Providing a sustainable future for glass architecture

Keywords: smart façade - solar shading – sustainable (solar) energy - transparent CPV – BIPV - built environment - circularity - indoor climate - LED media wall

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Figure 1:
Close up detail of the Lumiduct solar panels at the Mondial Movers pilot project.

Introduction

In the European Union, the built environment is responsible for approximately 40% of energy consumption and 36% of the CO_2 emissions. Currently, almost 75% of the building stock is energy inefficient, while only 0.4-1.2% of the building stock is renovated each year. To achieve climate neutrality in 2050 which is the ambitious goal set by the European Commission, this transition must be accelerated, and sustainable architecture must become the new benchmark for renovation and new-built projects. (European Commission (EC), 2019) (European Commission (EC), 2018)

The façade has a significant effect on the building performance due to possible overheating and glare which is caused by an excess of incident direct solar radiation. This results in reduced visual and thermal comfort and increased cooling load of a building. Due to the bad energy performance and correlated high CO2 emission of glass buildings, more legislation is being introduced to eliminate glass from buildings if they fail to improve their energy performance drastically. However, glass buildings are experienced as pleasant by its occupants due to their transparency and abundancy of daylight. To preserve these transparent, bright working and living environments, solutions need to be developed that combine the generation of solar energy with maximal daylight transmission and reduced solar heat gain.

For this, Wellsun has developed the Lumiduct, an energy producing solar shading device which addresses both challenges of making the built environment more sustainable, as well as improving the indoor climate for building occupants.

The Lumiduct is a transparent, electricity-generating solar shading that makes it possible to realize a completely glass façade that generates more energy than a façade covered with normal solar panels. In addition to generating electricity and providing savings on lighting, heating, and cooling, the Lumiduct increases the well-being of the users by realizing an ideal indoor climate with up to 3 times as much daylight than alternative shading solutions. The Lumiduct uses all the light from the sun in a positive way, preventing the negative effects of the sun, like glare and heating up of the building, that otherwise would have to be compensated.

The Lumiduct uses the most efficient solar panels in the world with an efficiency of 29.8% or 298 W_p/m^2 (Voarino, 2016). The direct light is concentrated on highly efficient triple junction solar cells, while the diffuse light can pass through the panel, making the solar panel translucent for daylight. These solar panels are mounted on vertical pillars and are continuously directed towards the sun by the sun tracking system, guaranteeing full sun protection while preserving daylight and transparency. Since the panels are always directed towards the sun, only the view in the direction of the sun is affected, while the view in other directions is maintained.

The pillars are placed behind a transparent façade, which protects the system from wind, dirt and moisture and therefore ensures reliable operation. The façade serves as a heat buffer for the building, which results in additional savings on heating and cooling. Since the entire façade can be covered with the Lumiduct, the complete surface of the façade, including both windows and opaque parts, becomes available for sustainable energy production while preserving the transparency of the façade. Alternative BIPV solutions do not solve the current problems related to glass façades:

- Poor energy performance
- Bad indoor climate
- An impossible business case for energy neutral buildings

The Lumiduct is able to solve those problems by:

- Generating record quantities of energy from the façade
- Saving energy through additional heat rejection and improved daylight entry
- Creating a constant indoor climate with less aircon and a high daylight level
- Contributing positively to EPC score, BREAAM and LEED certifications, and the nearly zero-energy building (nZEB) norm

The impact of these functionalities and benefits will be quantified in this white paper. The document will provide insight in how the Lumiduct exactly addresses the sustainability and well-being in the built environment. In section 1 and 2, information is given about the cell and concentrator technology used in the solar panels, followed by a description of all the important panel properties in section 3. In section 4 will be explained how the Lumiduct system acts in operation, and how this impacts a building in terms of energy and daylight. The results are based on a case study which will be introduced in section 4.5. In addition, the effect on several sustainability credentials will be explained in section 5. In Appendix A all information about the pilot project used for the validation of the simulation model is given. Finally, Appendix B will introduce the possible additional media feature and how this can further improve the business case of the Lumiduct.

1. Cell properties

The solar cell technology currently used in the Lumiduct has the best efficiency in the world and additionally shows the most potential for future efficiency increase. The National Renewable Energy Laboratory (NREL) listed the best research-cell efficiencies of several type of solar cell technologies since 1975. The four solar cell technologies reviewed are single- and multi-junction cells (purple), crystalline Silicon cells (blue), thin-film technologies (green) and emerging PV (orange) as shown in Figure 2 (NREL, 2019)

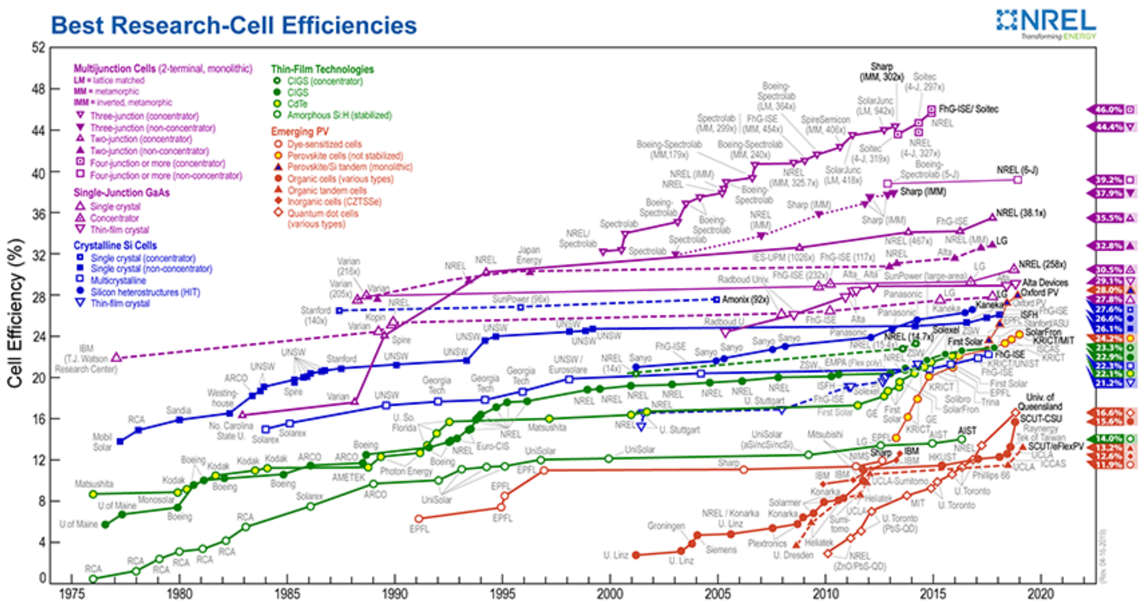


Figure 2:
Best Research-Cell efficiencies since 1975 according to the National Renewable Energy Laboratory.

The multi-junction solar cell technology used in the Lumiduct is labeled in the top right corner as Boeing Spectrolab (LM, 364x) and has an efficiency of 42%, showing its superior efficiency in comparison to other solar cell technologies. The theoretical maximum efficiency of multi-junction cells is 86.6%, which gives an indication of the potential for energy efficiency improvement in the future (Green M. A., 2014). Traditional solar panels use crystalline silicon cells and it can be seen from Figure 2 that this solar cell technology has improved slowly over the past years and seems to be reaching a plateau. This can be explained by the maximum theoretical efficiency of this technology which is 33.16% (Rühle, 2016). Therefore, the solar cell technology used in the Lumiduct is top of the market and has a much higher potential for efficiency improvement.

The major difference in technology responsible for the higher efficiency of multi-junction cells in comparison with traditional crystalline silicon cells is the number of layers of semiconducting material. The cells used for the Lumiduct have three layers, respectively; Indium gallium phosphide (InGaP), Gallium indium arsenide (GaInAs) and Germanium (Ge). Each layer of semiconductor material is sensitive to a different part of the solar spectrum, which is shown in Figure 3. This results in a broader range of the solar spectrum that can be captured by the cell resulting in a higher efficiency compared to crystalline silicon.

