### SOLAR - COOLING FAÇADES:

# AN INTEGRATED FAÇADE DESIGN WITH THERMOELECTRIC COOLING SYSTEMS FOR OFFICE BUILDINGS IN ATHENS

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#### SOLAR - COOLING FAÇADES:

# An Integrated Façade Design with Thermoelectric Cooling Systems for Office Buildings in Athens

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# Table of Contents

Ac	knowledge	ement	7
Ak	ostract		8
1.	Research	Framework	10
	1.1.	Background - Problem Field	10
	1.2.	Problem Statement	12
	1.3.	Objective	12
	1.4.	Research Questions	14
	1.5.	Approach and Methodology	15
	1.8.	Planning and Organization	18
	1.9.	Relevance	20
2.	Thermoele	ectric Technology	22
	2.1.	Technology description and principles	22
	2.2.	End-use applications	24
	2.3.	Types of TEMs	24
	2.4.	TE Technology Advantages and Disadvantages	24
	2.5.	Technical Maturity	25
	2.6.	Calculation of Thermoelectric Module Performance	26
	2.7.	Capacity of TE systems and comparison to vapor-compression systems	27
	2.8.	COP - Coefficient of Performance	28
	2.9.	Façade integration	29
3.	Photovolta	aic Technology	33
	3.1.	General Information and BiPVs	33
	3.2.	Available PV Technologies	34

	3.3.	Facade integration/application possibilities	37
	3.4.	Prospective development of PVs	38
4.	Climate		41
	4.1.	Climate of Greece - Mediterranean climate	41
	4.2.	Climate profile of Athens	44
_	4.3.	Urban Heat Island Effect	48
Э.	Building Ph		51 
	5.1.	Principles for heating, cooling, ventilation and lighting in Mediterrar	
	conditio		51
	5.2.	Vernacular Architecture	53
6	5.3.	Indoor Environmental Comfort  dings in Athens	55 <b>59</b>
٠.	6.1.	General Information and Statistics	59
	6.2.	Overview of façades of office buildings in Athens	62
	6.3.		
		Building Index	64
	6.4.	Categorization criteria according to facade construction principles	65
	6.5.	Summary office facades	67
	6.6.	Final scheme per facade category	69
	6.7.	Defining the 'Typical office building of Athens'	70
<b>7</b> .	6.8. <b>Calculation</b>	Drawings of Current Situation as (Design Builder)	71 <b>78</b>
	7.1.	Method Description	78
	7.2.	Design Builder Model and Settings	81
	7.3.	Results and Evaluation	85
	7.4.	Passive Optimization - Phase 3	86
	7.5.	Hand Calculations	93
	7.6.	System Sizing	97
8.	Design		102
	8.1.	Design Guidelines	102
	8.2.	System Design	105
	8.3.	Condensation and internal surface problems	108
	8.4.	Design Process	110
	8.5.	Architectural Possibilities	113
	8.6.	Final Design - Components	116
	8.7.	Visualization	123
	8.8.	Functional Schemes	126
9.	Daylight St	udy	128
	9.1.	Daylight Factor, Luminance and Illuminance	128
	9.2.	Solar Geometry	132
	9.3.	Sun Shading Device	133

10. Conclusions	134
11. Reflection	137
12. References	139
APPENDIX I - OFFICE BUILDINGS CASE STUDIES	148
APPENDIX II - BUILDING 12 (EXISTING) - DRAWINGS	164
APPENDIX III - GENERAL URBAN PLAN OF ATHENS	170

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Delft, 25th January 2018.

