

# PV . AS . ART

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Frédérique Sanders . TU Delft . AE Studio 2016



**PV as art:**

*integration of roof-mounted solar energy and daylight systems*

## **PV as art**

Architectural Engineering  
TU Delft . Studio 2016

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## ABSTRACT

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For centuries daylight has been used as the primary source of light in interiors and has been an implicit part of architecture for as long as buildings have existed. Somehow during the last century, we forgot everything we knew about the art and science of daylighting. Many studies show us now the importance and benefits of daylight; both for health as for economic and environmental reasons. It is an important parameter of an energy-efficient design.

The use of roof windows and skylights deliver significantly more light and a larger variation of light levels than vertical and dormer windows. Important for the best formation of roof daylight is to avoid direct light and allow diffuse light which is comfortable due the fact that the solar intensity is consistent and less clear shadows appear.

A database shows 26 different roof daylight project and indicates important design recommendations when creating a roof-mounted daylight system. At the current market two types of daylight systems exists which combine sunshading with solar energy. These designs are not optimal and have some strong disadvantages.

Therefore it is important that there will be innovation towards an aesthetic and eco-efficient roof-mounted sunshading system which not combines, but integrates daylight and solar energy. A system that even allows comfortable, diffuse daylight as prevents a high energy peak at noon. For this innovation a tracking system - preferred a low tech, passive tracking system - is an essential part.

***Keywords: daylight, solar energy, integration, energy peaks***







## PROLOGUE

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During my time at the TU Delft I was given the opportunity to study abroad; one time in la bella Venezia and another time in exciting London. I discovered that there are several different ways of approaching the architectural field and that there exists a gap between the more aesthetic and narrative approach of architecture and the technical method. This *'grey area'* where architecture and engineering come together interests me a lot. I believe that this integration will become more important in the future since the role of an autonomous architect is changing to an interacting designer and engineer.

*Frédérique Sanders, June 2016*





Figure 1.



Pantheon, Rome  
126 AD

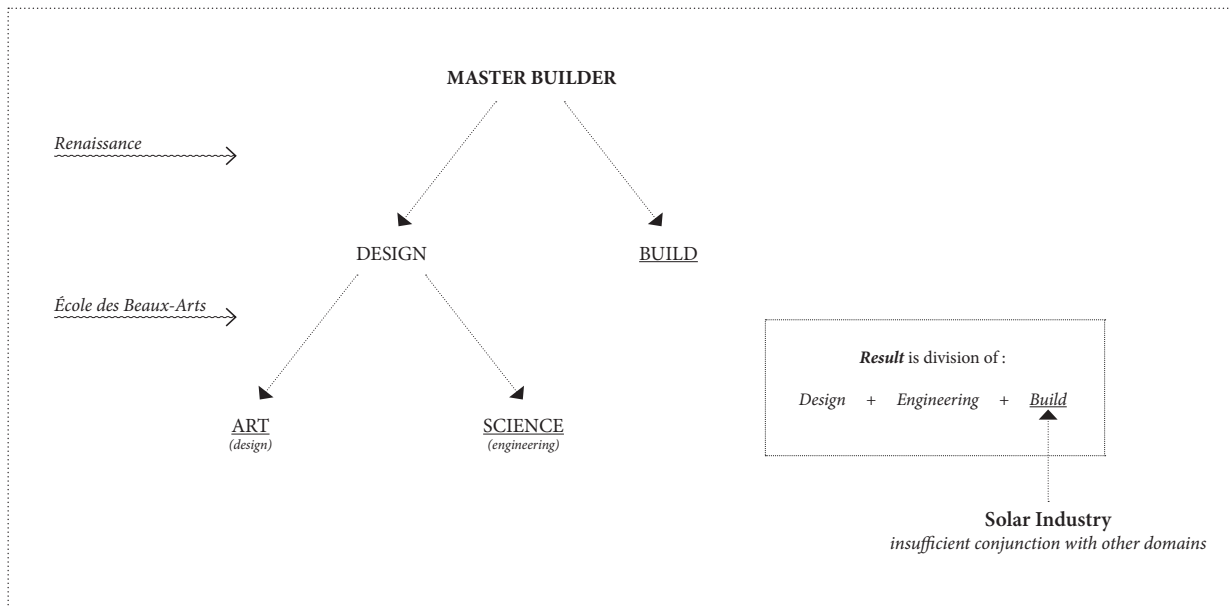
Figure 2.



SolarCity, California U.S.  
2016

12

Figure 3.





## RELEVANCE

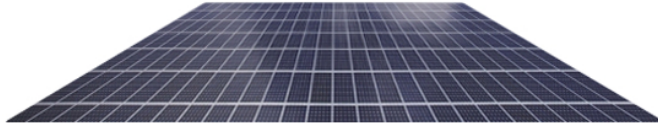
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The roof is the crowning glory of a building and often special care is given to their appearance. Each style period does have its own distinctive roof or facade designs. For example, the Gothic architecture has steep roofs, steeples and towers that transform a relatively nondescript building to striking homes, churches or cathedrals.

In contrast the current way of mounting solar panels on roofs, is not fed by an architectural approach, it is mostly induced by the ecology and economic policies and a sustainable, guilty feeling. When the property owners make the decision, contact is made with the solar contractors. These companies advice the building owners with the best intentions, but this advice will not go further then a calculation of the amount of panels and choice of a mounting system. Moreover the interest of the solar contractors is to sell as much as possible solar panels. The MRE (*Material Related*

*Energy*) of PV's is high, since the cells consist of many energy expensive materials (a.o. mono-crystalline silicon). Solar tracking is an eco-efficient strategy for improving the efficiency of the solar cells. With the same number of MRE a higher energy production can be reached in the morning and afternoon. Moreover research has to be done to the prospective regulation for curtailment to prevent overloading on the current power grid; one of the main problems in the future.

In short, the roof-mounted solar systems are an addition to the - by Koolhaas so-called - "*Junkspace*". Beside the solar cells or panels are not used on their best way. Therefore it is important that research will be done to the possibilities for an aesthetically appealing and eco-efficient roof-mounted solar system.



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Figure 4.

Current approach to energy is *hypocrite*

The New Stepped Strategy:

[Dobbelsteen, 2008]

1. Reduce
2. Reuse
3. Produce

> BETTER: instead of focusing on producing energy, the first steps should be to *reduce and reuse* existing energy

## PROBLEM 1

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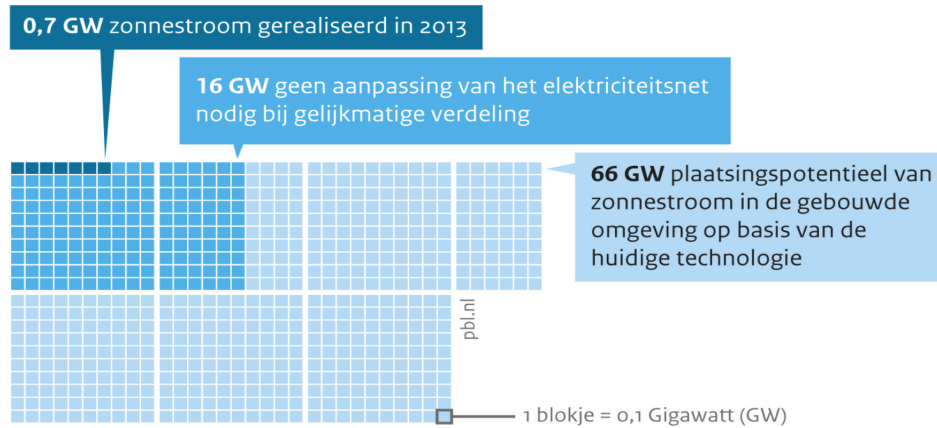
Due to the stimulation of policies of more and more countries which view PV as a power source with a large potential for the future, also property owners of existing buildings are installing solar panels on their roofs. Unfortunately the majority of these added solar panels are BAPV, which makes sense due their high efficiency and minimum costs.

To clarify: PV systems for buildings can be divided in two groups, Building Applied Photovoltaics (*BAPV*) and Building Integrated Photovoltaics (*BIPV*). This last group represents photovoltaic materials that are used to replace conventional building modules in parts of the building envelope such as the roof, skylights or facades. The advantage of integrated photovoltaics over more common non-integrated systems (BAPV) is that the initial cost can be offset by reducing the amount spent on building materials and

labor that would normally be used to construct the part of the building that the BIPV modules replace. Additionally BIPV systems - if designed in a good way - can improve the building's indoor climate (think of natural daylight instead of artificial lighting) and can add architectural interest to the building.

The fact that the added solar panels on the existing building stock are BAPV, means that the chances to improve the buildings' indoor climate are not be utilized and that the architectural quality of the building stock is even more decreased. The absence of an attractive, adaptable and especially low cost solar system for the existing building stock, that has both the qualities of BAPV (*high efficiency of PV's*) and BIPV (*improving indoor climate and architectural interest*) is a problem that has to be solved.

Figure 5.



Realized solar power and placement potential of solar power

Measures to **absorb** the peaks:  
(otherwise the power grid get overloaded)

**1. Curtailment**

Temporary production limitation of up to 70 percent at times when the sun is fully shining, achieves a power dissipation of up to 2 to 3 percent annually in the Netherlands

**2. Energy demand management**

Encourage the consumer to use more energy during peak hours by variable electricity rates  
(problem: consumer is more and more also producer)

**3. Local energy storage**

In electric cars / home battery e.g. Tesla's Powerwall  
(problem: still in early stages / expensive)

**4. Grid reinforcement**

Final - and most expensive - measure

--> BETTER: instead of absorb the peaks, **prevent** them

## PROBLEM 2

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By the end of 2014 the Netherlands have been achieved an increase of 40% in electric power by solar energy compared to 2013. Around 250 thousand households and businesses have solar panels on their roofs, which represents 1 gigawatt electrical power; comparable to the production of two coal plants. Keeping in mind the European Parliament mandate for all new buildings constructed in Europe after 2020 to be nearly carbon-neutral, it is generally expected that in this century photovoltaics will become a substantially contribution to the mainstream power production of buildings.

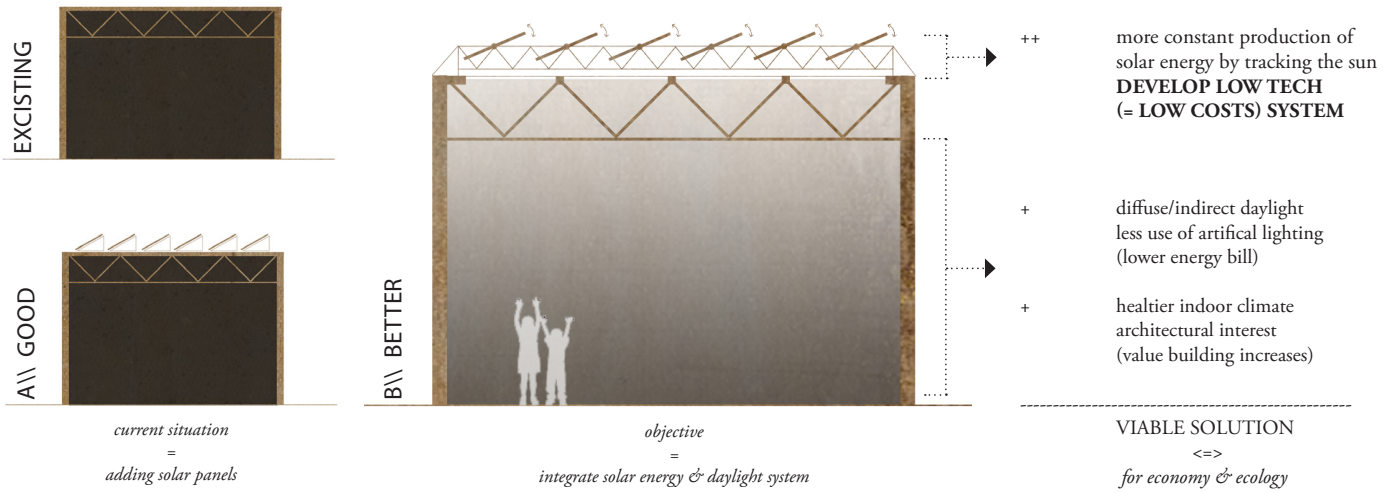
An increase to 16 GW by the current distribution in the Netherlands can be absorbed well. If the suitable roof surface of residential and commercial buildings will be fully used for

installing solar panels, it has an output of 66 GW. This would generate enough power for the entire built environment in the Netherlands (*PBL, 2014*). However, it is not possible to fully utilize this ability with the present techniques for season storage of electricity.

The challenge for the coming years is - instead of focussing on producing more electric energy by solar panels - preventing overloading on the current power grid. Beside exploration into measures to absorb the peaks (*see overview on left page*), research has to be done how to prevent the peaks. Solar tracking is a solution to get less and less higher peaks. This possible solution should be investigated further.

Figure 6.