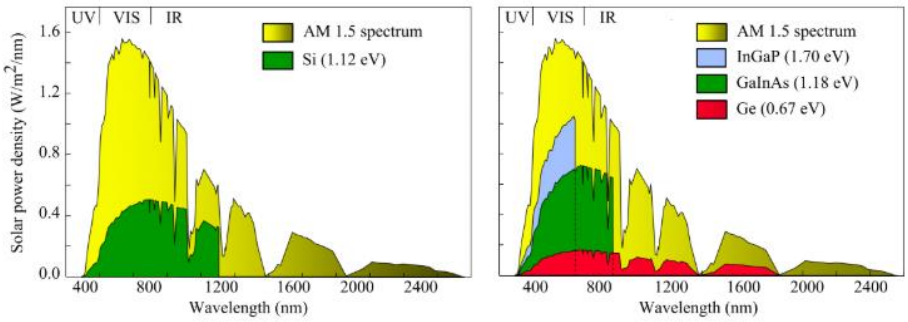


Figure 3:
Comparison of the spectral sensitivity of crystaline silicon solar cells (left) and triple junction solar cells (right)

The three layers of the triple junction solar cell are connected in series, which means that the power output is limited by the layer generating the least amount of current. In general, the Ge bottom cells receives a large excess of photons so that it never limits the current output. Under a certain spectral distribution of the light, the III-V cell has maximum power output if the InGaP top-cell and the GaAs-middle cell generate the same current. By optimizing the thicknesses, maximum overall power is achieved. Because during the day the spectral distribution of the sunlight changes from red-rich in the morning and evening (high AM[1] values) to blue-rich mid-day (low AM value), III-V cells are current matched to an average spectral distribution (typically AM1.5D) (Radboud, 2019).

[1] The air mass coefficient (AM) defines the direct optical path length through the Earth's atmosphere, expressed as a ratio relative to the path length vertically upwards

2. Concentrator properties

The solar cell configuration in the Lumiduct is optimized for maximum efficiency and low cost by partner company Morgan Solar. Since III-V cells have a high price-to-performance ratio, the use of this cell material should be minimized. This is achieved by concentrating the light on small solar cells as is schematically shown in Figure 4.

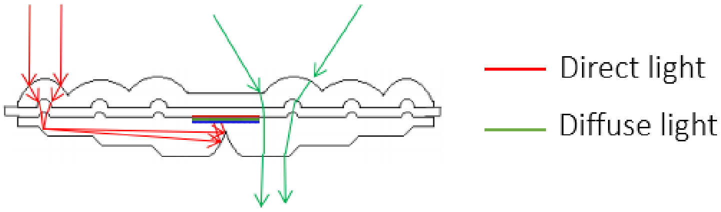


Figure 4:
Optical guide principle used in the solar panels

As can be seen from the figure, there are two types of optical elements used to guide light, which hits the solar panel at a right angle, onto the small solar cell; a focusing element on the front of the panel, and a reflecting element at the back. The focusing element guides the sun light towards the reflecting element which refocuses it onto the multi-junction solar cell. Hence, the solar panels should always be positioned perpendicularly towards the sun. In the figure, the red lines indicate the direct sunlight. The green, non-perpendicular, diffuse daylight passes through the panel, making it translucent.

By using this optical guide principle, a concentrator photovoltaic (CPV) panel is created with a concentration factor of 700x. This means that only 1/700th of the solar panel actually consists of solar cell material, which greatly reduces the cost while maintaining the benefit of the high efficiency cell technology.

The concentration factor of 700 is chosen because literature shows that the triple junction solar cells perform the best using this concentration factor, as is shown in Figure 5 (Spectrolab, 2009a).

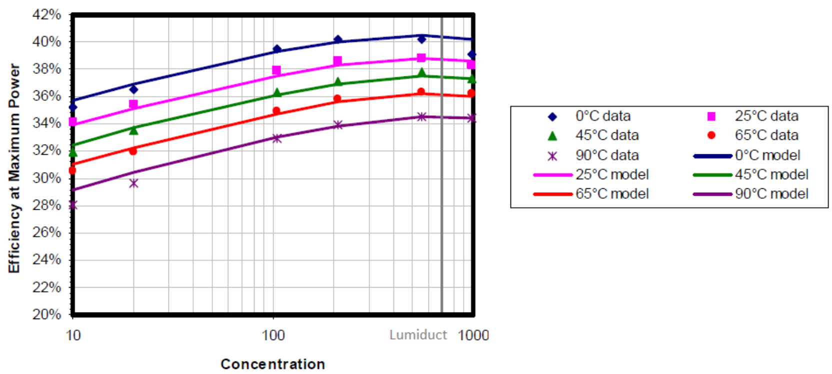


Figure 5:
Effect of temperature and concentration factor on the triple junction cell efficiency

3. Panel properties

3.1 DESIGN

The solar panel in the Lumiduct is covered with hexagonal optic elements to effectively cover the panel area as shown in Figure 6. The solar cell configuration consists of 36 parallel strings with each 15 cells in series, and Figure 7 shows a simplified version of this electrical circuit.

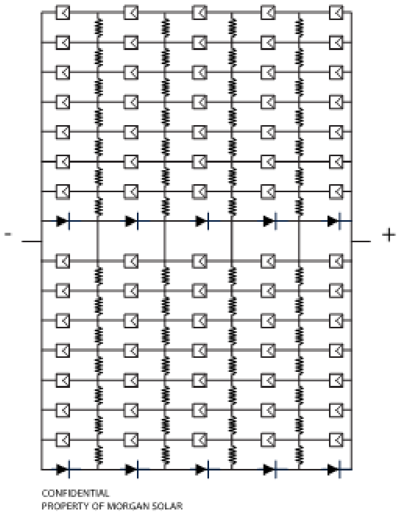


Figure 7:
Simplified schematic of the electronic circuit of the solar panel.

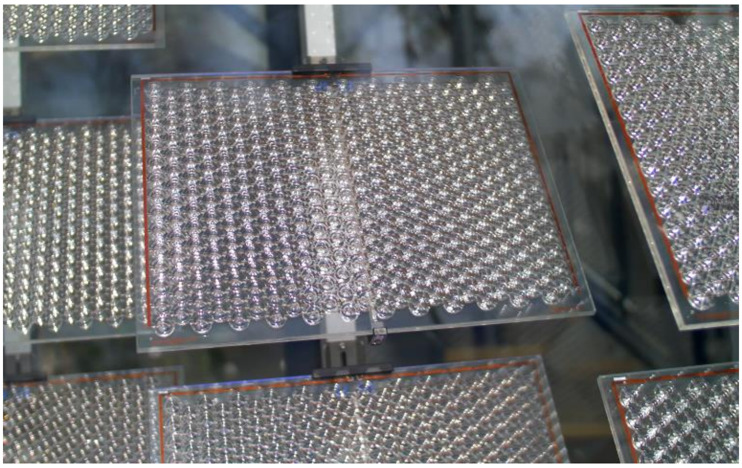


Figure 6:
Image of the solar panels used in the Lumiduct where the hexagonal optical elements are visible.

The solar panel design results in the following properties:

- Guiding perpendicular incident light to the PV cells as much as possible
- Blocking the direct harmful light and converting this into electricity with high efficiency
- Making it maximally transparent to all non-perpendicular incident light

To reach this maximum transparency, the non-transparent elements in the panel, like the edges of the receivers, the PV cells, and electrical leads, are designed to be as small as possible. However, taking this to the extreme (large receivers, small cells, and thin leads) would have negative effect on energy efficiency. Large receivers would minimize the surface of non-transparent edges but the average distance over which the direct light must be guided to the PV cell increases. This would result in an optical loss of the direct light and consequently lower output power. Thin leads would have resulted in high resistive losses and thus little power.

The panel was optimized regarding the aforementioned aspects, which led to the design and properties as listed in Table 1 and shown in Figure 8.

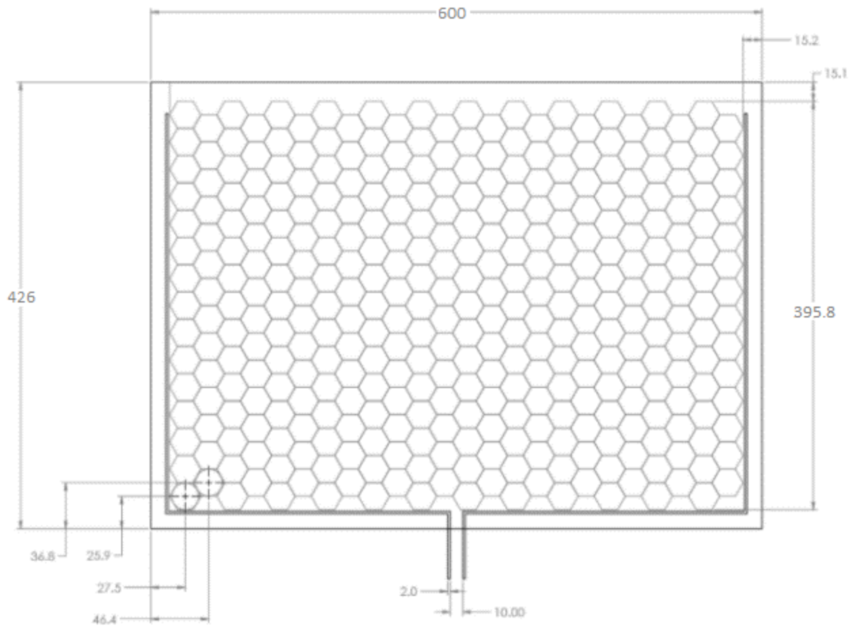


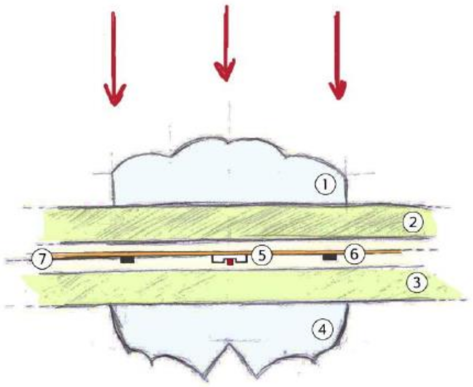
Figure 8:
Schematic of the solar panel design with important dimensions indicated.