## Abstract

Nowadays the use of renewable energy resources is a necessity. Approximately 13% of the energy spent in Greece comes from renewable energy resources, however a significantly higher percentage is essential in order to meet the European standards by 2020. A prompt solution is the in-situ energy generation. Additionally, the harmful emmisions of the various air-conditioning and refridgerating systems need to be eliminated. The current master thesis involves the use of solar energy for indoor temperature regulation, mainly for cooling purposes. This is achieved by the use of two different technologies; the photovoltaics and the thermoelectrics. A series of PV panels convert the solar energy to DC power, which is supplied to the thermoelectric devices. The TE modules are able to create temperature difference and depending on the direction of the DC current, they can function either for cooling or for heating. The system is 100% emissionfree and can operate entirely on renewable energy. Location of the project is set to Athens, Greece, a city with rather high air-conditioning demands during summer and high solar irradiation all year long, traits which make it very favorable for a PV-TE solar cooling application. Objective of the thesis is to develop a solar cooling facade concept which, along with the implementation of passive design strategies, is able to cover the cooling and heating demands of a certain office space. Considering the context, the local climate, the prominent vernacular building strategies have been studied. Moreover, a field research and analysis of 25 case study buildings has been carried out leading to the definition of the 'typical office building' in Athens. Based on the typical office, a passive optimization with the implementation of multiple passive strategies has been carried out resulting in the optimum scenario. The PV and TE system has been calculated and designed according to the optimum passive scenario and is applied on a case-study building. A range of architectural possibilities is explored, based on the typical office buildings of the area.

# RESEARCH FRAMEWORK



# 1. Research Framework

#### 1.1. Background – Problem Field

#### Context of the research project

In the modern society the habits of people involve spending great amount of time daily inside buildings. It is therefore important that the indoor environment provides comfortable conditions or if not, that appropriate measures are taken in order to achieve the desired level of comfort. Athens is the capital, most influential and largest city of Greece and with no doubt people's habits involve spending much time indoors.

Furthermore, the regulation of indoor environment conditions involves the use of energy in a very large degree. Under this scope somebody would reasonably wonder about the sources of the energy used. On the following map (Figure 01) is shown the share of renewable energy in gross final energy consumption. The percentage for Greece is 15.4% in Greece against 16.1% in European average. According to information from EUROSTAT, the goal for 2020 is to raise this percentage up to 18%.

In the greater discussion of energy resources, the buildings play a very bold role. This is clearly expressed in the following piece of legislation from 2014:

"Until December 31st 2020 all the newly constructed buildings in Greece ought to be nearly zero energy buildings, while after December 31st 2018 all the newly constructed buildings that host or belong to public authorities ought to be nearly zero energy buildings."

Decree of 2014 (K.∆.∏. 366/2014)

The need for using alternative sources of energy is now more urgent than ever. However, still in year 2017 the majority of buildings uses non-renewable energy resources for their needs. This points towards a general change in the way design has been carried out till now, change of habits, change of attitude.

On the one hand the necessity is imperative and highly significant, but on the other hand it does not always ask for complex treatment. The measures to be discussed in this paper employ simple climate and design means and in the boundaries of Zero Energy Buildings, these can be always regarded as the initial and most basic step before the use of mechanical means.

The Zero Energy Buildings (ZEBs) or Nearly Zero Energy Buildings involve in general two design strategies: minimizing the need for energy use in buildings through more energy-efficient measures, and adopting renewable energy and other technologies to meet the minimal energy needs. The building industry's advance toward zero energy means the probable integration of additional energysaving and clean energy producing components and systems. Energy saving in building envelopes, internal design conditions and building service systems are three main measures to minimize the energy demand in ZEBs. As to renewable energy application in ZEBs, the most commonly applied technologies are building-integrated PV technology, wind turbines technology and solar thermal technology.

#### **Basic Problem Analysis**

Generally, the thematology in this paper will revolve around the effort to improve the indoor environment conditions in the hot periods of the year while at the same time using renewable energy sources (solar energy) to the possible extent. In more detail, there is going to be explored the integration of solar cooling technology to the building envelope taking into consideration the climate conditions in Greece.

According to data of the Center of Renewable Energy Sources (CRES) the office buildings constitute the 3rd higher energy consumer. Moreover, as shown on Figure 03, the consumption in the average office building, the average share for cooling demand is approximately 9% of the total. What is more, the consumption of office and commercial buildings is in average the same throughout the whole country, despite the climate differences, contrary to other building categories like residential and hospital, whose demands vary significantly.

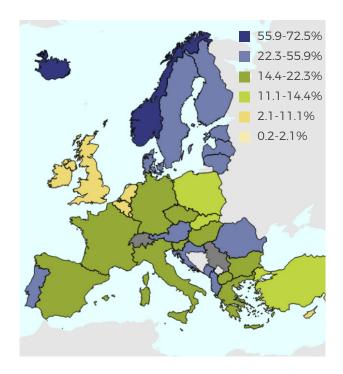


Figure 01: Share of renewable energy in gross final energy consumption (%). Source: EUROSTAT 2017.