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*combine solar energy and daylight system*

“ 1 + 1 = 3 ”

*more value with less impact*

## OBJECTIVE

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A guiding principle for this innovation is the term eco-efficiency. This sustainable development principle was established by the World Business Council for Sustainable Development (WBCSD) in the 1990s. By them eco-efficiency is defined as “*eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth’s estimated carrying capacity.*” In short, it is concerned with creating more value with less impact or in other words, eco-efficiency encourages low-impact growth.

Focusing this term on the current situation of adding solar panels to the existing building stock, it is important for creating a viable new solution to take into account both pillars of the term eco-efficiency: ecology and economy. The objective is to develop an attractive, adaptable and low costs solar system with both a high energy performance (economy) as a positive effect for the indoor climate (ecology). Only if the new solar panel system is economically attractive for the

existing building stock, it can be realistic. The philosophy of eco-efficiency says that this can be reached by reducing the ecological impact of the solar panels. In that way ecology and economy work together.

The use of tracking systems for the solar panels is an eco-efficient strategy for improving the ecology and economy: potentially lowering both costs and lifecycle environmental impacts per kWh generated. A good sun-tracking system must be reliable and able to track the sun at the right angle even in the periods of cloud cover. An autonomous, natural solar tracker can be cheaper and needs less maintenance due the absence of electrical components than existing solar tracking systems. **In other words the integration of a tracking system improves both the solar energy production (more constant) as the indoor daylight qualities (reflecting direct sunlight) (more value) without using significant more material (less impact).**

## OVERALL DESIGN QUESTION

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In which *aesthetic and eco-efficient* way,  
*solar energy and daylight* can be integrated in a *roof-mounted system*,  
using an existing building on the Marineterrein in Amsterdam as a test subject?



## THEMATIC RESEARCH QUESTION

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How can *solar energy and daylight* be integrated in a roof-mounted system,  
by using a *low tech solar tracking system*?



# RESEARCH METHODS

## thematic research

### I . DAYLIGHT

- What are the advantages and disadvantages of allowing daylight in a building through the roof? (*L*)
- What are good architectonic examples for allowing daylight through the roof? (*R + V*)
- In which way these examples reflect the direct sunlight? (make database) (*L + R*)

### II . SOLAR ENERGY

- What are the principles of solar tracking? (*L + I*)
- Which mechanical systems exist for solar tracking and what are their advantages and disadvantages? (*L + I*)
- Which active and passive drive systems exist for solar tracking and what are their advantages and disadvantages? (*L + I*)
- Introduce passive drive tracking system using electromagnetism and magnetic influence (*L + R*)

## integration

### III . MARINETERREIN

- In which way the Marineterrein can contribute to the energy transition (from a central to a decentral / independent energy system)? (*L + I + R*)
- Which building on the Marineterrein would be suited the best as a test subject? (*L + V*)
- How is the relevant building constructed and what are the current climate and lighting systems? (*L + I + V*)
- How is the insolation on the relevant building? (*L*)
- In which way or pattern panels can be placed on the roof to create a pleasant indoor climate? (make digital and physic models) (*D*)

## testing & applying

### IV . PROTOTYPE

- Make and test prototype (*D*)

### V . DESIGN

- Design and apply the roof system to an existing building on the Marineterrein in Amsterdam (*V + D*)

MSc 3  
research

MSc 4  
design (+research)

*L* = Literature study  
*I* = Interview  
*R* = Reference analysis  
*V* = Visit  
*D* = Research by Design





Figure 7.



**The Weather Project**

Artist: Olafur Eliasson  
Tate Modern, London - 2003

## HUMAN NEED FOR DAYLIGHT

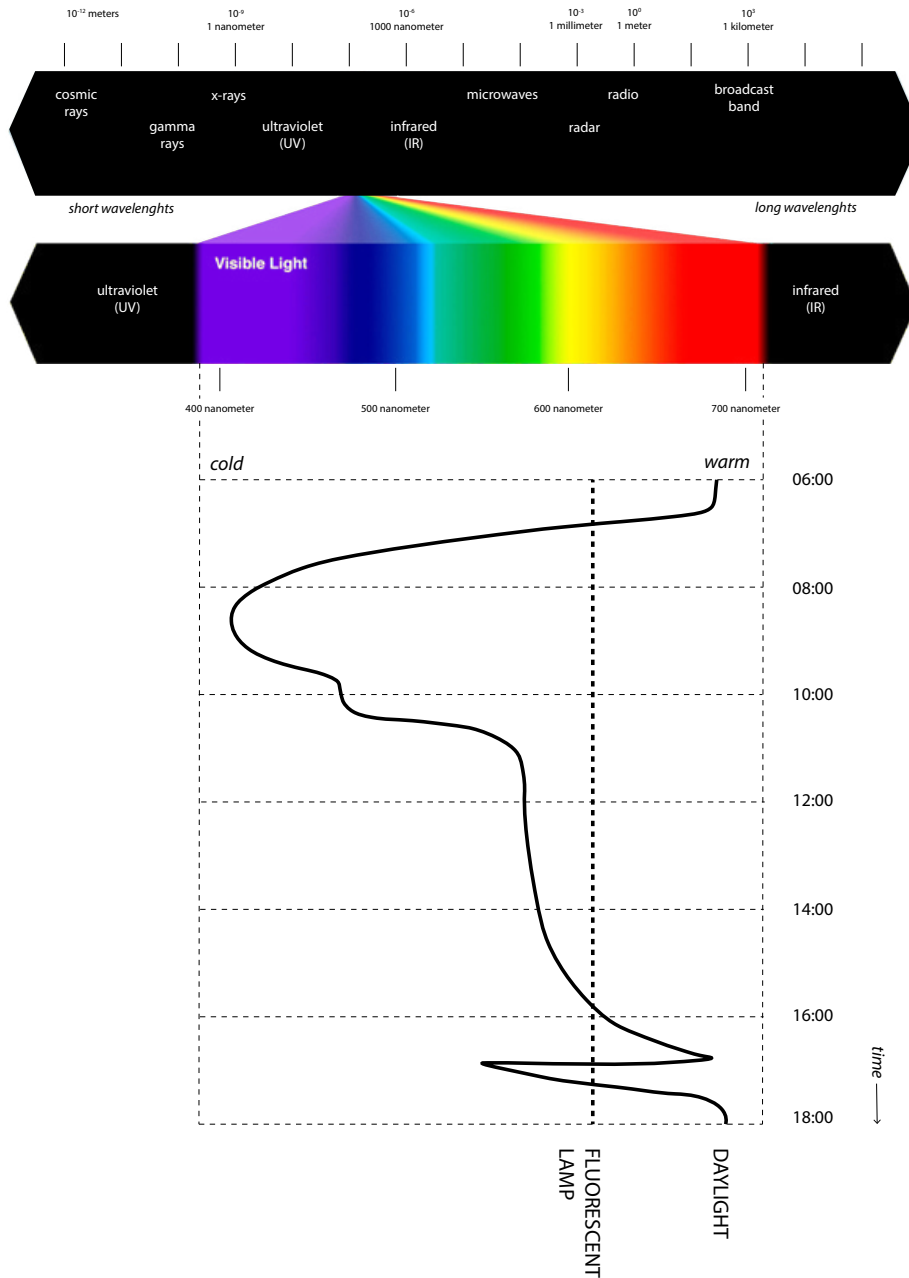
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Certainly, light is necessary for people to see too accomplish specific tasks such as reading, writing, sewing, and so forth. But even more important, our biological clock responds to light intensity, duration, timing and spectrum. The satisfying feeling of your first sips of water when you are very thirsty; the same way the first rays of sunshine feel in spring. Our body uses light as it uses food and water, as a nutrient for metabolic processes. Inadequate light exposure can disrupt normal circadian rhythms (our 24-hour daily rhythms) and have a negative effect on human performance, alertness, health and safety. We know that outdoor daily light exposure allows us to regulate our sleep/wake timing and levels of alertness.

But the reality is that **we spend 90% of our time indoors**, where we are exposed to relatively low light levels of a limited spectral range, and where the patterns of light and darkness occur at irregular intervals. Preliminary evidence suggests that low light exposure is associated with diminished health and well-being and can lead to reduced sleep quality, depressed mood, lack of energy and impaired social relations (*VELUX Knowledge Centre, 2014*).

Simply said, **humans have a natural attraction and need for daylight**. It creates a more calm and productive environment since it connects people to the outdoors, our originally habitat.

Figure 8.



Variation in the light spectrum of natural light vs. constant light of constructed light source



## NATURAL DAYLIGHT

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Daylight is described as the combination of all direct and indirect light originating from the sun during daytime. Of the total solar energy received on the surface of the earth, 40% is visible radiation and the rest is ultraviolet (UV) and infrared (IR) wavelengths. Daylight availability outside varies for different locations due to different sun paths and sky conditions through the course of the day, the season and the year (*see Appendix 1*). Put simply, the amount of light on the ground depends on the solar elevation; the higher the sun, the greater the illuminance on the ground.

While certain electric light sources can be constructed to match a certain spectrum of daylight closely, none have been made that mimic the variation in the light spectrum that occurs with daylight at different times, in different seasons, and under different weather conditions. The **light that is important to our circadian rhythm ( $C(\lambda)$ ) is different from the light that is important to our visual system ( $V(\lambda)$ )** because of the spectral difference in the light sensitivity of the individual photoreceptors (spectrum). The circadian system ( $C(\lambda)$ ) is most affected by the wavelength region 446 to 488 nm, whereas the visual system ( $V(\lambda)$ ) is most affected by the wavelength around 555 nm (*VELUX Knowledge Centre, 2014*). As shown in *Figure 8*, the spectral composition of daylight is much richer in these regions of the electromagnetic spectrum than typical electric light sources.

In short you can determine that throughout the day, the variation in the light spectrum of **natural daylight is unmatched by any constructed light source**.

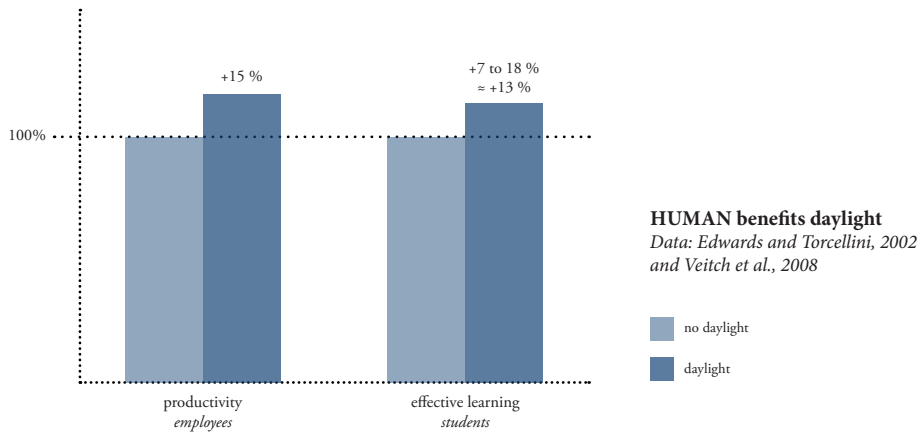


Figure 9.

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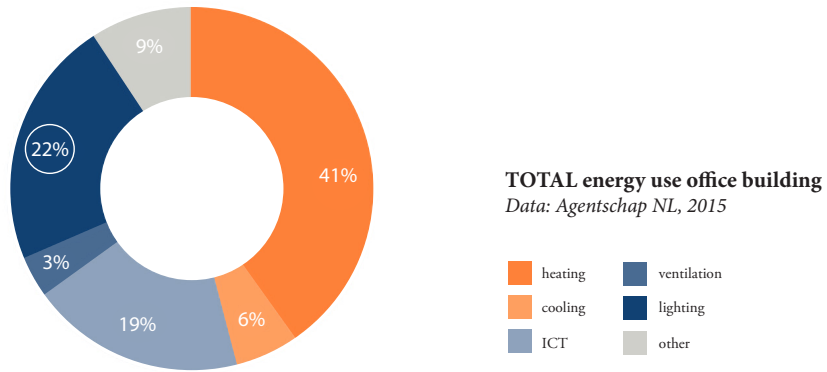


Figure 10.

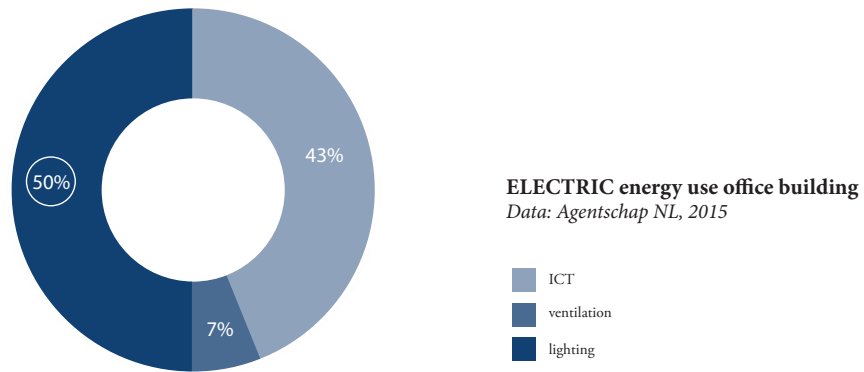


Figure 11.