Design characteristic	Value	Dimension
Height	426	mm
Length	600	mm
Thickness	14	mm
Surface area	0.25	m^2
Receiver total	540	-
Receiver diameter	23	-
Solar cell size	1x1	mm
Concentration factor	700	-
Angular acceptance	0.6	°

Table 1:
Panel characteristics and properties

The configuration of strings in series and parallel is chosen so that the cells that are connected in series result in a significant voltage output of the panel, while the parallel configuration of these strings ensures that if one cell or string behaves poorly due to shading, the other strings will still contribute as normal to the power output of the panel.

The cross section of the panel is shown in Figure 9 and the materials used in the solar panel are listed in Table 2.



1. Front Optic (FOE)
2. Top glass panel
3. Bottom glass panel
4. Back Optic (ROE)
5. Solar Cell assembly
6. Discreet components (Resistor, Diode)
7. Copper Heat Spreader Array (HSA)

Figure 9:
Schematic cross section of the solar panel showing terminology and the materials used.

Element	Material
Front optic	PMMA EXP-31
Glass	Laminated
Interlayer	Silicone
Back optic	PMMA
Electrical circuit	Silver screen printed wiring
HSA	Copper

Table 2:
Materials used in the solar panel

3.2 POWER CHARACTERISTICS

The electric performance of the CPV solar panels is measured under concentrator standard test conditions[2] (CSTC) and concentrator standard operating conditions (CSOC), which is a standard ensuring an independent comparison and output evaluation of different solar CPV modules. Testing has been conducted by CEA Tech (Technical Report DTS/RT/2016/259) and showed a peak power of 298 W_p under CSTC, which corresponds to an efficiency of 29.8%. The efficiency of the panels under operating conditions was found to be 26.9 %.

[2] CSTC is an industry-wide standard to indicate the performance of CPV modules. The standard defines the measurement procedures for the two reference conditions defined in IEC 62670-1 (Concentrator Standard Test Conditions (CSTC): DNI of 1000 W/m^2, 25 °C cell temperature and AM1.5d spectral irradiance and Concentrator Standard Operating Conditions (CSOC): DNI of 900 W/m^2, 20 °C ambient temperature and AM1.5d spectral irradiance) (Fraunhofer and NREL, 2017).

The power characteristics of the panel used in the Lumiduct (as shown in Figure 8) are shown in Table 3.

POWER GENERATION		
Pmpp	W	69
Vmpp	V	42
Impp	A	1.6
Voc	V	47
Isc	A	1.7
Fill factor		0.87

Table 3:
Power characteristics of the solar panel

3.3 DEGRADATION

Accelerated lifetime testing representing more than 40 years of exposure demonstrates that the PMMA used in the panels shows no observable degradation in transmission (Arnd et al, 2014) (Miller et al, 2010). Tests have been performed to measure stability in performance during its life time. Exposure to UV light causes many polymers to turn yellow over time, or to develop haze, either effect is detrimental to CPV performance by causing a reduction in light delivered to the cell. The material stack in the solar panels includes a UV stabilized PMMA (EXP-31) used as the entry material for sunlight which filters out UV-light from penetrating deeper into the concentrator where there are materials more sensitive to UV.

The temperature sensitivity of the III-V cells is found to be -0.15 %/°C under operation conditions (Spectrolab, 2009a). This is 3 times lower as compared to the temperature sensitivity of Silicon, 0.45 %/°C (Javid, 2014). The low temperature sensitivity of III-V cells makes them ideal for the application in the Lumiduct because the concentrated light results in high energy intensity. The correlated temperature increase has minimal effect on the performance of the panels which attributes to the high-power output of the panels.

3.4 MUTUAL SHADING

The solar panels in the Lumiduct perform well under shading. For shading in the horizontal direction, the power production decrease is linear, while for vertical shading there is a slightly higher than proportionality factor. The effect on the shading profiles on the solar panels was determined by the Radboud University of Nijmegen (RUN) under the TKI Urban Energy grant[3]. Simulation results are shown in Figure 10.

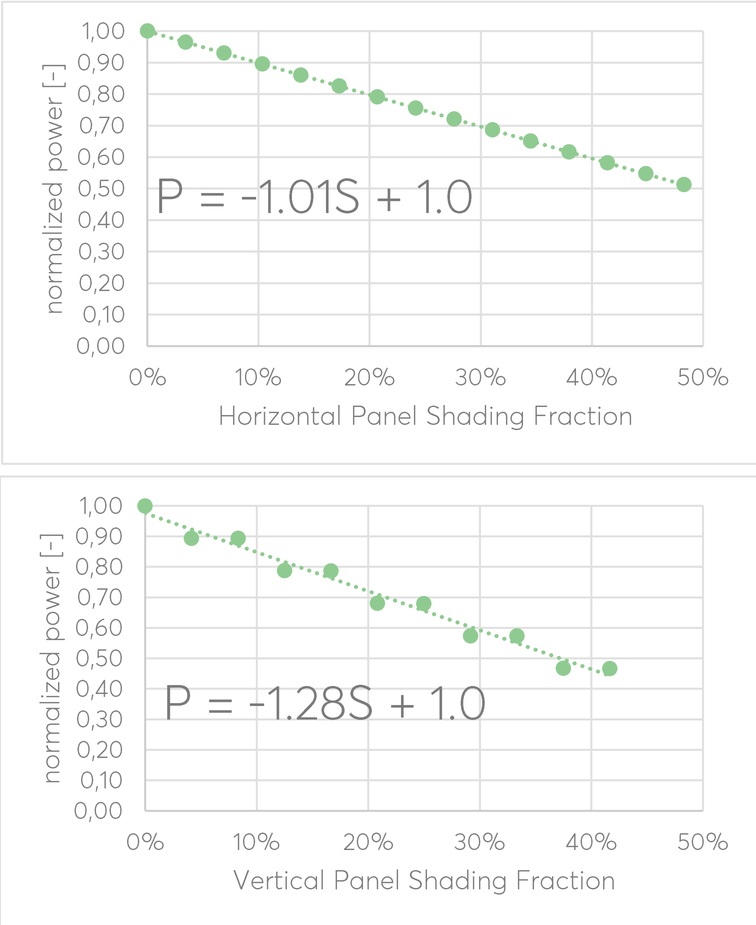


Figure 10:
Normalized power output of the solar panel as a function of the vertical and horizontal shading fractions. P represents the power loss. Results are from a simulated panel based on a model that was validated empirically.

To understand the performance of the solar panels under shading conditions, an electrical model of the panels was made in LT spice. The electrical layout was similar to Figure 7, consisting of 29 strings in parallel with 12 cells each in series. Actual resistances of the interconnects between cells have been provided by Morgan Solar. The model was designed such that each separate cell could be illuminated with a different light intensity. In this way, the shading pattern specific to the Lumiduct could be simulated. The two types of shading that are inherently present in the system are

[3] *"Integration of PV in the facade for energy-positive buildings"*, carried out with the Top Sector Energy subsidy of the Dutch Ministry of Economic Affairs (TEUE116184)

horizontal and vertical shading patterns, as shown in Figure 11. These patterns are caused by mutual shading of the Lumiduct pillars and panels, as these are mounted very close to each other for maximal solar shading and maximal energy generation.