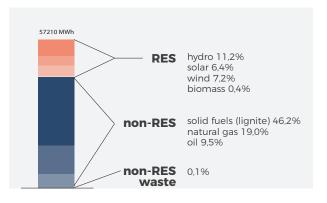


Figure 02: Fractions of gross energy consumption for 2013 (MWh). Source: Gaglia et al.

#### ENERGY CONSUMPTION $\,kWh/m^2$

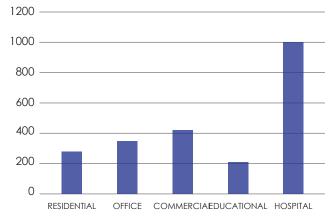


Figure 03: Energy consumption per building category.

Office buildings constitute the 3rd higher consumer.

Source: https://goo.gl/Lw2AZM

#### 1.2. Problem Statement

Taking into consideration the aforementioned problem analysis, the problem statement is:

- · Office space cooling constitutes a significant percentage of energy consumption.
- · There are many buildings which use non-renewable energy resources in year 2017.

#### 1.3. Objective

#### **General objective**

Objective of this graduation project is to develop a solar cooling facade concept and module. In general, this means that the solar energy is used and transformed accordingly in order to be able to cool an indoor space. Specifically, on this occasion PV panels capture and transform the solar energy into direct current, which flows through thermoelectric (TE) modules and ultimately generates cooling (or heating). This is summed up on Figure 04. The detailed function of the TE modules will be further explained in the chapter "Photovoltaic Technology" on page 33.

#### **Research sub-objectives**

- · Create understanding of the involved technologies and explore the state-of-the-art applications
- · Provide with adequate background information on the climatic characteristics of the study location.
- Find out to what extent can passive strategies be adequate to achieve indoor thermal comfort and what is the delta that needs to be covered by thermoelectric cooling.
- · Determine the 'typical office building' in Athens.

#### **Design sub-objectives**

- · Explore and discuss the architectural possibilities for TE solar cooling application.
- · Provide with an exemplary design proposal of facade component on a selected case study building.

#### **Final products**

Final product is a façade design component which integrates both bioclimatic strategies and solar thermoelectric cooling. (passive and active approach).



Figure 04: Functional scheme of facade integration and energy flow

#### **Constraints**

The first constraint regards the selection of a sole sun-driven cooling solution. Among the existing solar cooling technologies - thermoelectric, electric, sorption, dessicant, thermomechanical - (A. Prieto et al. 2017) the thermoelectric cooling has been selected. Cooling application is the main object of the research, as it has higher demand than heating in the context of Athens.

Office buildings present extra challenges compared to residential buildings due to higher technical demands and simultaneously have more fixed user patterns (compared to residential) and thus are more suitable for exploration.

Lastly, the location has been set to Athens, Greece. The intense solar irradiation throughout the year makes Athens a good location for a case study.

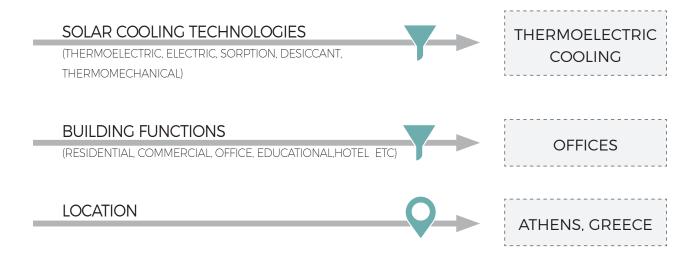


Figure 05: Scheme of the boundary conditions: Constraints

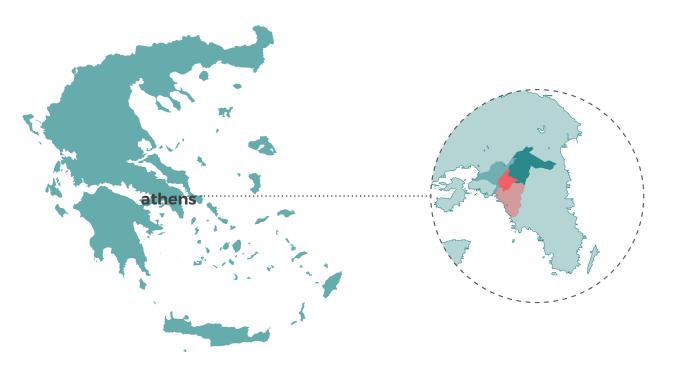


Figure 06: Geographical position of Athens in Greece and extract with center, north, west and south suburbs.