## BENEFITS OF DAYLIGHT

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Daylighting has always been of major importance, but somehow during the 1960s, we forgot everything we knew about the art and science of daylighting. Cheap energy and air conditioning did us in (*Evans, 1981*). Many studies show us now the importance and benefits of daylight; both for health as for economic and environmental reasons.

The performance and productivity of workers in office, industrial, and retail environments can increase with the quality of light. Companies have recorded an **increase in productivity** of their employees of about 15% after moving to a new building with better daylight conditions. This resulted also in considerable financial gains (*Edwards and Torcellini, 2002*). Another study demonstrated that greater satisfaction with lighting conditions (both daylight and electric lighting) contributed to environmental satisfaction, which, in turn, led to greater job satisfaction (*Veitch et al., 2008*). This leads to **less absenteeism**. Studies also show that daylight environments lead to **more effective learning**. It was found that students in classrooms with the most window area or daylighting produced 7% to 18% higher scores on the standardised tests than those with the least window area or daylight (*Heschong, 2002*).

Another benefit of using daylighting for illuminance in a space is that it can **save energy by reducing the need for electric lighting**. Several studies in office buildings have recorded the energy savings for electric lighting from using daylight by 50-60% (*Galasiu, 2007*). Decisive is the use of an automatic lighting control system. If no control system is installed, the occupant entering a space will still often switch on the electric lights. In an office building 50% of the electric energy use is lighting (*see Figure 10*); a saving of 50-60% on this part will ensure a significant **lower electric energy bill**.

Figure 12.



**KWR Watercycle Research Institute**

Architect: Cepezed  
Nieuwegein, The Netherlands - 2015

Figure 13.



**Plus Ultra**

Architect: Wiegierinck Architectuur  
Wageningen, The Netherlands - 2015

## STIMULATING ENVIRONMENTS

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BNA Best Building of the Year (*“Beste Gebouw van het Jaar”*) is the Dutch architectural competition for architects who offer added value to clients and society. The prize has been awarded since 2006 by the Association of Dutch Architects (BNA). Contributors for Best Building of the Year show that the building offers excellence in a broad sense. So besides the architectural quality, also the use and experiential value, the added social value and the quality of cooperation are taken into account.

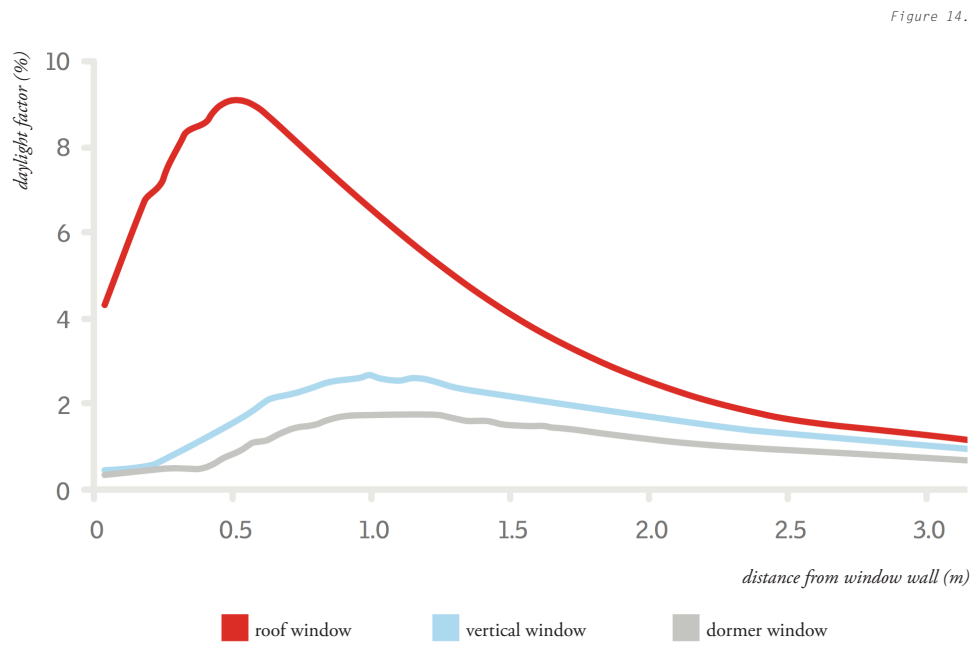
The category *“Stimulating environments”* refers to buildings that contribute to **improving the housed function**, as learning performance (education), healing (care) or work performance (offices). The two buildings which have been nominated in this category for the competition in 2016, both use daylight as a base / core element in the design. These two nominees are the KWR Watercycle Research Institute building and the Plus Ultra building (*see Figure 12 and 13*).

The atrium in the KWR building has a shed roof made of glass and steel, covered with solar panels. Meanwhile, more than a year in operation, the productivity of KWR has increased measurably. This was one of the aims of the architects to create a ‘stimulating environment’. On the new Plus Ultra building on the university campus in Wageningen, 200 solar panels are placed by the end of 2015. These are situated on the roof above all climate treatment equipment.

These two examples of good building design show that **daylight is a core element when creating a stimulating environment**.







Comparison of daylight factor levels along the depth of the room



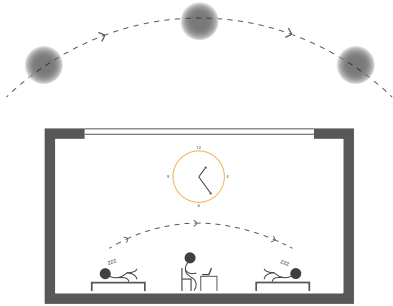
## ADVANTAGES ROOF DAYLIGHT

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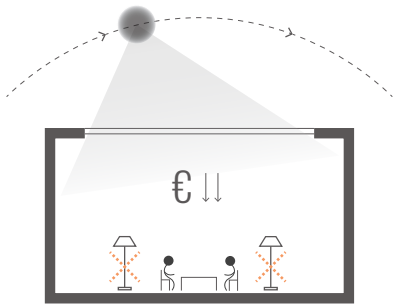
Roof windows and skylights deliver **significantly more light** than vertical and dormer windows. *Figure 14* shows the impact of three different window configurations on the daylight conditions. Under similar conditions, roof windows are shown to provide at least twice as much light as vertical windows of the same size, and three times more light as dormers of the same size. The roof window also provides a **larger variation of light levels**, which increases the visual interest of the room (*Johnsen et al., 2006*).

In addition to providing more daylight, roof windows are also shown to give **higher wall luminance** than dormer and facade windows. This results in a softer transition between the high luminance of the window pane and the adjacent wall, and thus reduces the risk of glare (*VELUX Knowledge Centre, 2014*).

ADVANTAGES  
roof daylight

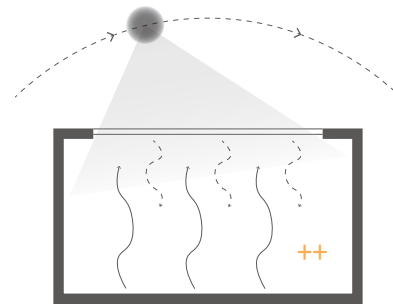


stimulate biorhythm of users

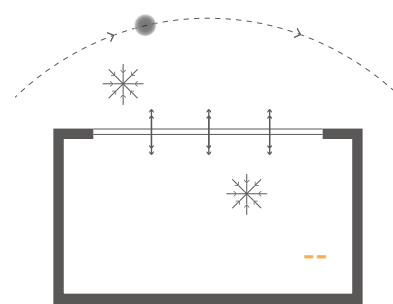


decrease in lighting / electricity costs

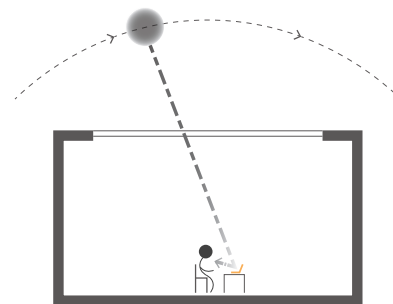
DISADVANTAGES  
roof daylight



summer: overheated by greenhouse effect



winter: high heat losses through glass



sun glare on screens

## DAYLIGHT SYSTEMS

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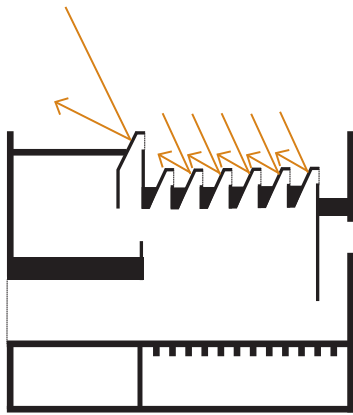
To describe the function of daylight systems, knowledge of the difference between direct and diffuse solar irradiance is required. On earth we perceive a beam or direct solar irradiance ( $B$ ) that comes directly from the disc of the sun (100.000 lux) and a diffuse or scattered solar irradiance ( $D$ ) that appear to come from all directions over the entire sky (around 10.000 lux in the winter and 30.000 lux in the summer). This diffuse solar irradiance is what permits us to see in the shade. If there was no diffuse component of solar irradiance, the sky would appear black at night and stars would be visible throughout the day. The first astronauts described this phenomenon to us from the moon where there is no atmosphere to scatter the solar radiation. The sum of direct and diffuse solar irradiance is called the global or total solar irradiance ( $G$ ) (Middelink *et al.*, 1999).

The best formation for a building is **to avoid direct light and allow diffuse light** which is comfortable - think of an art studio which is conveniently oriented to the North - due the fact that the solar intensity is consistent and less clear shadows appear. A daylight system ensures that the beam/direct radiation ( $B$ ) will be reflected and that the diffuse radiation ( $D$ ) will be transmitted to the inside.

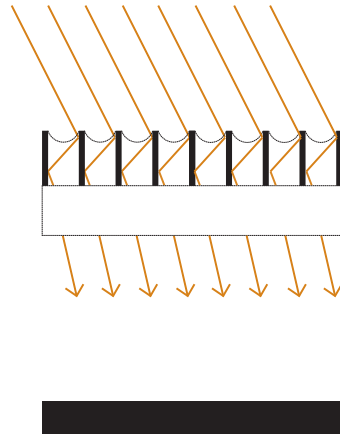
By reflecting the direct light, a **daylight system avoids the disadvantages of roof daylight**, like overheating in the summer and sun glare (see *Figure 15*). The advantages of roof daylight - human and economic benefits - shall still continue to apply.



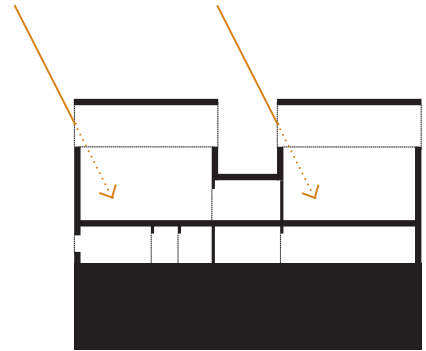




*rebound*



*reflection*



*filtration*

Figure 16.

