ_v of 0.72% to a glass façade decreases the artificial lighting by 30%.
- A high roof transmittance τ_v of 3% delivers great daylight autonomy of 47% and a CDA of 70% resulting in only 8.2 $kWh_{el}/m^2/a$ electricity demand for artificial lighting. However, the risk of glare starts to become an issue around that value of τ_v, especially close to the glass façade.
- Soiling decreases the hybrid construction's daylight performance (façade + roof), but not as much as expected. Lowering the τ_v from 0.72% to 0.46% increases the electricity demand from 13.8 to only 15.5 $kWh_{el}/m^2/a$, probably because of the support from the glass façade. In a situation with roof-only daylight, this could be worse. This scenario was not included yet and could be a focus of another study.
- To completely exploit daylight potentials, dimming control is recommended. It decreases electricity consumption by 10%/24% for target illuminances of 700lx/300lx compared to a manual user "on/off" behaviour. This percentage is lower than results from other articles because of the reference in this study, which is not a simple time schedule. In fact, the o/o control imitates human user behaviour with switching off the light very often.

Even though the electricity savings and the illuminance distribution of a roof-only translucent envelope may be better than the hybrid combination façade + roof, a transparent glass façade has a positive effect on the visual comfort feeling of the persons inside. Hence, a combination system could lead to an optimum configuration. A future study could use a more general setting with an occupancy profile with more night time use and a more common geometry without an indoor balcony.

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Nomenclature

Abbreviations		**Comment**
al	Artificial lighting	
el.	electrical	
tfa	Total floor area	With construction
tot	Total	
v	visual	
PE	Primary Energy	
PES	Polyester	
PTFE	Polytetrafluoroethylene	
PVC	Polyvinyl chloride	
IM	Inner Membrane	
MI	Membrane Interspace	
OM	Outer Membrane	
IV	Interior Volume	
DA	Daylight Availability	
CDA	Continuous Daylight Autonomy	
UDI	Useful Daylight Illuminance	
Symbols		
Q	Energy	[kWh]
$Q_{el,tot}$	Total electricitydemand	[kWh]
$Q_{el,al}$	El. demand for artificial lighting	[kWh]
τ_v	Light transmittance	[%]
E_v	(visual) illuminance	[lx]
G_{glob}	Global irradiance	[W/m^2]

Appendix A

Table A1. Building parameters and indicators for the calculated energy demand following the German Energy Saving Ordinance "EnEV 2009, Energieeinsparverordnung".

Heated Area	$A_{net\ ground\ area} = 4221\ m^2$
Annual final energy demand	178 kWh/m²a
Annual PE demand [1]	$Q_P = 129$ kWh/m²a
Average opaque envelope U-value	0.23 W/m²K
Average transparent envelope U-value	1.60 W/m²K

[1] heating with wood.

Table A2. Absolute electricity demand for AL and daylight indicators of all scenarios.

Scenario Name	Energy Consumption [kWh]				
	LG1	LG2	LG3	LG4	LG2–LG4
01_t0.72_300lx_opaque	3971	4117	4117	4117	12,351
02_t0.72_300lx_facade_onoff	1362	4026	3194	3359	10,578
03_t0.72_300lx_roof_onoff	3271	3457	3266	3695	10,418
04_t0.72_300lx_facade + roof_onoff	1339	3039	2404	2590	8033
05_t0.72_300lx_facade_dim	803	4017	2827	3047	9891
06_t0.72_300lx_roof_dim	2748	2881	2542	3109	8532
07_t0.72_300lx_facade + roof_dim	762	2441	1719	1949	6109
08_t0.72_700lx_opaque	9264	9607	9607	9607	28,820
09_t0.72_700lx_facade_onoff	3176	9394	7452	7836	24,682
10_t0.72_700lx_roof_onoff	7630	8067	7621	8620	24,309
11_t0.72_700lx_facade + roof_onoff	3124	7092	5610	6042	18,744
12_t0.72_700lx_facade_dim	2533	9385	7085	7525	23,996
13_t0.72_700lx_roof_dim	7107	7491	6887	8035	22,413
14_t0.72_700lx_facade + roof_dim	2404	6494	4898	5396	16,788
15_t0.47_700lx_facade + roof_dim	2541	7214	5236	6379	18,829
16_t3.00_700lx_facade + roof_dim	1619	3647	2620	3687	9954
17_t0.72_500lx_facade_onoff	2269	6710	5323	5597	17,630
18_t0.72_500lx_facade + roof_dim	1536	4467	3504	3860	11,831

	DA/CDA		
	300 lx	500 lx	700 lx
01_t0.72_300lx_opaque	0.00%/0.00%		
02_t0.72_300lx_facade_onoff	2.12%/33.93%		
03_t0.72_300lx_roof_onoff	16.74%/48.12%		
04_t0.72_300lx_facade + roof_onoff	39.49%/66.56%		
05_t0.72_300lx_facade_dim	2.12%/33.93%		
06_t0.72_300lx_roof_dim	16.74%/48.12%		
07_t0.72_300lx_facade + roof_dim	39.49%/66.56%		
08_t0.72_700lx_opaque			0.00%/0.00%
09_t0.72_700lx_facade_onoff			0.00%/14.71%
10_t0.72_700lx_roof_onoff			0.00%/23.04%
11_t0.72_700lx_facade + roof_onoff			1.47%/37.63%
12_t0.72_700lx_facade_dim			0.00%/14.71%
13_t0.72_700lx_roof_dim			0.00%/23.04%
14_t0.72_700lx_facade + roof_dim			1.47%/37.63%
15_t0.47_700lx_facade + roof_dim			0.02%/29.93%
16_t3.00_700lx_facade + roof_dim			46.86%/70.19%
17_t0.72_500lx_facade_onoff		0.07%/20.57%	
18_t0.72_500lx_facade + roof_dim		13.60%/50.12%	

Table A3. Material configuration file of DIVA.

```
# material name: Precontaint
# material color: 178,178,178
# material type: translucent panel
# author: Amando Reber
# comment: This is a membrane with a reflectivity of 69% and a transmission of 0.72%.
# specular transmittance and specular reflection is set to 0.


#
void trans Precontaint
0
0
7 0.6972 0.6972 0.6972 0 0 0.0103 0
```

Table A4. Absolute electrical energy savings for AL in completive to Table 8: Absolute differences of the column scenario related to the row scenario No. [MWh/a] (negative values are savings).