#### 1.4. Research Questions

#### Main research question

How can a façade regulate the indoor temperature in an office building located in Athens by using bioclimatic strategies and thermoelectric technology in order to reduce the amount of energy needed for cooling?

#### Main design question

Which is an architectural design that integrates PV and TE systems for cooling/heating generation and is suitable for a typical office building in Athens?

#### **Research sub-questions**

- · What is the state-of-the art of PV and TE technology and what are the future potentials?
- Which are the most distinctive climate characteristics that need to be considered and which passive design strategies can be applied to an office façade in Athens?
- To what extend can these building physics strategies be adequate for the achievement of indoor thermal comfort? (How far can we go with passive strategies?)
- · What is the typical office building in Athens?

#### **Design sub-questions**

- · What are the architectural possibilities for TE solar cooling application?
- · What is an exemplary design proposal of facade component on a case study?

#### 1.5. Approach and Methodology

#### Literature review

In the first phase, (P2, P3 and also before the P4), literature has been studied regarding the theoretical background. More specifically, the main topics studied are: thermoelectric technology for cooling (principles, applications, potential and performance), photovoltaic technology, climate data for Greece and Athens and bioclimatic strategies for reduction of heating, cooling and ventilation demands.

#### Field research

During the study of office buildings and facades of office buildings in Athens there are collected photographs depicting office facades which are used for future reference.

#### **Data Analysis**

In order to get acquainted with the current building condition, there are collected data from the Greek Statistic Service and the Organization for the Master Plan and Environmental Protection of Athens (maps, statistic tables) and analysed in order to find the percentage of buildings which are used as offices, their exact regions in the city and their age.

#### **Dynamic Calculations (Simulations)**

The typical building is tested for: Cooling Demands (annually, summer design week and summer design day) and Cooling Design Capacity (summer design day). For a certain number of passively optimized scenarios the Cooling Demand in summer design day and the Lighting Demand (annually) are simulated in order to end up to the optimum scenario that employs only passive design strategies. The Design Builder software is used for the passive optimization. Additionally there are carried out simplified numerical calculations for the system's cooling capacity for one case. For light study is used the Velux Daylight Visualizer 2 software.

#### Design Task

The design task includes a façade design proposal, after the completion of the basic literature review, and the system sizing.

In the following schemes is presented in more detail the work flow and the research methodology table (what-why-how) as well as the corresponding research sub-questions for each research topic.