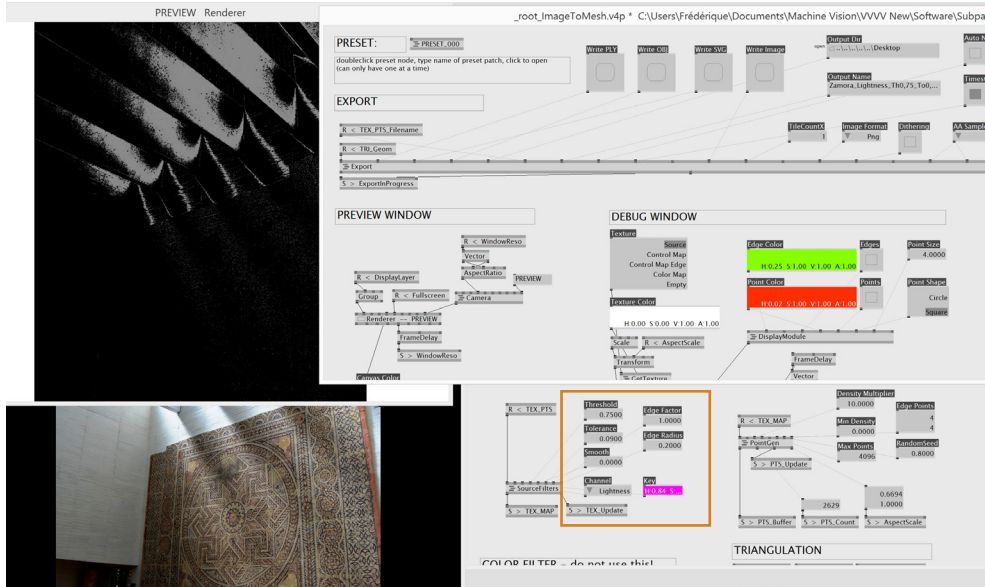
## CLASSIFICATION

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As described in chapter “2.2 Daylight Systems”, the function of a roof daylight or sunshading system is to ‘rebound’ the *beam/direct radiation (B)* or to transform this direct light into *diffuse radiation (D)*. Attached to this Research Paper you can find a database with 26 different roof sunshading projects. The different systems in the database are arranged in three groups:

1.     **Rebound**  
*Direct light not admitted / openings towards the North*
2.     **Reflection**  
*Direct light bounced back and forth*
3.     **Filtration**  
*Direct light transmitted through different material layers*

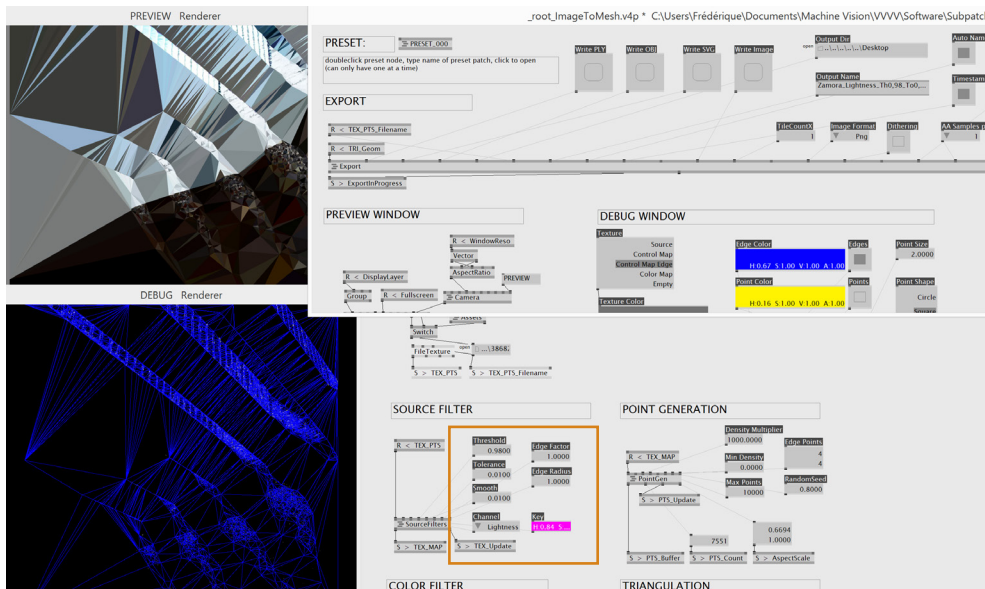
Figure 17.



VVVV-1 software analyzes points of lightness

44

Figure 18.



VVVV-2 software analyzes connections in lightness



## ANALYSIS METHOD

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In order to compare the 26 different daylight projects, of each project a representative interior photo will be subjected to the VVVV-1 and VVVV-2 analysis software. This is a computational reinterpretation program based on procedural digital workflows. With this software the light intensity in the building can be measured.

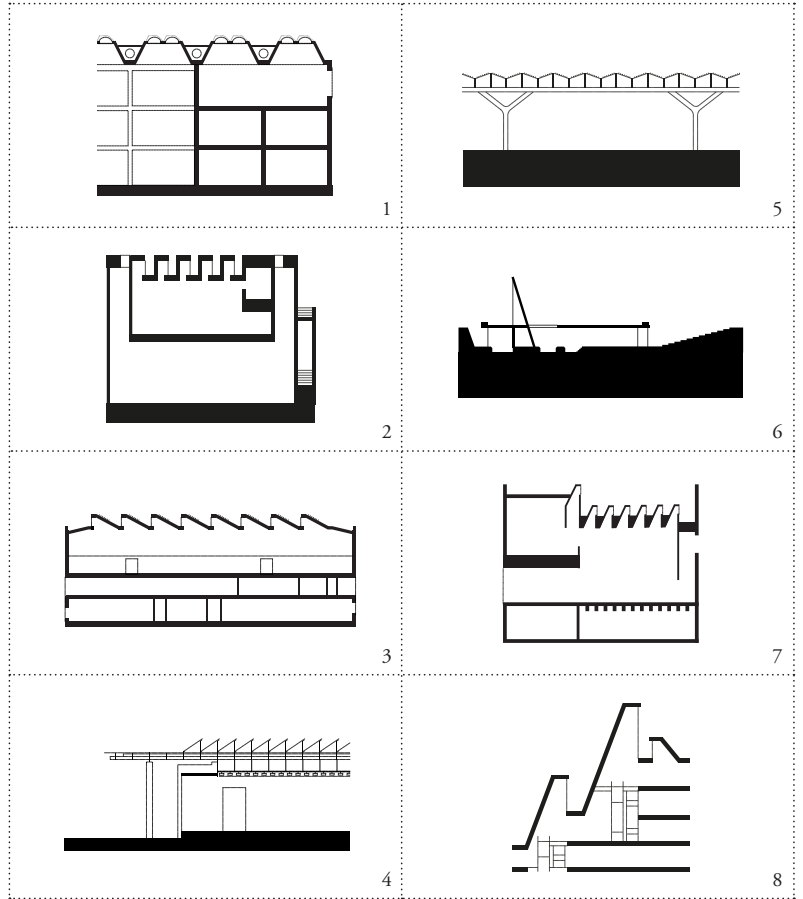
The VVVV-1 analysis software focuses on the points of lightness; the VVVV-2 analysis software on the connections in lightness. **The higher the Threshold and lower the Tolerance of the output, the higher is the light intensity in the building.**

3.3  
OVERVIEW

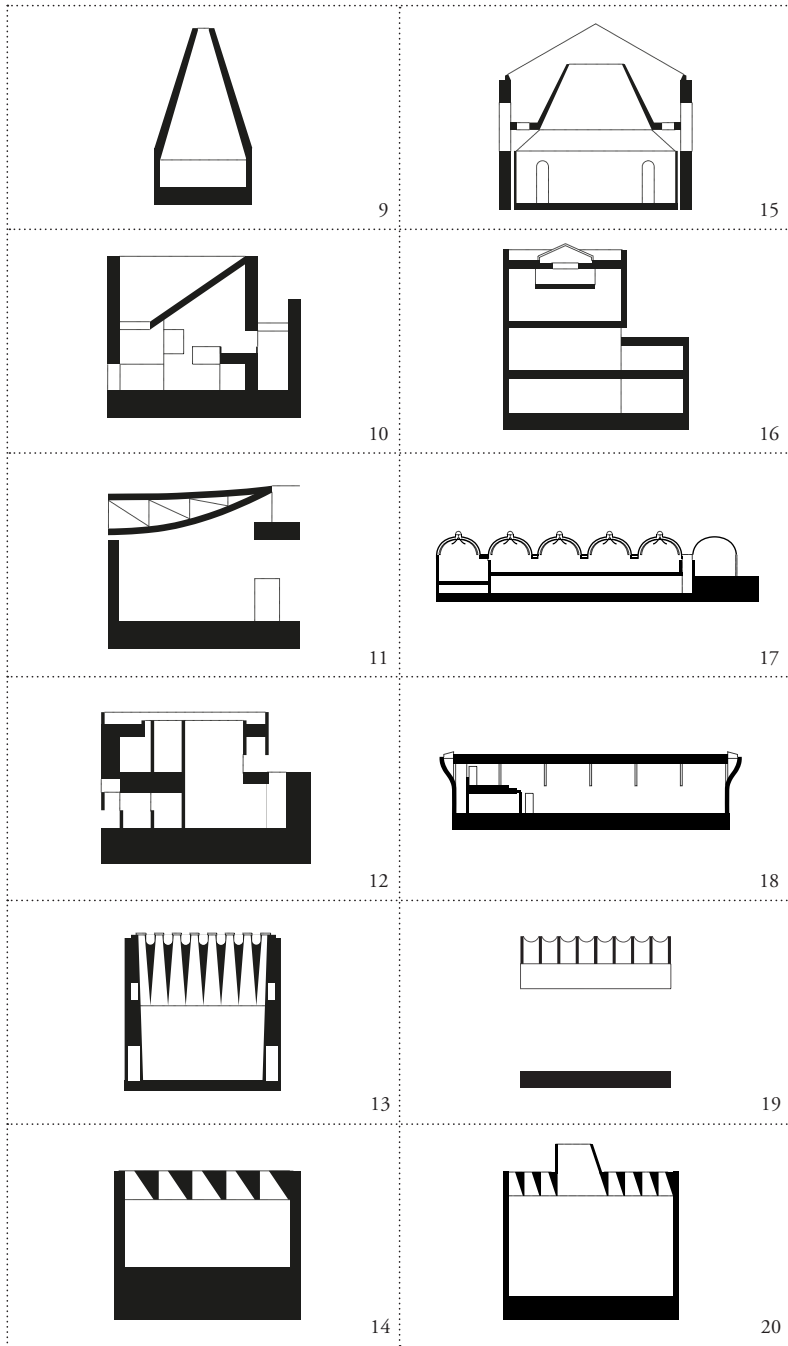
REBOUND

**rebound**

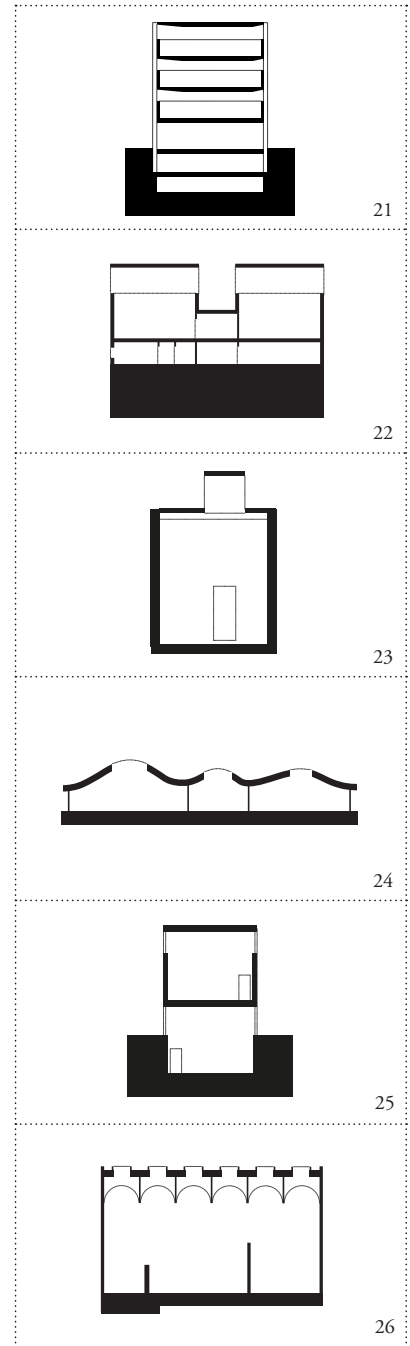
- 1 *Yale Center for British Art*  
Connecticut, United States  
TH: 0.75 - TO: 0.03
- 2 *Centro das Artes Casa das Mudas*  
Madeira, Portugal  
TH: 0.93 - TO: 0.07
- 3 *Pajol Sports Centre*  
Paris, France  
TH: 0.74 - TO: 0.08
- 4 *Beyeler Foundation*  
Riehen, Switzerland  
TH: 0.88 - TO: 0.02
- 5 *Rotterdam Central Station*  
Rotterdam, The Netherlands  
TH: 0.88 - TO: 0.07
- 6 *Museo dei Maestri IUAV Sala Aldo Rossi*  
Venice, Italy  
TH: 0.89 - TO: 0.05
- 7 *Museo Provincial de Zamora*  
Zamora, Spain  
TH: 0.75 - TO: 0.09
- 8 *Congress Centre of Aragón Expo 2008*  
Zaragoza, Spain  
TH: 0.82 - TO: 0.06
- reflection**
- 9 *Casa das Histórias Paula Rego*  
Cascais, Portugal  
TH: 0.86 - TO: 0.04
- 10 *Contemporary Art Centre*  
Córdoba, Spain  
TH: 0.68 - TO: 0.06
- 11 *Herning Museum of Contemporary Art*  
Herning, Denmark  
TH: 0.86 - TO: 0.03
- 12 *Fernando Botero Library Park*  
Medellín, Colombia  
TH: 0.65 - TO: 0.06
- 13 *Herz Jesu Kirche*  
Munich, Germany  
TH: 0.65 - TO: 0.06
- 14 *Nottingham Contemporary*  
Nottingham, Great Britain  
TH: 0.95 - TO: 0.04
- 15 *Musée de l'Orangerie*  
Paris, France  
TH: 0.95 - TO: 0.04
- 16 *CGAC . Centro Galego de Arte Contemporânea*  
Santiago de Compostela, Spain  
TH: 0.87 - TO: 0.05
- 17 *Kimbell Art Museum*  
Texas, United States  
TH: 0.86 - TO: 0.05
- 18 *Gym Hall TNW*  
Utrecht, The Netherlands  
TH: 0.93 - TO: 0.07
- 19 *Nordic Pavilion Venice Biennale*  
Venice, Italy  
TH: 0.75 - TO: 0.04
- 20 *Museo dei Maestri IUAV Sala Aldo Rossi*  
Venice, Italy  
TH: 0.98 - TO: 0.02
- filtration**
- 21 *Kunsthau Bregenz*  
Bregenz, Austria  
TH: 0.75 - TO: 0.06
- 22 *Kirchner Museum Davos*  
Davos, Austria  
TH: 0.89 - TO: 0.05
- 23 *Museum La Congiunta*  
Giornico, Switzerland  
TH: 0.70 - TO: 0.04
- 24 *Guggenheim Helsinki Design Competition*  
Helsinki, Finland  
TH: 0.78 - TO: 0.04
- 25 *Sammlung Goetz*  
Munich, Germany  
TH: 0.93 - TO: 0.08
- 26 *Daylight House*  
Yokohama, Japan  
TH: 0.80 - TO: 0.05