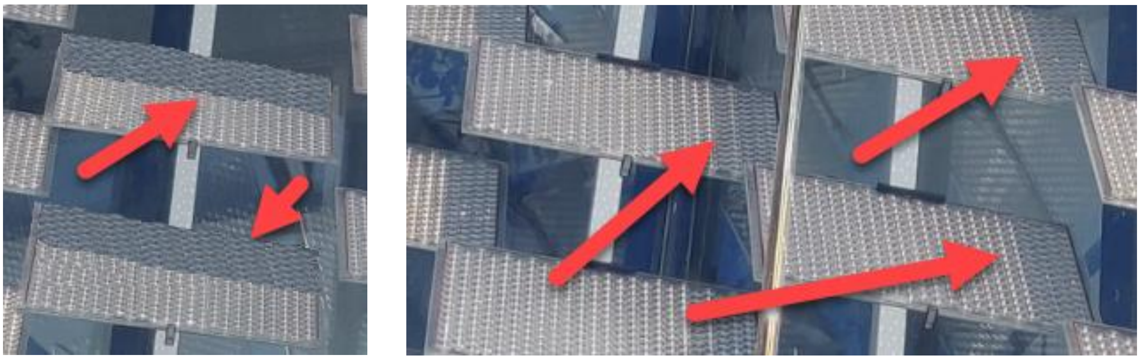


Figure 11:
(Left) Horizontal shading pattern on the Lumiduct panels caused by shading by the panel located directly above.
(Right) Vertical shading pattern caused by the panels directly adjacent.

The output of the model was verified by measurements performed by the Radboud University of Nijmegen at the pilot project, realized at Mondial Movers, see Figure 12. This system has been in operation since 2017 and provides valuable data for simulation model validation. During these measurements, a solar panel that was pointed on sun was deliberately shaded in either the horizontal or the vertical direction, and panel output power was monitored. The results of the simulation and the actual measurements were in good accordance.

Figure 12:
Pilot project realized at Mondial Movers, Alblasserdam, The Netherlands

4. System properties

4.1 SUN TRACKING

The Lumiduct consists of up to 8 solar panels coupled to a vertical pillar. With a dual-axis sun tracking system, integrated within the pillar system, the panels are continuously positioned towards the sun. The panels can track the sun in full range in both elevation as well as azimuth direction. The operation mode is visualized in Figure 13.

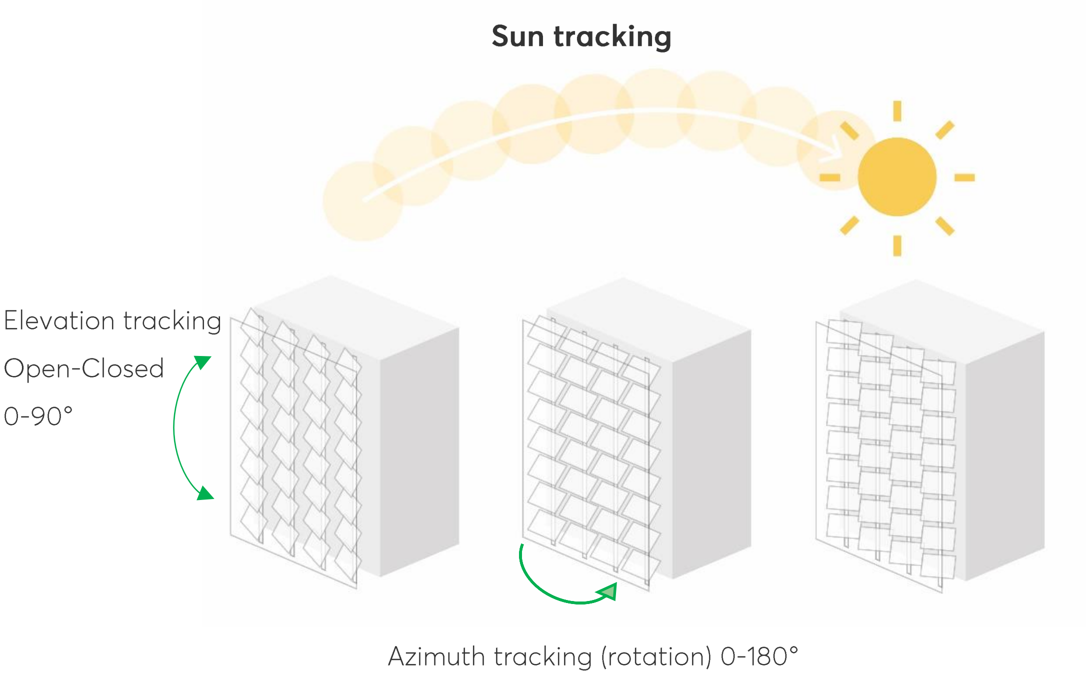


Figure 13:
Solar tracking principle of the Lumiduct system

4.2 CONTROL

In addition to sun tracking, the Lumiduct can also be controlled manually by the building occupant. There are two useful features; override- and privacy mode. In Figure 14, the so-called open position is visualized where the panels are positioned horizontally. Unless the Lumiduct is installed close to the equator, this position will not be reached in sun tracking mode. However, an override mode/open position will be made available for overcast days to improve the transparency of the façade. The solar energy production and solar shading functionalities of the Lumiduct are directly related to the availability of direct light. When it is heavily clouded, the panels can therefore be set in the open position to maximize the view towards the outside of building occupants, without compromising on energy production. This will also increase the natural daylight entering the building. In addition, a manual override is possible to meet the building occupants' preferences. In case it is preferred for the building occupants to close the Lumiduct and make the façade translucent, the panels can be set in a vertical/privacy position to reduce visibility to or from the outside, as shown in Figure 14 as well.

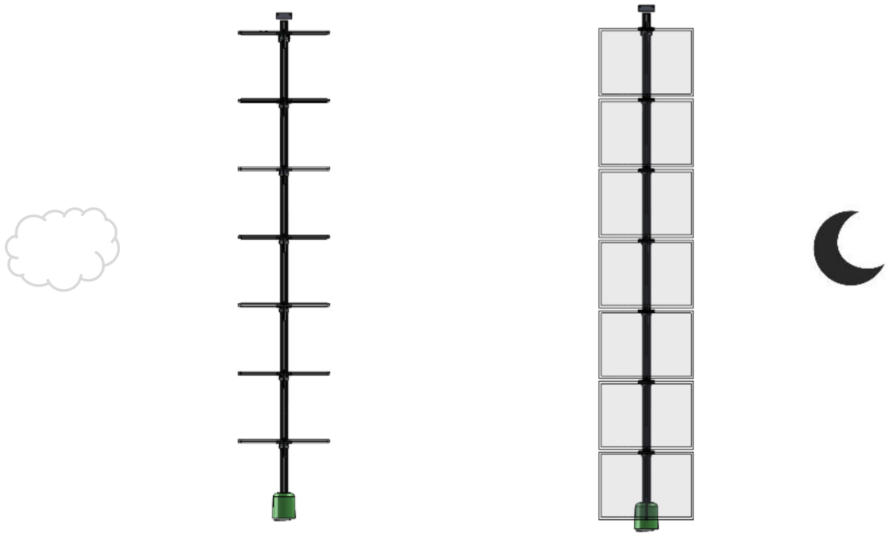


Figure 14:
(Left) A Lumiduct pillar in "open" position, used during cloudy days. (Right) A Lumiduct pillar in "closed" position, used for privacy and during the night.

The most important system control features and characteristics in terms of accuracy and monitoring are listed below.

- Solar tracking algorithm ensures target precision of +/-0.0003 degrees (Reda and Andreas, 2008)
- Feed forward positioning has tracking accuracy of 0.2 degrees.
- Overall system accuracy maintained at 0.3 degrees by:
  - daily automatic calibration routines to correct for small positioning displacements and;
  - automatic optimization based on electricity output during clear sky conditions.
- Continuous energy production is logged offsite for monitoring system performance which is also available to the end user.
- Multiple error detection algorithms continuously monitor the operating state of the system and respond to eventual changes to facilitate safe operation. Errors are logged for analysis and system improvement.

4.3 FRONT SKIN EFFECT ON SYSTEM

The Lumiduct is placed behind a protective transparent façade which ensures reliable operation and provides the possibility for heat harvesting. The front skin prevents the accumulation of dirt, dust and sand on the surface of the solar panel which would prevent the light from reaching the solar cells, lowering their energy performance up to 80% (Sulaiman et al, 2014). The protection from water will ensure reliable operation while protection from wind results in a slimmer and lighter pillar design which still allows safe operation in high rise buildings.

However, the front skin does create extra costs and has a negative effect on the electricity production due to absorption and reflective losses of the front skin material. To quantify this effect, the absorption and reflection losses of different front skin materials on the electricity production have been studied. The typical front skin materials must be highly transparent and should be able to resists wind loads. In the pilot project, laminated glass was used with a thickness of 2 times 12 mm with a 2 mm pvb foil (12-2-12). An alternative material is Ethylene Tetra Fluoro Ethylene (ETFE), which is a transparent polymer that is extruded into a thin foil and which can be used to form either a single layer membrane or multi-layer cushions. It is increasingly used in buildings like shopping malls, because it is unaffected by UV-light, atmospheric pollution and other forms of environmental weathering. Façade engineering for our next full-scale project proved that a thickness of 250 μm is sufficient to create a fully functional front skin. In Table 4, the effect on transmissivity losses is shown for glass and ETFE with their common thicknesses and compared to the case without a protective front skin façade.