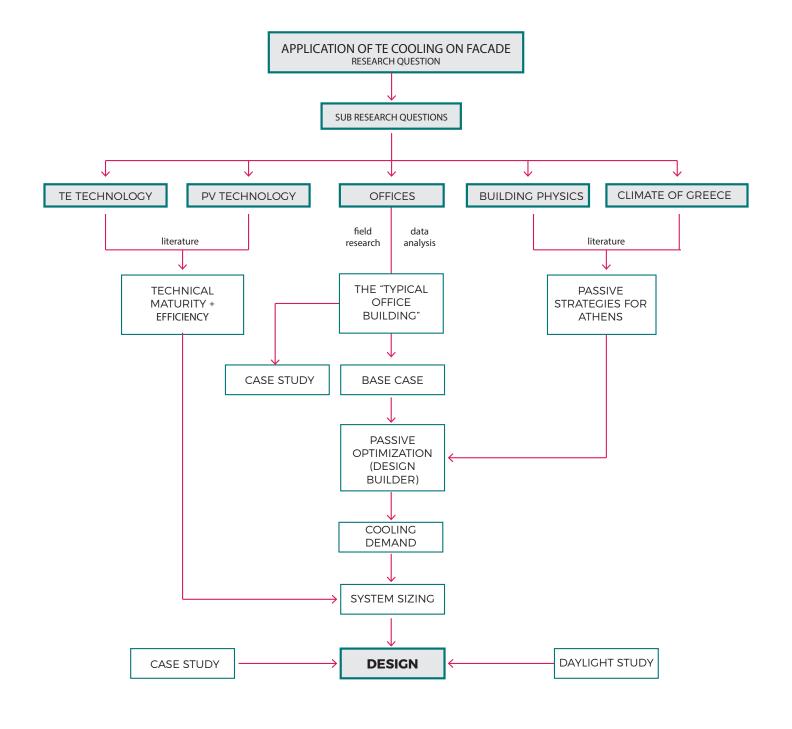


Figure 07: Work Flow Scheme

	Research Part (what)	Objective (why)	Method (how)	Corresponding research part (subquestions)
а	TE cooling technology (theoretical background)	<ul><li>technical maturity</li><li>capacity</li><li>commercial</li><li>products</li><li>potential</li></ul>	- literature review	- What is the state-of-the art of PV and TE technology and what are the future potentials?
b	PV technology	> technical maturity > efficiency > potential	- literature review	- What is the state-of-the art of PV and TE technology and what are the future potentials?
С	Climate (theoretical background)	> context	- literature review	- Which are the most distinctive climate characteristics that need to be considered in this design?
d	Building Physics (theoretical background)	> passive strategies > vernacular examples > comfort level	- literature review	- Which are the most distinctive climate characteristics that need to be considered and which passive design strategies can be applied to an office façade in Athens? - How far can we go with passive strategies?
е	Office buildings in Athens (empirical research)	> context > available building stock > typical building	- site observation - case study analysis - data analysis	- What is the typical office building in Athens?

Figure 08: Research methodology in regard to research part, objective, method and corresponding research subquestion.

#### 1.8. Planning and Organization

Regarding the planning and the division of the work, the following scheme gives an overview. The research question is related to the theoretical research, which are divided into separate parts:

Research about offices in Athens, concerning numbers, regions and common façade design expressions. Aim is to create an understanding of the existing situation and approximately estimate the annual demands in cooling.

Research about thermoelectric (TE) technology, examining the principles of function, the current end-use applications and capacity of the TE systems. Aim is to examine the potential of the system and explore its potential for façade integration in order to reduce a building's cooling demands.

Research about bioclimatic strategies according to Building Physics. As this project pursues to suggest a cooling solution, the emphasis in this research is given on cooling strategies. There are going to be briefly investigated ways in which the Greek vernacular architecture has dealt in the past with the space cooling challenge. Aim is to find which of the discussed strategies are suitable for use in this situation.

Research about the climate profile of Greece and Athens. Aim is to justify the choice of selecting a solar technique and show the potential of application in Athens.

Last but not least, the state-of-the-art of photovoltaic and available commercial products is looked into.

The structure of this report follows these thematic categories.

Before the P3 the research continues and afterwards, steps towards the passive optimization are being taken. The system sizing is calculated, as well as the final cooling demands. The first concept is designed. Also the daylight study takes place, as part of the façade design parameters.

The time frame and organization is given on Figure 09.

Figure 09: Time plan

#### 1.9. Relevance

#### Societal relevance

The societal relevance of the current graduation project lies on the following main factors: reduction of the urban heat island effect, environmental-friendly cooling solution, façade design and effect on the image of the city.

To be more specific, the need for cooling is very strong in Athens, especially in the center. By the use of strategic climate design, appropriate materials and integration of the thermoelectric technology, the project pursues to solve the problem in a sustainable and to the possible extent nearly-zero-energy solution.

As for the significance of the façade design, the majority of the existing building stock in Athens dates already 30-60 years. Among the existing office buildings there are many which are outdated and not properly or not at all maintained. The photographs in the chapter about office buildings can provide a rather representative image of this. Besides, the use of air-conditioning units is the most common means of space cooling but the current demands imply that it be replaced with a more environmental-friendly solution, such as the proposed design. Nonetheless, by designing a façade system we make a bold statement in the urban image.

#### Scientific relevance

Concerning the scientific relevance of the current thesis, the main points are the following: research and application of thermoelectric technology for façade systems, nearly-zero energy approach for cooling.