REFLECTION



FILTRATION

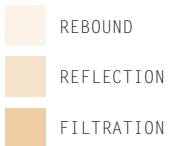
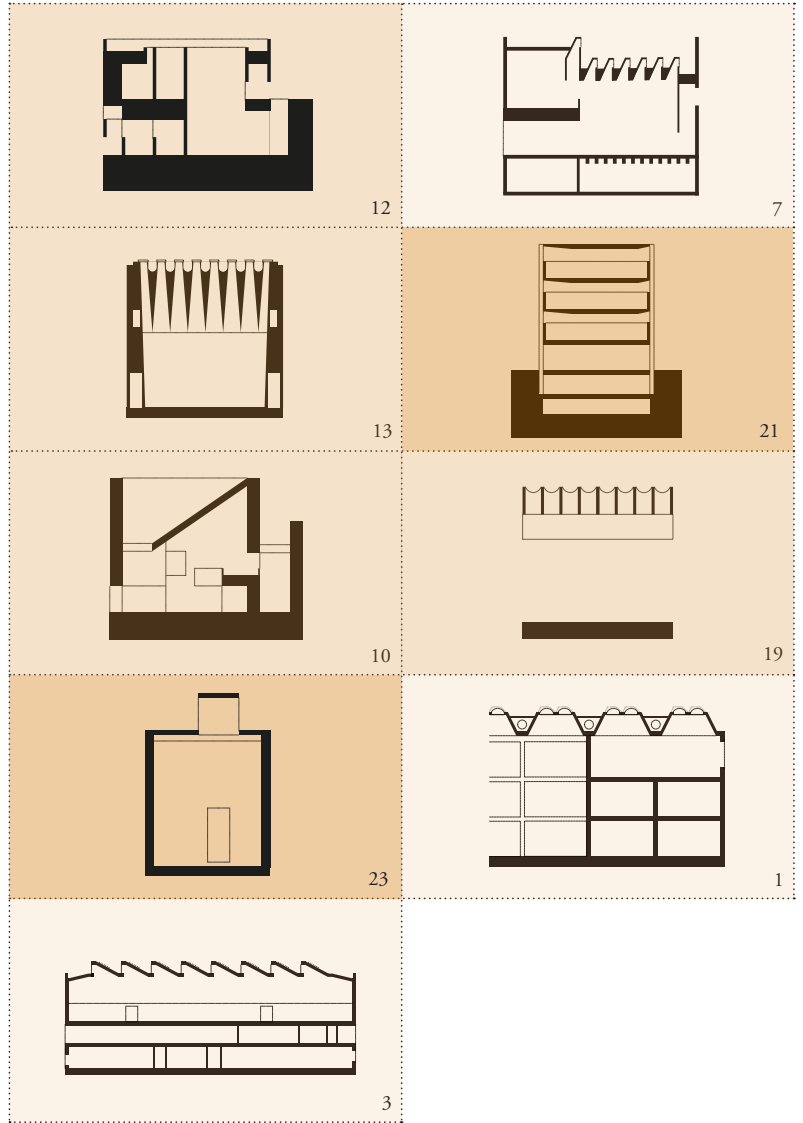


TH LOW [0.60-0.75] ; TO HIGH [HIGH-LOW]

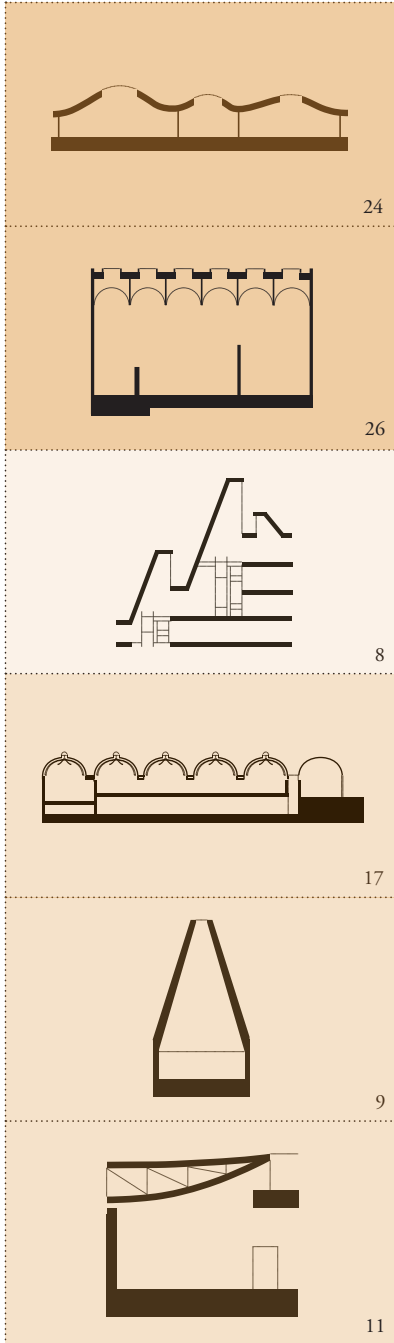
**rebound**

- 1 *Yale Center for British Art*  
Connecticut, United States  
TH: 0.75 - TO: 0.03
- 2 *Centro das Artes Casa das Mudas*  
Madeira, Portugal  
TH: 0.93 - TO: 0.07
- 3 *Pajol Sports Centre*  
Paris, France  
TH: 0.74 - TO: 0.08
- 4 *Beyeler Foundation*  
Riehen, Switzerland  
TH: 0.88 - TO: 0.02
- 5 *Rotterdam Central Station*  
Rotterdam, The Netherlands  
TH: 0.88 - TO: 0.07
- 6 *Museo dei Maestri IUAV*  
*Sala Aldo Rossi*  
Venice, Italy  
TH: 0.89 - TO: 0.05
- 7 *Museo Provincial de Zamora*  
Zamora, Spain  
TH: 0.75 - TO: 0.09
- 8 *Congress Centre of Aragón*  
*Expo 2008*  
Zaragoza, Spain  
TH: 0.82 - TO: 0.06
- reflection**
- 9 *Casa das Histórias Paula Rego*  
Cascais, Portugal  
TH: 0.86 - TO: 0.04
- 10 *Contemporary Art Centre*  
Córdoba, Spain  
TH: 0.68 - TO: 0.06
- 11 *Herning Museum of Contemporary Art*  
Herning, Denmark  
TH: 0.86 - TO: 0.03
- 12 *Fernando Botero Library Park*  
Medellín, Colombia  
TH: 0.65 - TO: 0.06
- 13 *Herz Jesu Kirche*  
Munich, Germany  
TH: 0.65 - TO: 0.06

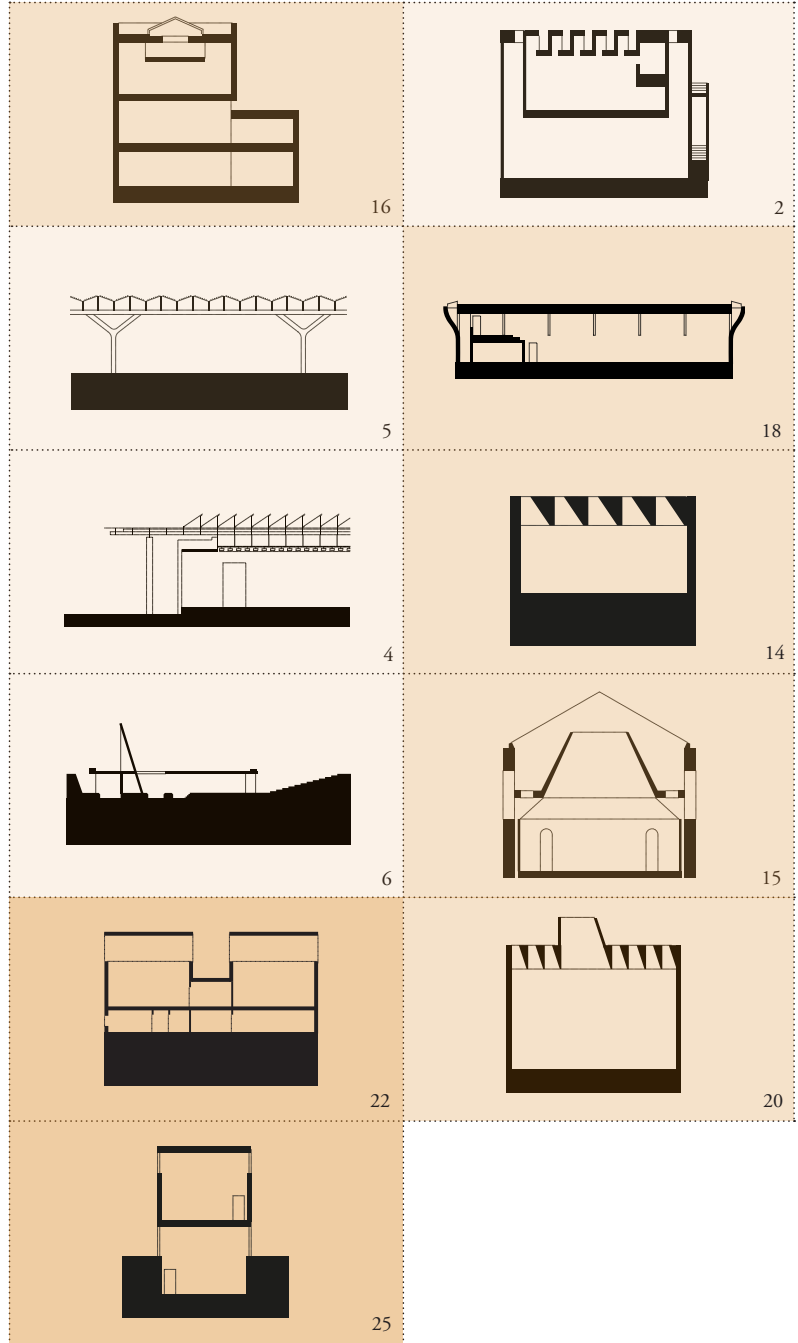
- 14 *Nottingham Contemporary*  
Nottingham, Great Britain  
TH: 0.95 - TO: 0.04
- 15 *Musée de l'Orangerie*  
Paris, France  
TH: 0.95 - TO: 0.04
- 16 *CGAC . Centro Galego de Arte Contemporânea*  
Santiago de Compostela, Spain  
TH: 0.87 - TO: 0.05
- 17 *Kimbell Art Museum*  
Texas, United States  
TH: 0.86 - TO: 0.05
- 18 *Gym Hall TNW*  
Utrecht, The Netherlands  
TH: 0.93 - TO: 0.07
- 19 *Nordic Pavilion Venice Biennale*  
Venice, Italy  
TH: 0.75 - TO: 0.04
- 20 *Museo dei Maestri IUAV*  
*Sala Aldo Rossi*  
Venice, Italy  
TH: 0.98 - TO: 0.02
- filtration**
- 21 *Kunsthau Bregenz*  
Bregenz, Austria  
TH: 0.75 - TO: 0.06
- 22 *Kirchner Museum Davos*  
Davos, Austria  
TH: 0.89 - TO: 0.05
- 23 *Museum La Congiunta*  
Giornico, Switzerland  
TH: 0.70 - TO: 0.04
- 24 *Guggenheim Helsinki*  
*Design Competition*  
Helsinki, Finland  
TH: 0.78 - TO: 0.04
- 25 *Sammlung Goetz*  
Munich, Germany  
TH: 0.93 - TO: 0.08
- 26 *Daylight House*  
Yokohama, Japan  
TH: 0.80 - TO: 0.05



TH MEDIUM [0.76-0.86] ; TO MEDIUM [HIGH-LOW]



TH HIGH [0.87-1.00] ; TO LOW [HIGH-LOW]