Spectrum	InGaP-top [mA/cm^2]	GaAs-mid [mA/cm^2]	Ge-bottom [mA/cm^2]	Mismatch losses	Absolute losses
AM matched	12.45	12.45	Excess	0	0
AM1.5D	12.38	12.51	Excess	-0.07/0.6%	0.07/0.6%
AM1.5D Glass	10.49	10.11	Excess	+0.19/1.8%	1.96/18.8%
AM1.5D 250um ETFE	11.18	11.72	Excess	-0.27/2.4%	1.27/10.2%

Table 4:
Sub cell current densities, mismatch losses and absolute losses for several solar spectra and front skin materials.

Table 4 shows that the 12-2-12mm glass results in a transmission loss of 18.8% while the single layer ETFE of 250 μm results in a transmission loss of 10.2%.

The difference in losses between glass and ETFE is related to their transmissivity as shown in Figure 15 and Figure 16 for ETFE and glass respectively. Note that the visual light spectrum is represented by wavelengths between 380 and 780 nm and transmission is preferred to be as high as possible within this range to allow abundant daylight entrance in the building.

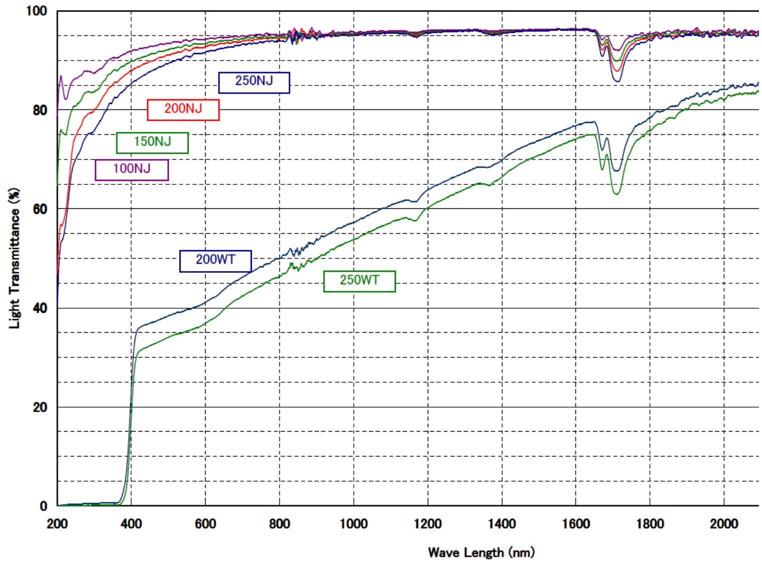


Figure 15:
Transmission spectrum of several types of ETFE foil. For the front skin, a foil of 250 um is used, represented in the figure by the dark blue line designated 250NJ.

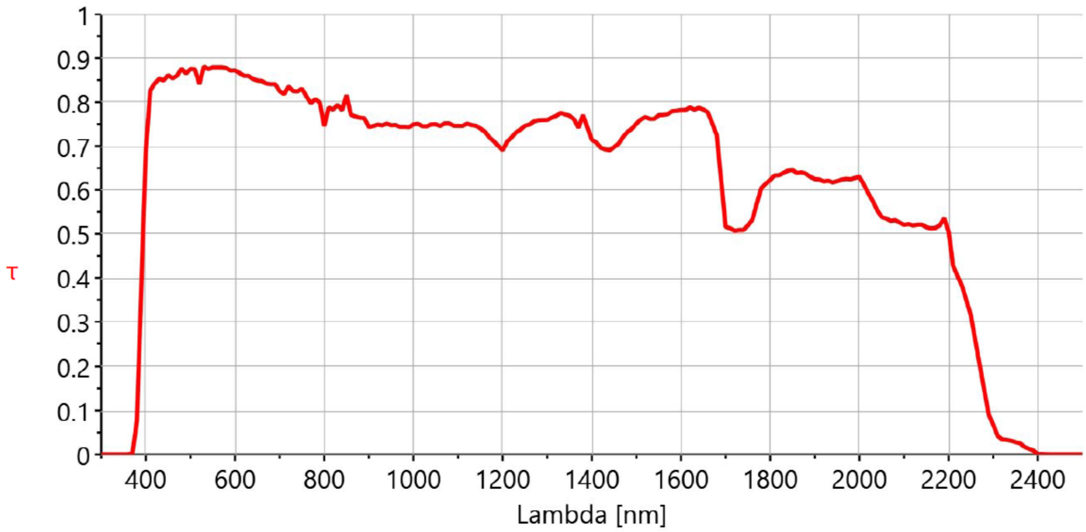


Figure 16:
Transmission spectrum of 12-2-12 glass as used in the pilot project at Mondial Movers.

When designing the front skin façade, the type and thickness of the skin material has a significant effect on the energy performance of the Lumiduct. As each second skin comes with its own specific support structure, when optimizing the design for energy production, also the negative effect from the shading of the mullions and frames has to be taken into account. Especially vertical panel shading should be minimized due to its disproportional negative effect on the energy production.

4.4 ENERGY GENERATION

The Lumiduct generates around 60 kWh/m²/year electrical energy on a south façade in the Netherlands, and around 105 kWh/m²/year of heat energy. Energy production depends on the location, façade orientation and front skin façade design and values for electrical energy generation of several locations worldwide are shown in Figure 17. These values are based on a validated simulation model. Validation is done by measurements at the pilot project. The electrical energy generation is normalized to the value of 60 kWh/m²/year so that the effect of different façade orientations can clearly be seen.

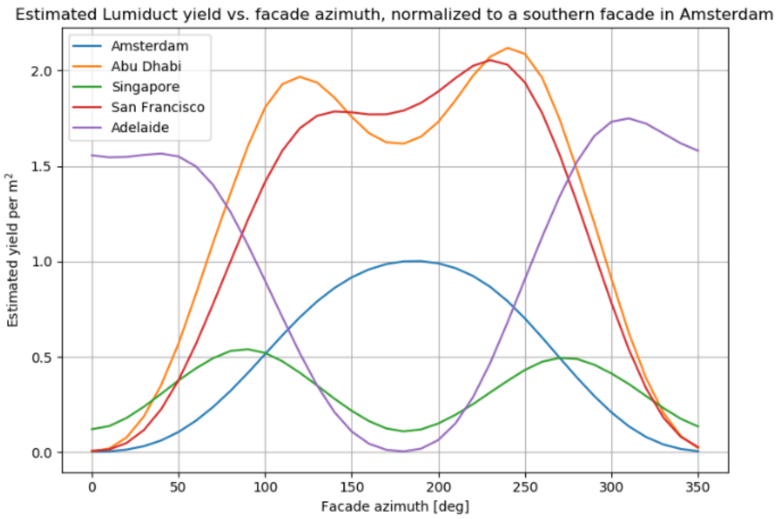


Figure 17:
Energy production of a Lumiduct system for several locations as a function of facade orientation. The energy performance is normalized to the peak performance in Amsterdam which is 60 kWh/m2/year.

The energy production estimates are based on the following assumptions:

- ETFE as front skin material (92% transmission at perpendicular incidence of light)
- Panel efficiency of 30%
- Cavity ambient temperature of 60 degrees
- Tracking accuracy of ± 0.3 degrees
- Slim front skin support structure

The Lumiduct guides the direct light on highly efficient III-V cells to produce electrical energy. Apart from electrical energy, the heat generated by the solar cells accumulates within the air cavity of the double skin façade and can be captured and transformed into useful energy by installing a heat exchanger at the top of the façade. This unlocks a heat energy potential which can be used for the indoor heating system or to preheat boiler water inside the building. The estimated heat energy production for a south façade in the Netherlands is 105 kWh/m²/year based on an air-water heat exchanger. To validate this heat energy potential, such a heat exchanger is placed at our first project. Under the TKI Urban Energy grant, measurements are done to study the heat energy potential, results will be published in Q4 2019.

Apart from energy generation, the Lumiduct system also consumes energy while tracking the sun and during performance monitoring. These parasitic losses are minimized by using low power chips and smart usage of peripherals. At night, when no motion is required, the system switches to an even lower power consumption mode. The energy consumption of the system will be dependent on the energy produced but is generally less than 1% of produced power.

4.5 CASE STUDY

Wellsun has collaborated with the Building Physics Team of Eindhoven University of Technology in order to quantify the effect of the Lumiduct on the indoor building environment. The interaction between the simulation models used are shown in Figure 18. The output of the models has been validated with the measurements from the pilot project at Mondial Movers in Alblasserdam. For the case study, with these models, a simple office space in Amsterdam, The Netherlands has been modeled with a south façade orientation and with dimensions as shown in Figure 19.