The commercial development of thermoelectric modules for the space heating and cooling is currently non-existent, on the grounds of the thermoelectrics' low efficiency compared to other cooling technologies (eg vapour compression systems). Considering, however, the potential technology development and the benefits of thermoelectrics (no emissions, no noise production, low maintenance, small size etc) against other technologies, a study employing this technology would be more beneficial in the future despite the current low performance.

#### **Projected innovation**

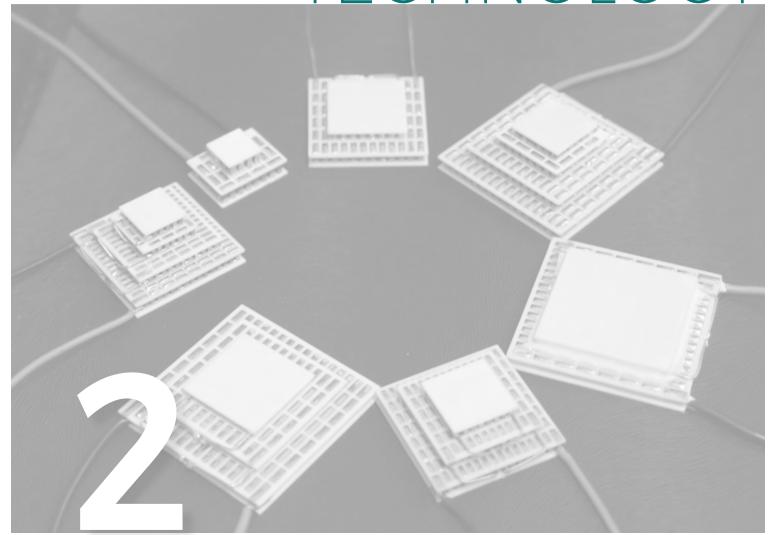
As it has been mentioned previously, the current commercial applications do not include thermoelectric modules as a solution for space cooling. However, the current project pursues to study a way of integration of TEs to a façade component. It is a challenging task, especially because the current situation is not very promising, but innovative in the sense that it explores the potential future trends.

Moreover, the thermoelectric technology demonstrates a substantial innovation as it is 100% emission-free, so it does not harm the environment.

#### Embedding in research programs and relationship with other research projects

The current graduation project follows the guidelines of the PhD research of Alejandro Prieto Hoces with thematic "Coolfacade. Architectural integration of solar driven cooling strategies into the curtain-wall". This thesis focuses on one of the examined technologies and investigates further the application of TEs in an integrated design providing a range of architectural possibilities and an exemplary design proposal.

THERMOELECTRIC TECHNOLOGY



# 2. Thermoelectric Technology

#### 2.1. Technology description and principles

Thermoelectric systems are solid-state systems that convert electrical energy into temperature gradients that drive thermal-energy flows. A thermoelectric element consists of two thermoelectric semiconductors: an n-type conductor (containing negative charge carriers) and a p-type conductor (containing positive charge carriers), connected electrically in series and thermally in parallel, mounted between two ceramic surfaces, shown on Figure 10. The ceramic surfaces provide electrical insulation and thermal conduction from the elements to the heat sinks (Yang et al. 2008).

The physical phenomenon that describes both the energy harvesting and thermal conditioning behavior of thermoelectric materials is the Seebeck effect. When placed within a thermal gradient, thermoelectric materials accumulate charge internally on both the hot and cold surfaces. If the temperature difference is great enough between the hot and cold surfaces, the buildup of charge on the opposite sides of the material creates a voltage difference resulting in a flow of current from the material. Conversely, when a voltage is placed across a thermoelectric material, the resulting current moves electrons from one surface to another. This phenomenon, which creates a thermal gradient, is known as the Peltier effect. Stacking multiple thermoelectric devices in series can increase the generated temperature difference.

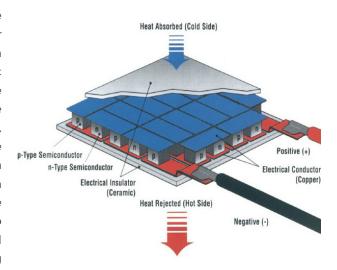


Figure 10: Thermoelectic (TE) module 3D scheme. Source: lairdtech.com

Ideal thermoelectric modules have low thermal conductivity and high electrical conductivity properties, but most materials feature both high thermal conductivity and high electrical conductivity. Scientists rate thermoelectric materials using a dimensionless figure-of-merit based on their physical properties and thermal performance. Known as ZT, this figure compares a material's thermoelectric properties with its thermal conductivity and electrical resistivity in the following relationship:

$$ZT = \frac{\alpha^2 T}{\rho \lambda}$$
 (1)

 $\alpha$ : (or S) Seebeck coefficient

T: absolute temperature

ρ: electric resistivity

λ: (or k) thermal conductivity

A thermoelectric material's ZT is one of the most important factors in determining its effectiveness and, therefore, the efficiency of the system into which it is placed.