**rebound**

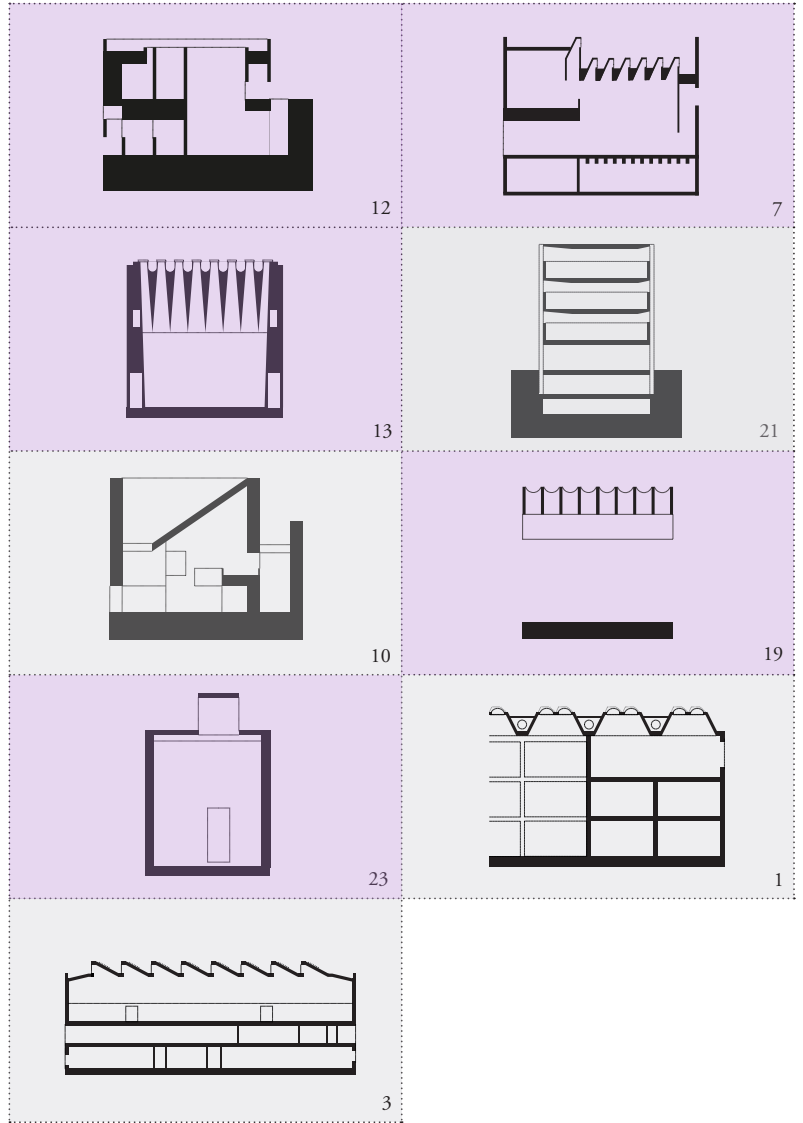
- 1 *Yale Center for British Art*  
Connecticut, United States  
TH: 0.75 - TO: 0.03
- 2 *Centro das Artes Casa das Mudas*  
Madeira, Portugal  
TH: 0.93 - TO: 0.07
- 3 *Pajol Sports Centre*  
Paris, France  
TH: 0.74 - TO: 0.08
- 4 *Beyeler Foundation*  
Riehen, Switzerland  
TH: 0.88 - TO: 0.02
- 5 *Rotterdam Central Station*  
Rotterdam, The Netherlands  
TH: 0.88 - TO: 0.07
- 6 *Museo dei Maestri IUAV*  
*Sala Aldo Rossi*  
Venice, Italy  
TH: 0.89 - TO: 0.05
- 7 *Museo Provincial de Zamora*  
Zamora, Spain  
TH: 0.75 - TO: 0.09
- 8 *Congress Centre of Aragón*  
*Expo 2008*  
Zaragoza, Spain  
TH: 0.82 - TO: 0.06

**reflection**

- 9 *Casa das Histórias Paula Rego*  
Cascais, Portugal  
TH: 0.86 - TO: 0.04
- 10 *Contemporary Art Centre*  
Córdoba, Spain  
TH: 0.68 - TO: 0.06
- 11 *Herning Museum of Contemporary Art*  
Herning, Denmark  
TH: 0.86 - TO: 0.03
- 12 *Fernando Botero Library Park*  
Medellín, Colombia  
TH: 0.65 - TO: 0.06
- 13 *Herz Jesu Kirche*  
Munich, Germany  
TH: 0.65 - TO: 0.06
- 14 *Nottingham Contemporary*  
Nottingham, Great Britain  
TH: 0.95 - TO: 0.04
- 15 *Musée de l'Orangerie*  
Paris, France  
TH: 0.95 - TO: 0.04
- 16 *CGAC . Centro Galego de Arte Contemporânea*  
Santiago de Compostela, Spain  
TH: 0.87 - TO: 0.05
- 17 *Kimbell Art Museum*  
Texas, United States  
TH: 0.86 - TO: 0.05
- 18 *Gym Hall TNW*  
Utrecht, The Netherlands  
TH: 0.93 - TO: 0.07
- 19 *Nordic Pavilion Venice Biennale*  
Venice, Italy  
TH: 0.75 - TO: 0.04
- 20 *Museo dei Maestri IUAV*  
*Sala Aldo Rossi*  
Venice, Italy  
TH: 0.98 - TO: 0.02

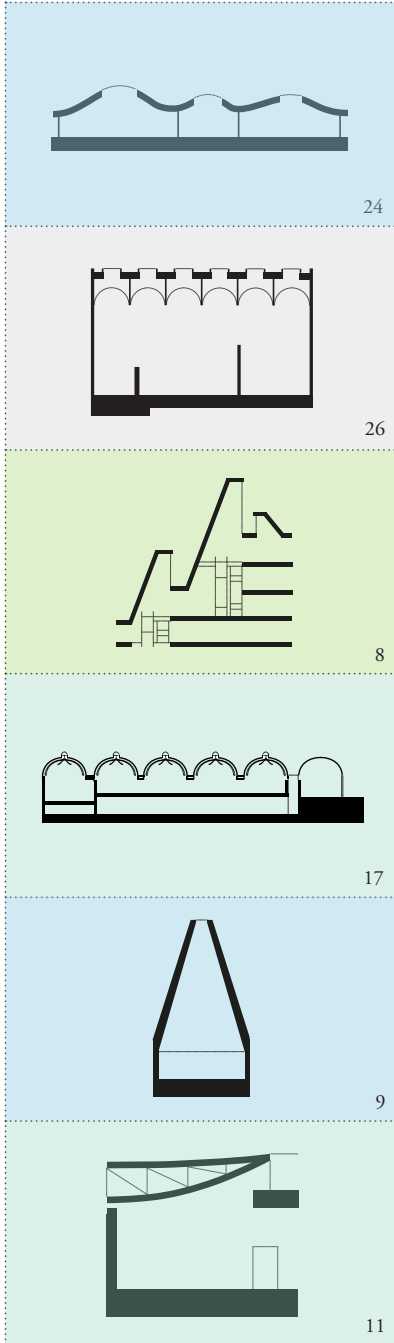
**filtration**

- 21 *Kunsthau Bregenz*  
Bregenz, Austria  
TH: 0.75 - TO: 0.06
- 22 *Kirchner Museum Davos*  
Davos, Austria  
TH: 0.89 - TO: 0.05
- 23 *Museum La Congiunta*  
Giornico, Switzerland  
TH: 0.70 - TO: 0.04
- 24 *Guggenheim Helsinki*  
*Design Competition*  
Helsinki, Finland  
TH: 0.78 - TO: 0.04
- 25 *Sammlung Goetz*  
Munich, Germany  
TH: 0.93 - TO: 0.08
- 26 *Daylight House*  
Yokohama, Japan  
TH: 0.80 - TO: 0.05

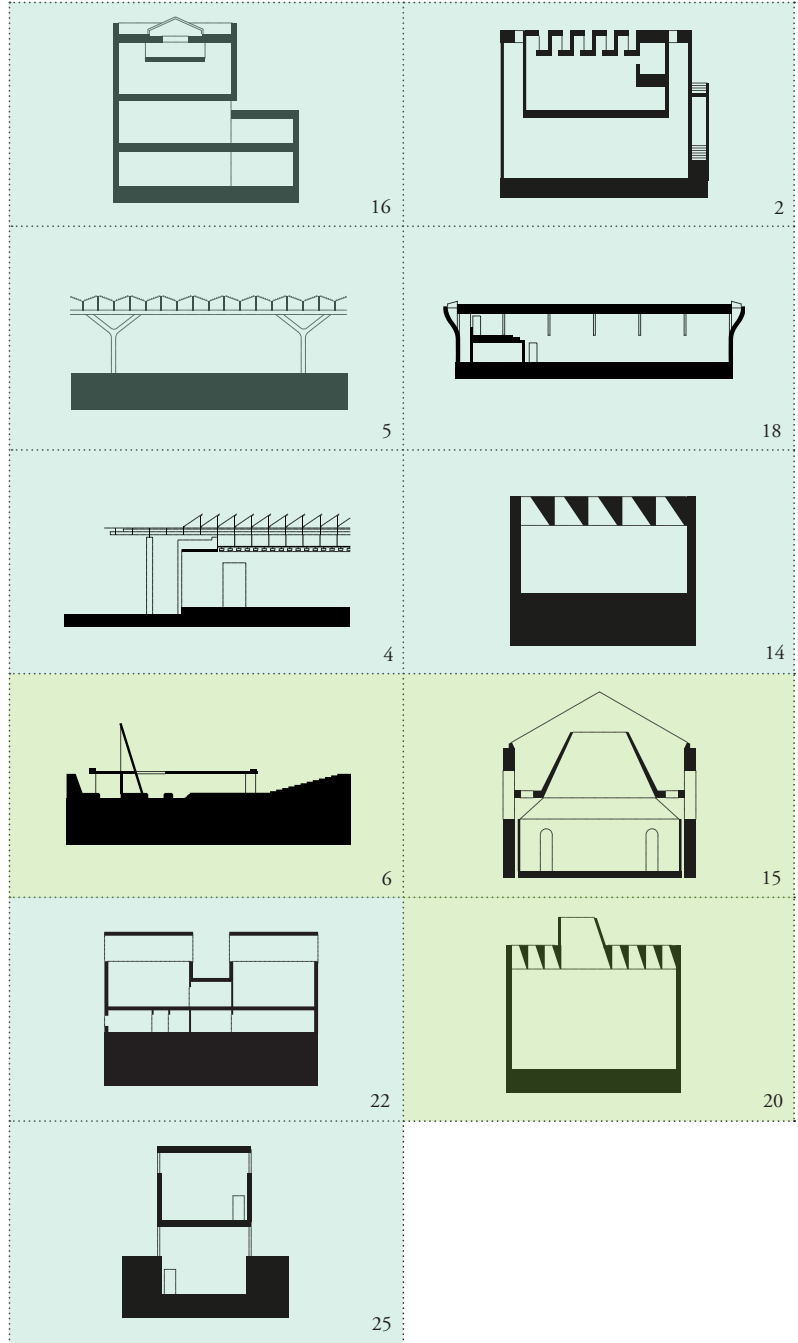


- REFLECTIVE CEILING
- REFLECTIVE FLOOR
- REFLECTIVE WALLS
- REFLECTIVE CEILING + WALLS
- REFLECTIVE CEILING + WALLS + FLOOR

TH MEDIUM [0.76-0.86] ; TO MEDIUM [HIGH-LOW]



TH HIGH [0.87-1.00] ; TO LOW [HIGH-LOW]



	TH LOW TO HIGH	TH MEDIUM TO MEDIUM	TH HIGH TO LOW
REBOUND	$3/8 = 9/24$	$1/8 = 3/24$	$4/8 = 12/24$
REFLECTION	$4/12 = 8/24$	$3/12 = 6/24$	$5/12 = 10/24$
FILTRATION	$2/6 = 8/24$	$2/6 = 8/24$	$2/6 = 8/24$
	↓ <i>most rebound</i>	↓ <i>most filtration</i>	↓ <i>most rebound</i>

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	TH LOW TO HIGH	TH MEDIUM TO MEDIUM	TH HIGH TO LOW
REFLECTIVE CEILING	$5/5 = 20/20$	$0/5 = 0/20$	$0/5 = 0/20$
REFLECTIVE FLOOR	$4/5 = 16/20$	$1/5 = 4/20$	$0/5 = 0/20$
REFLECTIVE WALLS	$0/2 = 0/20$	$2/2 = 20/20$	$0/2 = 0/20$
REFLECTIVE CEILING + WALLS	$0/10 = 0/20$	$2/10 = 4/20$	$8/10 = 16/20$
REFLECTIVE CEILING + WALLS + FLOOR	$0/4 = 0/20$	$1/4 = 5/20$	$3/4 = 15/20$
	↓ <i>most reflection ceiling</i>	↓ <i>most reflection walls</i>	↓ <i>most reflection ceiling + walls</i>



## CONCLUSION DATABASE

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The different daylight projects are placed in order of the intensity of light in the building (based on an interior photograph representing the project). The light intensity is higher when the Threshold is higher and the Tolerance lower.