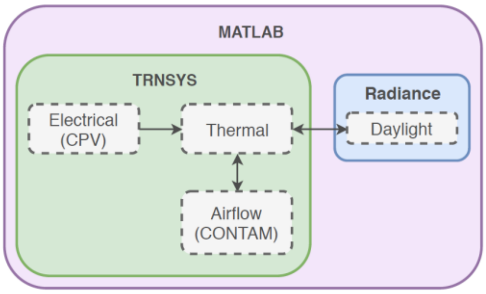


Figure 18:
Diagram indicating the separate modules of the simulation and their interaction.

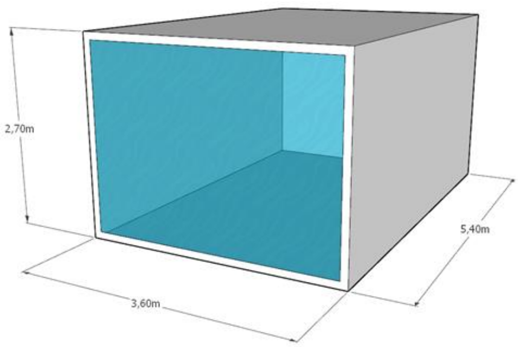


Figure 19:
Standard office dimensions used for the case study of the simulation model.

The performance of the office with respect to the indoor building climate has been investigated for the following cases:

Case 1: No shading - triple glazing with low-e
Case 2: Case 1 + internal roller shades (openness factor = 4%)
Case 3: Case 1 + external roller shades (openness factor = 2.5%)
Case 4: Lumiduct
Case 5: Lumiduct with override

Additional information and assumptions made for the model are listed in Table 5. Comparison of the building physics and the indoor climate in the different cases, will be discussed in the following chapters.

Room design		**References**
Single occupancy office building	9am – 5pm (weekdays)	
Façade window to wall ratio	87%	
Desk center of room with illumination threshold	500 lux	
Internal Wall roof and floor	Adiabatic	
Construction External Wall U	0.35 W/m²K	
Energy		
Internal heat gains (sensible)	120 W	
People (occupancy based)	11 W/m²	(ASHRAE, 2009)
Equipment (occupancy based)	10 W/m²	(Goia et al, 2013)
Lighting (occupancy based)	7.5 W/m²	(Goia et al, 2013)
Heating Ventilation Air-conditioning (HVAC)	unlimited capacity	
Heating set points	20°C/14°C	
Cooling set points	24°C/32°C	
Ventilation	2.5L/s with 90% heat recovery	(ASHRAE, 2004)
Infiltration	0.15 ACH	(BSRIA, 1998)
Material reflectivity		
Walls and partitions	0.5	
Ceiling	0.8	
Floor	0.2	
Ground	0.2	

Table 5:
Base values and assumptions for the simulation model and its case study.

4.6 ENERGY SAVINGS

The Lumiduct reduces the primary energy demand of a building by shielding the harmful direct sunlight which is responsible for the overheating of a building. Based on a case study performed by the Building Physics team of Eindhoven University of Technology, savings in heating (24%), artificial lighting (36%), and cooling (40%) are found in comparison to traditional internal shading techniques. The results are shown in Figure 20. The reduction in heating demand is a result of improved insulation by using the double skin façade which also acts as a heat buffer for the building due to the accumulation of heat generated by the solar cells. The reduction of artificial lightning is a result of the increased transmission of diffuse daylight, which is even more improved for the Lumiduct override mode. The reduction in cooling is achieved by blocking the direct energy intensive sunlight and keeping this energy out of the building.

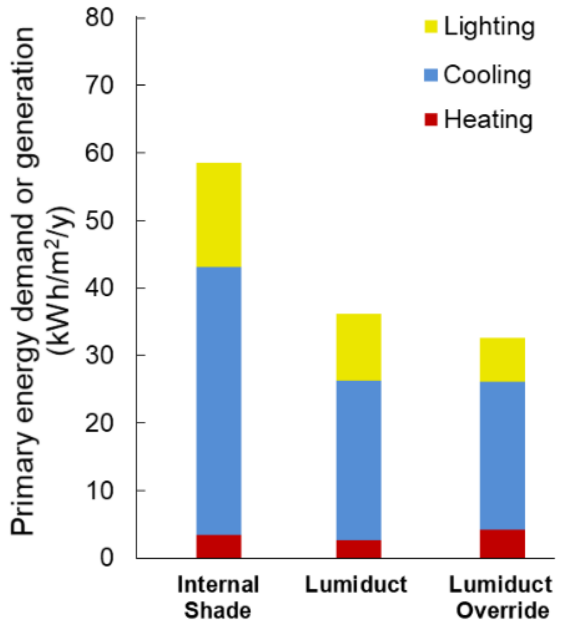


Figure 20:
Comparison of the primary energy demand per square meter when using internal shades or the Lumiduct. A division is made between lighting (yellow), cooling (blue), and heating (red).

4.7 THERMAL PROPERTIES

Thermal properties are used by architects, building physics and façade engineers to optimize their façade in terms of visual light transmittance and solar heat gain. It is considered optimal to allow maximal daylight entrance while blocking the solar heat of the sunlight, preventing overheating of buildings.

The thermal transmittance (U-value) is the measurement for heat transfer which is the ability of a material to transfer heat by conduction, convection and radiation. All components of a building have U-values and the lower the value, the slower the heat loss through the material. Therefore, a material with a low U-value is a good insulator. The U-value of glazing is always improved by installing blinds, shutters or the Lumiduct.

The solar heat entrance (g-value) is the measurement of the total energy passing through the glazing when exposed to solar radiation. The 'g-value (normal beam incidence)', represents clear sky conditions while the 'g-value (diffuse radiation incidence)' represents partial cloudy conditions. A low g-value indicates that a plane lets through a low percentage of the solar heat (Page, 2012).

The thermal properties of the Lumiduct, calculated according to ISO150994 are listed in Table 6.

U-value (closed-cavity)	1.16 W/m^2-K
g-value (normal beam incidence)	0.255
g-value (diffuse radiation incidence)	0.293

Table 6:
U- and g-values for the Lumiduct system.

4.8 EFFECT ON DAYLIGHT

The Lumiduct acts as a selective solar shading device, selectively blocking the harmful direct light, which can cause glare, while letting 70% of the diffuse daylight pass through the panels. It can be concluded from the results of the Useful Daylight Illuminance (UDI) analysis, conducted by the Eindhoven University of Technology, that the Lumiduct has best in class performance in comparison to no shading, internal- and external shading devices.

[4] Note: these values come with the disclaimer that they should not be taken at their face value because multi-domain interactions of Lumiduct cannot be captured with a single U-value and g-value. The Lumiduct is not quite compatible with the standards that are used for conventional glazing products.

The best in performance is defined as a combination of the highest percentage of working hours where artificial light is not needed, while high lux levels which are likely to cause glare are minimal. For this, three light levels are introduced as listed in Table 7. In short, the distinction is made between the need for artificial light for lux values until 500 lux and higher lux values without any need for artificial light and lux values so high that it could cause glare.

UDI	Annual occurrence (%) of illuminances across the work plane that are within a range considered "useful" by occupants	Range (lux)
UDI-n	UDI-not-sufficient; artificial light needed to supplement daylight	0 – 500
UDI-a	UDI-autonomous; artificial light not needed	500 - 3000
UDI-x	UDI-exceeded; excess daylight likely to cause glare	> 3000

Table 7:
Definition of the UDI light levels

The occurrence in terms of percentage of working hours per year is shown for all three light levels in Figure 21. It shows that the Lumiduct results in most working hours were artificial light is not needed (green) while hours with lux levels which can cause glare (red) are minimal.

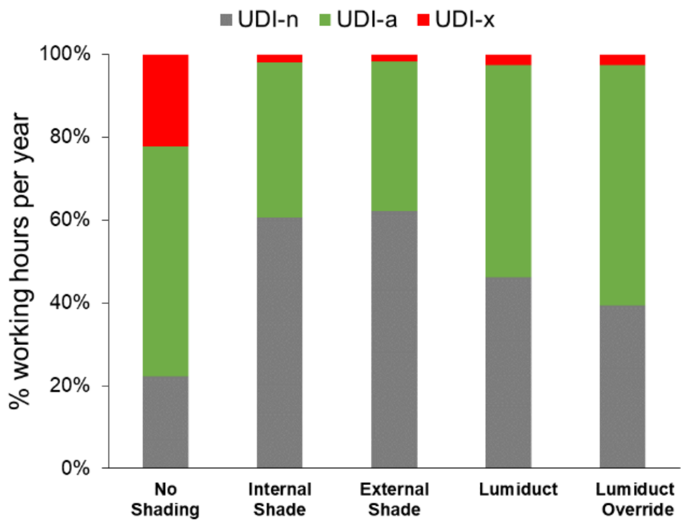


Figure 21:
Percentage of the total working hours for which a certain UDI level is present in the office environment, computed for several solar shading alternatives.