The maximum theoretical efficiency achievable is described by the following formula:

$$\Phi = \frac{(1+ZT)^{0.5}-T_{H}/T_{L}}{(1+ZT)^{0.5}+1}$$
 (2)

As an example of this equation, we can observe the following scheme (Figure 11), for  $T_H=40^{\circ}$ C and  $T_L=0^{\circ}$ , which shows that state-of-the-art materials have a maximum theoretical  $\Phi\approx0.18$  the maximum reported ZT value of 2.4 results in theoretical  $\Phi\approx0.37$ , and that a ZT value of approximately 4.4 would be needed to achieve a theoretical  $\Phi\approx0.50$ , which is achievable by today's vapor compression technology.

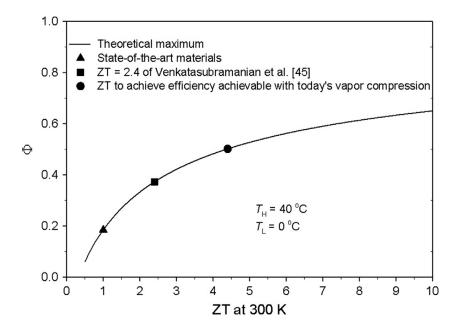


Figure 11: Second Law efficiency as a function of non-dimensional figure of merit (ZT). Source: Liu et al. 2015

#### 2.2. End-use applications

The TEs do not have any commercial application on façade systems yet. Currently the commercial end-use applications of TE include:

- · automotive
- · consumer products
- · industrial waste heat
- · marine
- wearables
- aerospace
- · self-powered sensors

#### 2.3. Types of TEMs

The applications of TEMs include industrial and domestic use. There is variety in geometry and according to the function. In the following pictures are presented some commercially available TE modules of the company "Kryotherm".

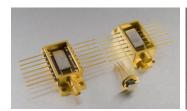








Figure 12: Various types of commercially available thermoelectric modules.

From left to right: thermoelectric coolers for radio applications, standard single-stage thermoelectric coolers, multi-stage thermoelectric coolers, round thermoelectrics. Source: http://kryothermtec.com

#### 2.4. TE Technology Advantages and Disadvantages

#### **Advantages**

Overall the thermoelectric technology offers a number of benefits with the most crucial of them being the absence of moving parts and thus the absence of noise production and low maintenance requirements. Besides, due to their small size, thermoelectric modules could be packaged and implemented to cool individual rooms or portions of rooms, rather than an entire building (Brown 2010). Some of the most significant benefits are listed below.

- · Solid State Construction (no moving parts)
- Precise temperature Control
- · Vibration-free operation and shock/vibration resistance
- No acoustical or electrical noise
- Low maintenance and high reliability (20-30 years life expectancy)

- · Performance in any physical or gravitational orientation, including upside down or sideways
- Size and performance output highly scalable 2mm to 60mm. Diffusion barriers enable superior long term thermal stability and high reliability
- Operates in zero-gravity
- · Withstands the g-force of space and military applications
- · Not environmentally harmful due to absence of FCs, CFCs and HFCs
- · Fully scalable microW to kW of heatpumping or power output depending on design

#### **Disadvantages**

- · Low efficiency compared to other cooling technologies (eg vapor-compression systems)
- · There is a trade-off between COP and energy output
- Need for battery as backup
- Need for auxiliary equipment, such as heat sinks, batteries and fans

#### 2.5. Technical Maturity

In general, the Peltier and the Seebeck effect have been known and studied since the early 1800s, however, the current HVAC and façade applications are in early research and development phase.