Linking this order to the characteristics of the different projects, it becomes visible that it doesn't matter if the sunshading system is based on a rebound, reflection or filtration system. The filtration system is with the same number (8/24) represented in the "TH low - TO high", "TH medium - TO medium" and "TH high - TO low" groups. The differences of amount in these groups of the rebound and reflection systems are also negligible.

By contrast the effects of various reflective surfaces in the projects are much more noticeable. The table shows that the combination of reflective ceiling, walls and floor, is the most important in controlling the daylight coming into the space. Beside the table shows that reflective walls have more effect on the light intensity than a reflective floor.

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**Three important design recommendations can be extracted from this database:**

- 1. The difference in reflective surfaces has more influence on the light intensity in the building, than the difference in type of sunshading system (rebound, reflection or filtration);**
- 2. Reflective walls have more effect on the light intensity than a reflective floor. This indicates to the designer: keep the walls as light in color as possible and use the floor surface for deep colors or character-giving patterns;**
- 3. To create an interesting interior with a pleasant light intensity, the sunshading system has to be composed of several different layers.**





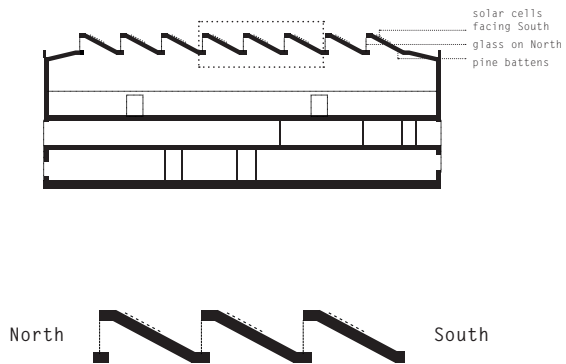
### Pajol Sports Centre

Architect: Brisac Gonzalez  
Paris, France - 2012

Figure 19.



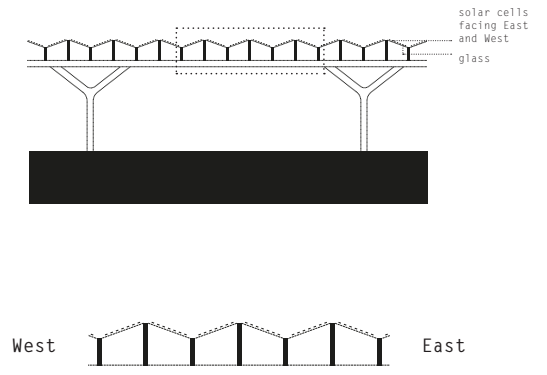
56



### Rotterdam Central Station

Architect: Team CS (Bentham Crouwel Architects + MVSA Architects + West 8)  
Rotterdam, The Netherlands - 2014

Figure 20.



Two existing roof systems which *combine* daylight and solar energy

## SOLAR ENERGY IN DATABASE

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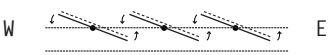
In the roof daylight database only 2 out of 26 projects, are **combining sunshading with solar energy**. These two are the Pajol Sports Centre in Paris (2012) and the Central Station in Rotterdam (2014) (see *Figure 19 and 20*). Partially this is because a majority of the projects in the database are from the 20th century, a time when solar energy was not yet such a matter of course. However, **the two projects are representative for the currently only two existing types** of combining sunshading with solar energy.

In the first type the solar cells are facing towards the South and the glass faces the North. The Pajol Sports Centre is an example for this system. Other examples are the two buildings discussed in chapter “1.4 Stimulating Environments”. Both the nominees the KWR Watercycle Research Institute building and the Plus Ultra building have solar panels on the roof facing southwards and the windows under these panels are facing to the North.

The second type is indicated by the Rotterdam Central Station. Solar cells are facing East and West and placed parallel to the glass. This glass can be positioned at an angle of around 10° or can be placed horizontally.

In the next chapter these two types will be compared to each other.

Figure 21.

	<i>existing</i>		<i>innovation</i>
	TYPE 'Pajol Sports Centre'	TYPE 'Rotterdam Central Station'	NEW
			 <p style="text-align: right;"><i>[conceptually]</i></p>
<i>Description</i>	<ul style="list-style-type: none"> <li>- Solar cells facing South and positioned at an angle of 36°</li> <li>- Glass facing North and positioned vertically</li> </ul>	<ul style="list-style-type: none"> <li>- Solar cells facing East / West and positioned at an angle of 10°</li> <li>- Glass facing East / West and positioned at the same angle of 10°</li> </ul>	<ul style="list-style-type: none"> <li>- In the morning /afternoon solar cells facing East / West and positioned at an angle of 10°</li> <li>- At noon solar cells are positioned horizontally / at an angle of 0°</li> <li>- Openings for daylight facing the opposite direction from the beam / direct light</li> </ul>
<i>Advantages</i>	<ul style="list-style-type: none"> <li>- Allows comfortable Northern, diffuse light</li> </ul>	<ul style="list-style-type: none"> <li>- At noon no peak of produced energy ; in morning / afternoon maximum production of energy</li> </ul>	<ul style="list-style-type: none"> <li>- Allows comfortable, diffuse light</li> <li>- At noon no peak of produced energy ; in morning / afternoon maximum production of energy</li> </ul>
<i>Disadvantages</i>	<ul style="list-style-type: none"> <li>- At noon high peak of produced energy ; in morning / afternoon minimum production of energy</li> </ul>	<ul style="list-style-type: none"> <li>- Allows not comfortable beam / direct light</li> <li>- Clear shadows of the solar cells appear</li> </ul>	N.A.

Comparison of existing, *combined* daylight and solar energy systems with a new, *integrated* system

## INNOVATION

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Figure 21 shows the advantages and disadvantages of the two existing roof-mounted systems which combine daylight and solar energy. As you read in the descriptions, the advantage of type 'Pajol Sports Centre' is missing at type 'Rotterdam Central Station' ; and vice versa. None of the systems is optimally.

As stated before, it is important that there will be innovation towards a roof-mounted sunshading system which not combines, but **integrates** daylight and solar energy. A system that even allows comfortable, diffuse daylight as prevents a high energy peak at noon. A tracking system - preferred a passive tracking system - could be useful by designing this ideal system.

In the appendix more information about existing and potential passive solar tracking systems can be found.







Daylight has been used for centuries as the primary source of light in interiors and has been an implicit part of architecture for as long as buildings have existed. Regrettably somehow during the 1960s, we forgot everything we knew about the art and science of daylighting. Cheap energy and air conditioning did us in (*Evans, 1981*). Recent research has proved that daylight provides an array of health and comfort benefits that make it essential for buildings' occupants. By origin humans have a natural attraction and need for daylight, but the reality is that we spend 90% of our time indoors. The light that is important to our circadian rhythm (our 24-hour daily rhythm) is different from the light that is important to our visual system. In that way the variation in the light spectrum of natural daylight is unmatched by any constructed light source.

Many studies show us the importance and benefits of daylight; both for health as for economic and environmental reasons. Companies have recorded an increase in productivity of their employees of about 15% after moving to a new building with better daylight conditions (*Edwards and Torcellini, 2002*). Another study demonstrated that greater satisfaction with lighting conditions contributed to environmental satisfaction, which led to greater job satisfaction and less absenteeism (*Veitch et al., 2008*). Beside it was found that students in classrooms with the most window area or daylighting produced 7% to 18% higher scores on the standardised tests than those with the least window area or daylight (*Heschong, 2002*).

Using daylight is beside these human benefits, also an important parameter of an energy-efficient design. It does not only replace electric light during daytime - reducing the electric energy use with 50-60% -, it also influences both heating and cooling loads (*Galasiu, 2007*). Decisive is the use of an automatic lighting control system.

When creating a stimulating environment, daylight is a core element. A stimulating environment refers to a building that contribute to improving the housed function, as learning performance (education), healing (care) or work performance (offices). The use of roof windows and skylights deliver significantly more light than vertical and dormer windows. The roof window also provides a larger variation of light levels, which increases the visual interest of the room (*Johnsen et al., 2006*). In addition to providing more daylight, roof windows are also shown to give higher wall luminance than dormer and facade windows. This results in a softer transition between the high luminance of the window pane and the adjacent wall, and thus reduces the risk of glare (*VELUX Knowledge Centre, 2014*).

The best formation for a building is to avoid direct light and allow diffuse light which is comfortable due the fact that the solar intensity is consistent and less clear shadows appear. A daylight system ensures that the beam/direct radiation (*B*) will be reflected and that the diffuse radiation (*D*) will be transmitted to the inside. In this way a daylight system avoids the disadvantages of roof daylight, like overheating in the summer and sun glare.

The roof daylight database explaining 26 different daylight concepts, indicates three important design recommendations. Firstly it shows that the difference in reflective surfaces has more influence on the light intensity in a building, than the difference in type of sunshading system (rebound, reflection or filtration). Secondly it says that reflective walls have more effect on the light intensity than a reflective floor. This suggests to the designer: keep the walls as light in color as possible and use the floor surface for deep colors or character-giving patterns. As last the database shows that to create an interesting interior with a pleasant light intensity, the sunhading system has to be composed of several different layers.

In the database only 2 of the 26 projects combine sunshading with solar energy. Though, these two projects are representative for the currently only two existing types. In the first type the solar cells are facing towards the South (positioned at an angle of  $36^\circ$ ) and the vertical glass faces the North. The disadvantage of this system is that the amount of produced energy is not constant: at noon it gives a high peak of energy and in the morning and afternoon it has a minimum production of energy.

The second type is indicated by solar cells which are facing East and West and placed parallel to the glass. This glass can be positioned at an angle of around  $10^\circ$  or can be placed horizontally. The downside of this system is that it allows not comfortable direct light to the interior. Beside clear shadows of the solar cells will appear.

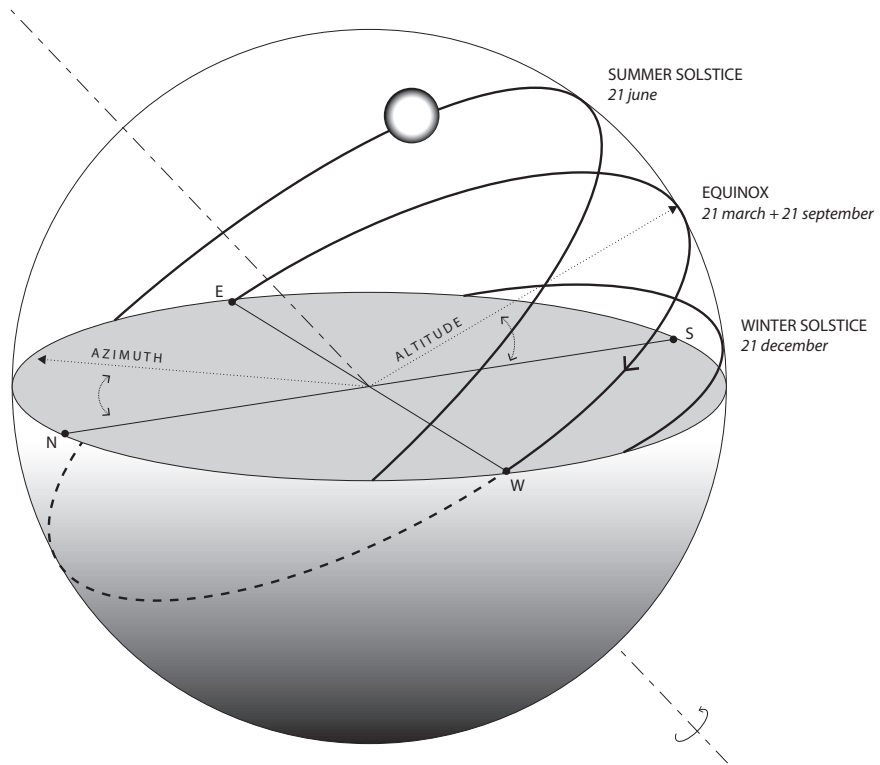
It is important that there will be innovation towards an aesthetic and eco-efficient roof-mounted sunshading system which not combines, but integrates daylight and solar energy. A system that even allows comfortable, diffuse daylight as prevents a high energy peak at noon. For this innovation a tracking system - preferred a low tech, passive tracking system - is an essential part. For this design use could be made of bimetal, shape-memory alloys (SMA), hydraulic pressure or a magnetic solenoid. An overview of these different methods can be found in "Appendix 6".