Apart from the light levels inside the building, the outside view is an important measurement of how building occupants experience buildings. This is because people love to be connected to the surroundings and do not want to feel trapped inside a building. The outside view towards the surroundings is indicated by the unobstructed view index (UVI) where the value 0 represents full obstruction and the number 1 no obstruction at all. The distribution of UVI in working hours per year of traditional shading and the Lumiduct with or without override mode is shown in Figure 22.

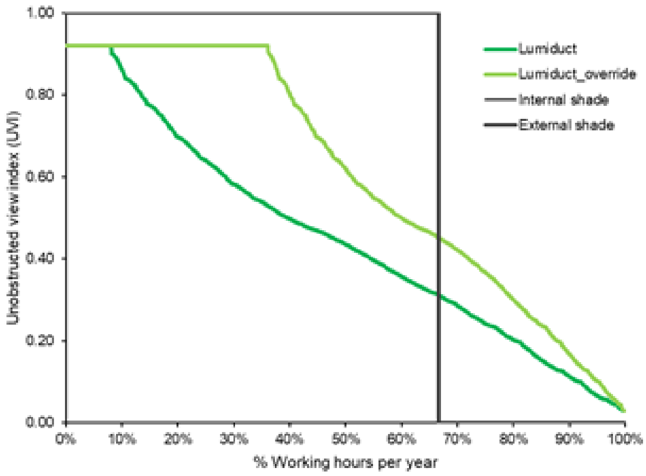


Figure 22:
Unobstructed view index (UVI) for different solar shading alternatives.

The roller shades are either open (UVI=1) or closed (UVI=0), depending on the need for solar shading which is defined by an incident solar radiation exceeding 250 W/m². For the case study building in Amsterdam, The Netherlands, shading is necessary for around 33% of the total working hours per year. The UVI of the Lumiduct is maximally 0.9 due to the vertical pillar system and always higher than 0 because the panels will never completely close off the façade due to the sun's position. This shows that solar shading does not have to result in blocking off the entire view and that year-round there will always be a connection to the outside. To improve the UVI of the Lumiduct even more, the override mode is introduced, meaning that the panels will be placed horizontally when it's heavily clouded and there is no need for solar shading and energy production would be minimal. This results in an overall improved UVI where the maximum UVI of 0.9 is realized for almost 40% of the working hours.

The Lumiduct also has a positive effect on the Spatial Daylight Autonomy (SDA) in comparison to other shading alternatives as shown in Figure 23. The ($SDA_{300/50}$) represents the percentage of floor area that that receives at least 300 lux for at least 50% of the annual occupied hours and is one of the daylight metrics in Leadership in Energy and Environmental Design (LEED) version 4 and WELL daylight metrics.

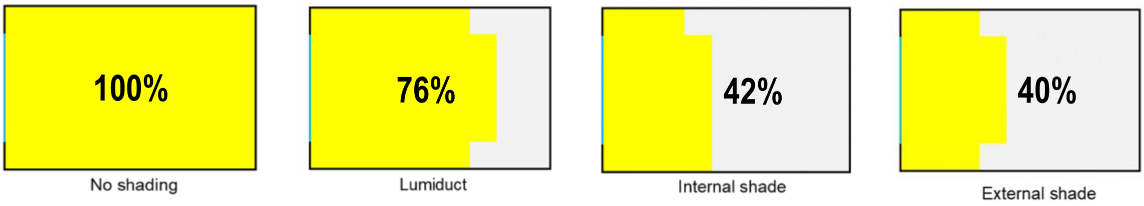


Figure 23:
Spatial Daylight Autonomy for the case study office and different solar shading alternatives.

The Lumiduct is the best in its class and the natural daylight entrance is greatly improved in comparison to the reference cases, this is mostly a result by the improved diffuse daylight entrance. Note that no shading is not a valid option due to the occurrence of excessive lux values which are likely to cause glare.

Results show that the Lumiduct has lowest amount of glare, consisting of 6% of the total time where the light is perceived either disturbing or intolerable as shown in Figure 24. Comparison can be made with no shading, 50%, and traditional roller shades, 12%.

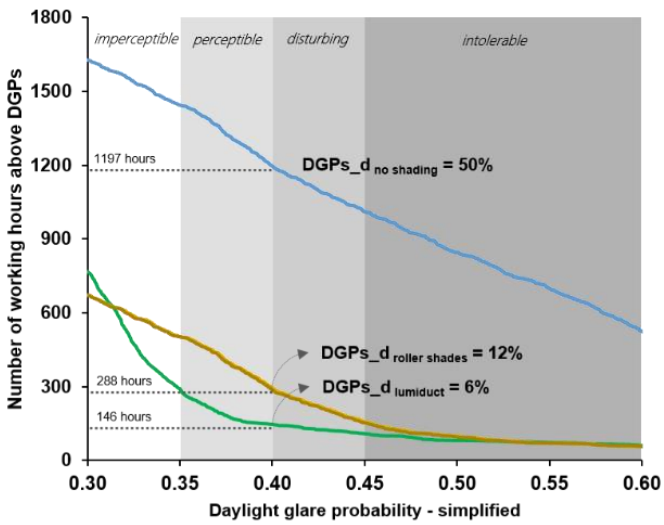


Figure 24:
Daylight glare probability for several solar shading alternatives.

To study glare, the performance indicator Daylight Glare Probability (DGP) is used to evaluate the occurrence of glare over the year. DGP is currently the most promising and computationally the most expensive glare evaluation metric. DGP-simplified (DGP-s) approximates DGP based on vertical eye illuminance alone. These metrics are categorized into four different categories - imperceptible glare ($DGP < 0.35$), perceptible glare ($0.35 \leq DGP < 0.4$), disturbing glare ($0.4 \leq DGP < 0.45$), and intolerable glare ($DGP \geq 0.45$). Occupants are likely to deploy the shading devices due to increased visual discomfort when glare reaches disturbing levels (i.e. values higher than 0.4). In this graph, cumulative DGP-s profile is shown for every case, marked with the number of hours over the year for which glare reached disturbing levels. This glare caused by the Lumiduct is mostly related to high levels of diffuse daylight since the direct light is completely blocked by the solar cells, as the panels track the sun continuously and there is no delay in response time for solar shading.

It can be concluded that the Lumiduct delivers its promises because of the improved solar shading, additional daylight entrance in combination with less need for heating and cooling. Therefore, the indoor climate is improved both visually and thermally.

5. Effect on sustainability credentials

The Lumiduct has a unique positive effect on sustainability credentials such as LEED (Leadership in Energy and Environmental Design) and BREAAM (Building Research Establishment Environmental Assessment Method). Sustainability credentials take into account primary energy usage and the sustainability of materials used in buildings. Primary energy consumption for utility buildings include energy used for heating, cooling and artificial lighting. Energy generated locally by sustainable energy technologies like the Lumiduct can be deducted.

Due to the high optical concentration achieved, the panel is only covered for 1/700th with solar cell material. This limited use of solar cell material has strong positive effect on sustainability credentials which consider the use of scares materials. In addition, the solar panels in the Lumiduct are fully recyclable. The materials used consists for 99% out of PMMA, glass and silicone. The PMMA optics and the flat glass can be fully recycled. The silicone is currently not recyclable, but edible and nontoxic which has no risk of breaking down into micro plastic. Because the solar panels used in the Lumiduct are recyclable, they score positively on the sustainability of the used materials. This is unique because traditional solar panels are not recyclable and contain silicon cells, glass, EVA, Teflon or PET-films. The EVA and Teflon/PET are non-recyclable plastics that can break down and lead to pollution and micro plastics in the oceans that can get into the food chain and cause problems for all living organisms. The EVA binds strongly to the silicon PV cells making it hard to separate the materials so that the silicon could be recycled. Recycling the panels in the Lumiduct starts by separating the lenses from the glass panel which can easily be done with a sharp blade as shown in Figure 25.