	300 lx							700 lx							τ Low	High	500 lx	
		O/O			Dim				O/O			Dim			Dim		O/O	Dim
	op.	f.	r.	f + r	f.	r.	f + r	op.	f.	r.	f + r	f.	r.	f + r	f + r	f + r	f.	f + r
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0.0	−1.8	−1.9	−4.3	−2.5	−3.8	−6.2	16.5	12.3	12.0	6.4	11.6	10.1	4.4	6.5	−2.4	5.3	−0.5
8	−16.5	−18.2	−18.4	−20.8	−18.9	−20.3	−22.7	0.0	−4.1	−4.5	−10.1	−4.8	−6.4	−12.0	−10.0	−18.9	−11.2	−17.0
2	1.8	0.0	−0.2	−2.5	−0.7	−2.0	−4.5	18.2	14.1	13.7	8.2	13.4	11.8	6.2	8.3	−0.6	7.1	1.3
9	−12.3	−14.1	−14.3	−16.6	−14.8	−16.1	−18.6	4.1	0.0	−0.4	−5.9	−0.7	−2.3	−7.9	−5.9	−14.7	−7.1	−12.9
5	2.5	0.7	0.5	−1.9	0.0	−1.4	−3.8	18.9	14.8	14.4	8.9	14.1	12.5	6.9	8.9	0.1	7.7	1.9
12	−11.6	−13.4	−13.6	−16.0	−14.1	−15.5	−17.9	4.8	0.7	0.3	−5.3	0.0	−1.6	−7.2	−5.2	−14.0	−6.4	−12.2
14	−4.4	−6.2	−6.4	−8.8	−6.9	−8.3	−10.7	12.0	7.9	7.5	2.0	7.2	5.6	0.0	2.0	−6.8	0.8	−5.0
17	−5.3	−7.1	−7.2	−9.6	−7.7	−9.1	−11.5	11.2	7.1	6.7	1.1	6.4	4.8	−0.8	1.2	−7.7	0.0	−5.8
4	4.3	2.5	2.4	0.0	1.9	0.5	−1.9	20.8	16.6	16.3	10.7	16.0	14.4	8.8	10.8	1.9	9.6	3.8
11	−6.4	−8.2	−8.3	−10.7	−8.9	−10.2	−12.6	10.1	5.9	5.6	0.0	5.3	3.7	−2.0	0.1	−8.8	−1.1	−6.9

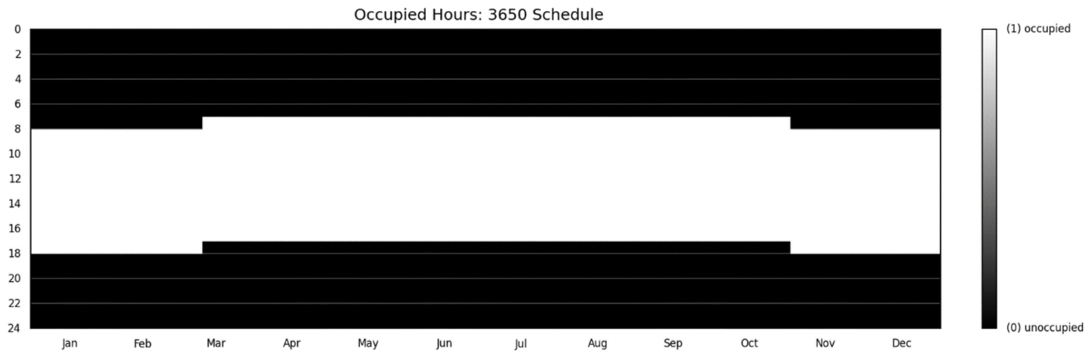

Figure A1. Occupancy profile.

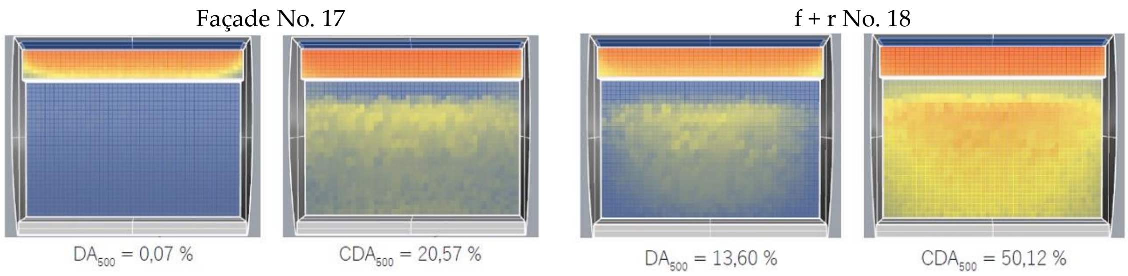

Figure A2. Spatial distribution of annual daylight indicators for scenarios with target illuminance 500 lx (Nos. 17 and 18).

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