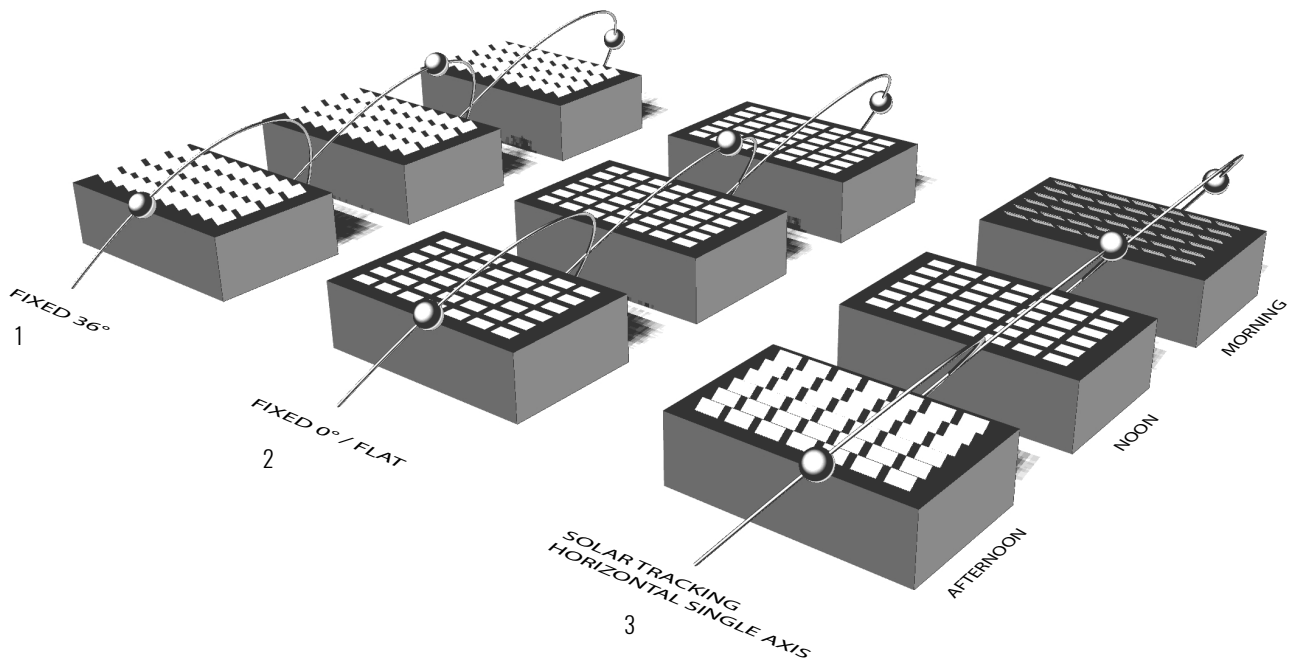
1. Motion of the sun

Figure 22.

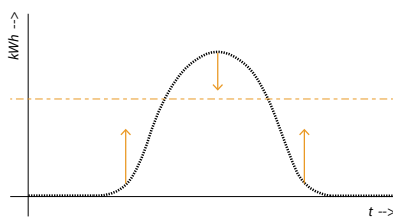


## 2. Solar tracking

Figure 23.



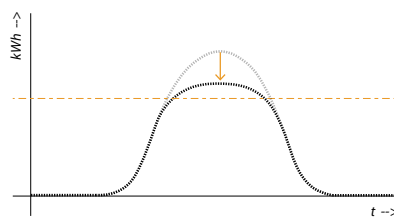
67



1

noon: high peak

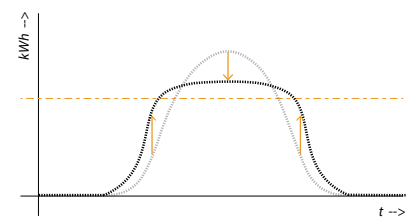
CURRENT SITUATION



2

noon: less high peak

GOOD



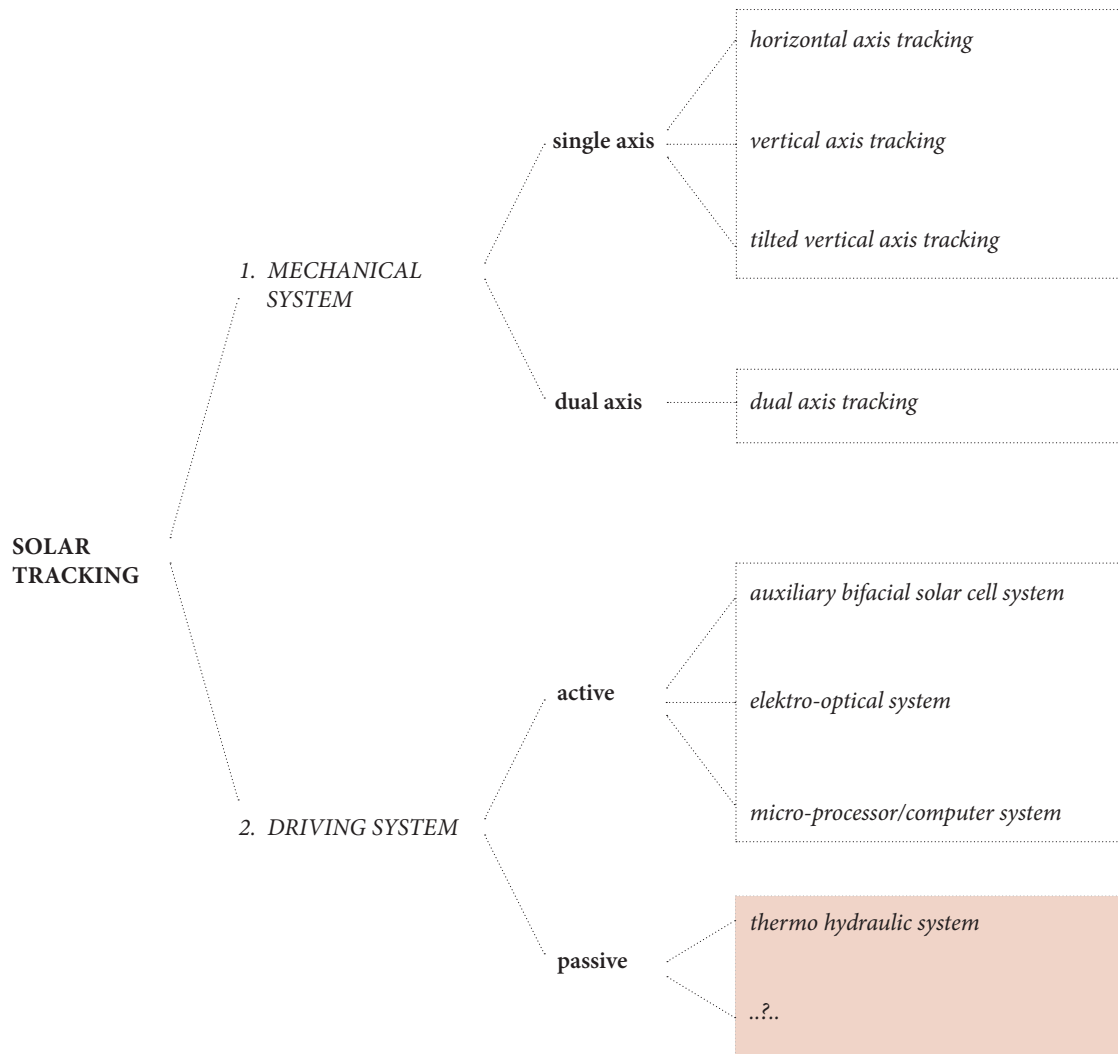
3

noon: less high peak  
morning/afternoon: higher efficiency

BETTER


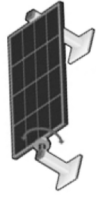


### 3. Solar tracking systems

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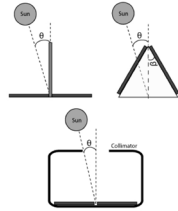
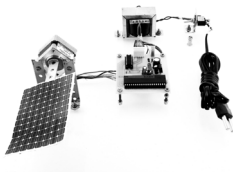
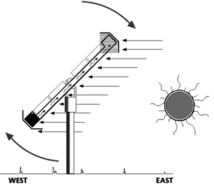


#### 4. Existing mechanical systems

	SINGLE AXIS			DUAL AXIS
	HORIZONTAL AXIS TRACKING	VERTICAL AXIS TRACKING	TILTED VERTICAL AXIS TRACKING	DUAL AXIS TRACKING
				
<i>θ and ζ</i>	$0^\circ < \theta < 90^\circ$ and $\zeta = 0^\circ$	$\theta = 90^\circ$ and $-90^\circ < \zeta < 90^\circ$	$\theta = \pm 36^\circ$ and $-90^\circ < \zeta < 90^\circ$	$0^\circ < \theta < 90^\circ$ and $-90^\circ < \zeta < 90^\circ$
<i>Description</i>	Tracks sun <b>Altitude</b> changes within day and during seasons	Tracks Sun <b>Azimuth</b> changes within day and during seasons	Tracks sun <b>Azimuth</b> changes within day and during seasons	Tracks sun <b>Altitude</b> and <b>Azimuth</b> changes within day and during seasons
<i>Advantages</i>	<ul style="list-style-type: none"> <li>- Relatively simple/cheap (simple side supports)</li> <li>- Can be manually adjusted for only seasonal tracking</li> </ul>	<ul style="list-style-type: none"> <li>- Relatively simple/cheap (top-bottom supports)</li> </ul>	<ul style="list-style-type: none"> <li>- Good (similar) tracking characteristics for much lower cost compared to dual axis</li> </ul>	<ul style="list-style-type: none"> <li>- Very high performance potential especially with concentrated PV</li> <li>- Limited space requirements per output if combined with concentrated PV</li> </ul>
<i>Disadvantages</i>	<ul style="list-style-type: none"> <li>- Does not efficiently track daily Azimuth (East-West)</li> <li>- Prone to partial shading in low Latitudes (high sun)</li> <li>- Makes less sense in high Latitudes (low sun)</li> </ul>	<ul style="list-style-type: none"> <li>- Does not efficiently track sun Altitude change</li> <li>- Needs constant automatic tracking during the day (running cost)</li> </ul>	<ul style="list-style-type: none"> <li>- Needs constant automatic tracking during the day (running cost)</li> </ul>	<ul style="list-style-type: none"> <li>- Complicated structure</li> <li>- Expensive</li> <li>- Cost only justified for concentrated PV and high direct light values</li> </ul>
<i>Tracks Altitude</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●
<i>Tracks Azimuth</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●
<i>High performance</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●
<i>Low costs</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●
<i>Low maintenance</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●

DATA:  
Sampatakos, D. (2014). *Development of three dimensional PV structures as shading devices for a decentralized facade unit of the future* (Graduation Report). Delft: Building Technology TU Delft

## 5. Existing driving systems

	ACTIVE		PASSIVE	
	AUXILIARY BIFACIAL SOLAR CELL SYSTEM	ELEKTRO-OPTICAL SYSTEM	MICRO-PROCESSOR/ COMPUTER SYSTEM	THERMO HYDRAULIC SYSTEM
				
<i>Description</i>	A bifacial solar cell is fixed to the rotary axle of the tracker and is placed perpendicular to the main solar panel array. The sensor cell is connected directly to a motor, usually a DC electro motor. When the sun moves, the angle of incidence increases on the sensor cell, which at a point produces enough power to activate the motor and the solar panel array.	Two photo resistors or PV cells are used as sensors. These sensors are positioned near one another and have a divider, a tilted mount at a calculated angle, or use a collimator to create a useful current and/or voltage difference between the two sensors. The output of the comparing circuit powers a driver circuit, which in turn activates a motor and changes direction according to which sensor receives a higher amount of illumination.	The system uses algorithms to determine the position of the sun instead of using sensors. It only uses sensors to reduce error or calibrate the system. In many systems a cheap microprocessor such as a Programmable Interface Controller (PIC) will have the algorithm for tracking, while information is fed to a computer for analysis purposes.	The TrackRack™ from the company Zomeworks Corporation is a thermo hydraulic system consisting of two tube tanks which are placed at the sides of the photovoltaic panels. If the PV system is not aligned with the sun, the liquid in the tanks will heat unevenly resulting in pressure difference that will drive the liquid through a connecting pipe into the tube tank with the lowest temperature. Due to gravity, the shift in weight will cause the photovoltaic solar panels to rotate and face the sun.
<i>Advantages</i>	- Runs on own produced solar energy	- Runs on own produced solar energy	- No problems with cloudy or foggy days	- Cheaper than an active system - Needs less maintenance
<i>Disadvantages</i>	- Needs electrical devices - Problems are ascertained on cloudy or foggy days (very common in The Netherlands)	- Needs electrical devices - Problems are ascertained on cloudy or foggy days (very common in The Netherlands)	- Needs electrical devices - Uses electricity (running cost)	- Not as efficient as active solar tracking systems - Tends to be slowly particularly in the morning
<i>Uses sensor</i>	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●	NO ● ● ● ● YES ●
<i>Uses algorithm</i>	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●
<i>Hight accuracy</i>	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●
<i>Low costs</i>	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●
<i>Low maintenance</i>	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●	● ● ● ● ●

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figure

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