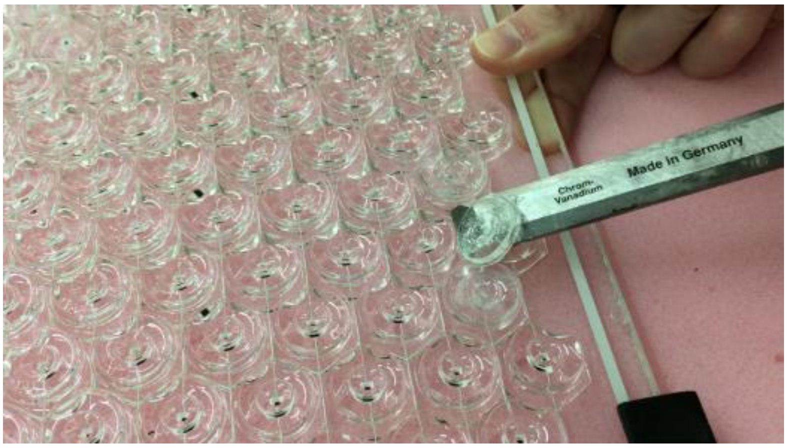


Figure 25:
Demonstration of one of the recycling steps: scraping the optic elements off the glass laminate.

LEED and BREAAM are the most used sustainability credentials in America and Western Europe respectively and focus on energy and materials. Recently an upcoming sustainability credentials, WELL, goes a step further and incorporates the wellbeing of building occupants as well.

The WELL Building Standard® is a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing, through air, water, nourishment, light, fitness, comfort, and mind (WELL, 2019). Indoor climate and well-being are closely related and the benefits the Lumiduct gives in terms of improved visual and thermal comfort results in an additional positive score in WELL certifications (Al Horr et al, 2016). WELL provides guidelines that minimize disruption to the body's circadian system, enhance productivity, support good sleep quality and provide appropriate visual acuity. This can be found in features; 56 (solar glare control), 57 (low-glare workstation design), 62 (daylight modeling) and 63 (daylighting fenestration). A specific example for the relationship between daylight and WELL points can be demonstrated by the $sDA_{300,50\%}$, which was simulated for the case study of the office in Amsterdam. The $sDA_{300,50\%}$ for the Lumiduct was found to be 72% while internal and external solar shading gave values of respectively 42% and 40%. Since a $sDA_{300,50}$ above 55% results in credited points, the benefit of the Lumiduct improved entrance of natural daylight becomes clear[5].

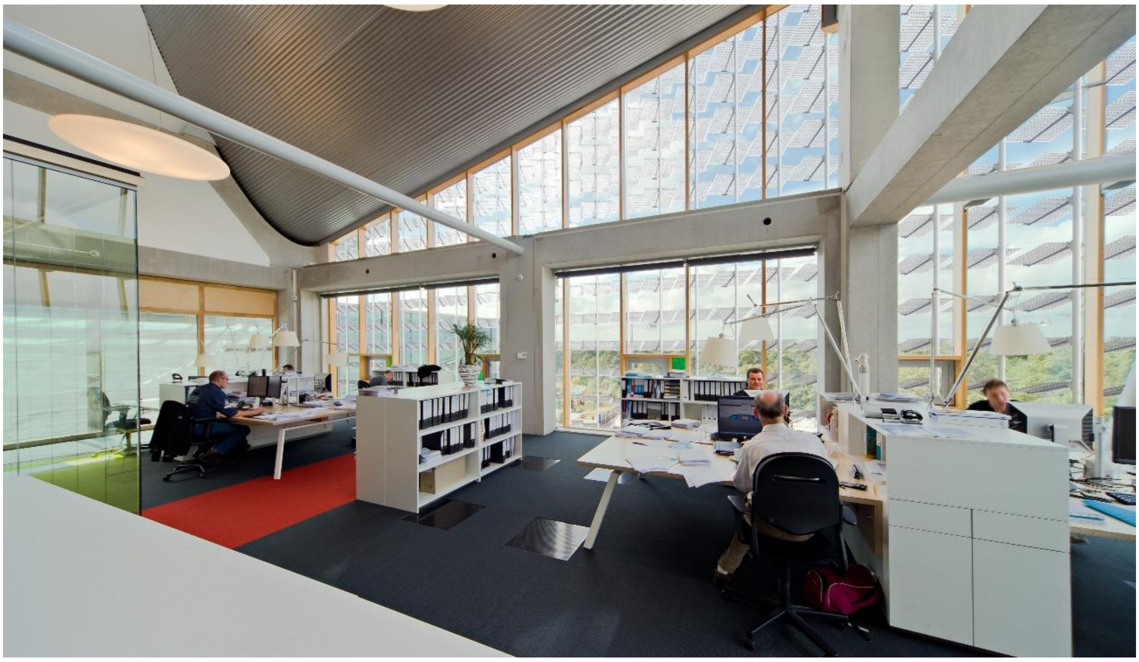


Figure 26:
Rendering of the indoor office environment where the Lumiduct is applied on the facade.

[5] WELL v2.0, Daylight Modeling, URL: https://standard.wellcertified.com/light/daylight-modeling

Conclusion

In order to make the built environment carbon neutral by 2050, the energy transition must be accelerated, and sustainable architecture must become the new benchmark for renovation and new-built projects. The façade has a significant effect on the building performance. Due to esthetics and desired transparency, glass facades will remain popular. Traditional technology, however, does not effectively prevent the access of incident direct solar radiation with glass façades. Effective measures need to be developed that maintain the good esthetics and transparency, but also prevent the possible overheating and glare which reduce visual and thermal comfort and increase the cooling load of a building.

Wellsun has developed the Lumiduct, an energy producing solar shading which addresses both challenges of making the built environment more sustainable, as well as improving the indoor climate for building occupants. The Lumiduct makes it possible to create complete glass and transparent façades, using transparent solar panels which turn the harmful light into useful energy while allowing natural daylight to enter the building.

In this white paper the following features and functionalities of the Lumiduct have been substantiated and the supporting technology has been explained.

- Highly efficient energy generation
- Optional heat harvesting capability
- Large savings on cooling (40%), heating (24%) and lighting (36%)
- Perfect solar shading (completely blocking the direct sunlight, while transmitting the diffuse daylight)
- Pleasant indoor building climate (visually and thermally)
- Better outside view than blinds
- Beautiful sustainability
- Recyclable solar panels

The above functionalities will lead to the following secondary effects:

- Higher productivity of people
- Improved public awareness for sustainability
- Reduced heat island effect
- Increased property value
- Higher rating at certification because of unique BREEAM / LEED points
- Enabling sustainability subsidies
- Free up rooftop space for alternative usage

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Appendix A - Pilot Project

Company	Mondial Movers
Location	Alblasserdam, The Netherlands
Installation date	October 2017
In full operation	October 2017 - now
Façade orientation	South-West (azimuth 225°)
Façade surface area	40 m
System configuration	
Ground floor	6 pillars, 7 panels each
First floor	6 pillars, 7 panels each
Top floor	6 pillars, 8 panels each
Total solar panels	132

Figure 27:
The pilot porject facade realized at Mondial Movers, Alblasserdam

A heat exchanger based on air-water has been placed to investigate the heat energy production of the Lumiduct system. The system at Mondial Movers is used to validate the algorithm used for electrical energy production simulations.

Testimonial: *With the placement of the Lumiduct, two problems have simultaneously been solved:*

- The rooftop offered insufficient space for extra solar panels to become more energy independent

- The south orientation of the façade resulted in extreme high temperatures (up to 40 degrees)

The Lumiduct delivers the expected electrical energy and the solar shading capability of the Lumiduct results in significant energy savings for cooling. At last, our office looks visually more attractive and our brand name improved drastically on both national as international level. **Tom Stuij, Director of Mondial Movers**

Figure 28:
Rendering of the pilot project facade made by EGM architects.

Appendix B - Additional media functionality

In order to make the business case of the Lumiduct even more attractive, additional media functionality can be implemented in the system. This makes the façade even more multifunctional and unlocks the possibility of using the façade during the night when solar shading and solar energy generation is not relevant. This version is called the Lumiduct Media and has all the same functionalities as described in this document. The integration of LED lights has minimal effect (0.01%) on the transparency of the panels due to their limited size and will not have impact on the energy generation or solar shading capabilities of the system.

By placing the solar panels of the Lumiduct in closed position, with the panels being positioned vertically, the façade can be transformed into a media wall. For the LED implementation, single addressable white or RGB LED's are used to make it possible to display *any* video imaging with high refresh rate and pixel resolution up to 1300 pixels per m^2. Energy consumption will depend on pixel resolution and brightness chosen by the client.

While the media functionality demands a higher investment, the business case is strongly improved. The broadcasting allows for an additional, valuable and quantifiable revenue stream. Simultaneously, it improves the company's branding which will be associated to visible impact on sustainability. Visualization of the Media Wall functionality can be seen in Figure 29 and shows the potential of this additional Media function. Note that this example only shows a fixed image while video imaging is also possible**.**

Figure 29:
Rendering of the Lumiduct Media system in front of a car dealership.