According to Goetzler, 2014, the market maturity towards thermoelectrics is estimated as 'low', as thermoelectric technology is widely commercially available in very low-load applications such as electronics cooling and small residential refrigeration. However, it has not yet been commercialized to meet HVAC loads. At the same time, there are many stakeholders who focus on thermoelectric generation but few are promoting their development for HVAC applications.

Equation 1 (paragraph 2.1 on page 22) aims to describe the efficiency of a thermoelectric system by using the ZT number. ZT is dependent on the physical and electrical properties of the materials used. The two most efficient materials are the  ${\rm Bi}_2{\rm Te}_3$  (bismuth telluride) and the  ${\rm Sb}_2{\rm Te}_3$  (antimony telluride). Yet, the current thermoelectric systems use materials with ZTs around 1.0, however, for most space-cooling applications, TE devices must achieve a ZT of 3.0 or greater to be competitive with vapor-compression technology (Dieckmann 2011).

#### 2.6. Calculation of Thermoelectric Module Performance

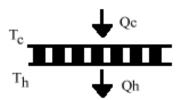
There are five variable parameters applicable to a thermoelectric module that affect its operation. These parameters include:

- I the input current to the module expressed in amperes
- $V_{in}$  the input voltage to the module expressed in volts
- $T_{h}$  the hot side temperature of the module expressed in  $^{\circ}$ K
- T<sub>c</sub> the cold side temperature of the module expressed in °K
- $Q_c$  the heat input to (or heat pumped by) the module expressed in watts

In order to calculate module performance it is necessary to set at least three of these variables to specific values. Two common calculation schemes involve either (a) fixing the values of  $T_{h'}$ , I, and  $Q_c$  or, (b) fixing the values of  $T_{h'}$ , I and  $T_c$ . For the computer-oriented individual, a relatively straightforward calculation routine can be developed to incrementally step through a series of fixed values to produce an output of module performance over a range of operating conditions. (Ferrotec 2017)

#### Single-stage module calculations

These equations mathematically describe the performance of a single-stage thermoelectric module. When entering numerical data, temperature values must be expressed in degrees Kelvin (°K). Calculations of the various parameters should be performed in the order shown.



a) The temperature difference (DT) across the module in °K or °C is:

 $DT = T_b - T_c$ 

Figure 13: Scheme showing the heat flow between the hot and the cold plate of a TEM Source: Ferrotec

b) Heat pumped (Q<sub>c</sub>) by the module in watts is:

$$Q_c = (SM \times T_c \times I) - (0.5 \times I2 \times RM) - (KM \times DT)$$

c) The input voltage (V<sub>in</sub>) to the module in volts is:

$$V_{in} = (SM \times DT) + (I \times RM)$$

d) The electrical input power (P<sub>in</sub>) to the module in watts is:

$$P_{in} = V_{in} \times I$$

e) The heat rejected by the module (Q<sub>b</sub>) in watts is:

$$Q_h = P_{in} + Q_c$$

f) The coefficient of performance (COP) as a refrigerator is:

$$COP = Q_c / P_{in}$$

(Ferrotec 2017)

#### 2.7. Capacity of TE systems and comparison to vapor-compression systems

A small comparison of thermoelectrics to other cooling technologies has been already made in previous paragraph. In order to get a better view, the thermoelectrics will be compared to the current vapor compression technology and to the ideal Carnot efficiency.

According to Zhao, the average commercial TE unit currently has effectiveness Qav=63W (info collected from Figure 15).

Furthermore, Figure 14 displays the cooling coefficient of performance (COP) of thermoelectric coolers with different ZT values along with the ideal Carnot efficiency. Moreover, with any value smaller than ZT=3.0, the thermoelectrics will not be able to compete with vapor compression systems.

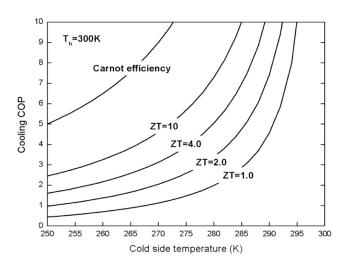


Figure 14: Cooling COP of a thermoelectric module under optimum electrical current with fixed hot side temperature of 300K.

Source: D. Zhao et al. 2014

Table 2 Summary of commercially available thermoelectric modules from published literature.

Module type	Company	Q <sub>max</sub> (W)	ΔT max (°C)	Dimensions (mm)	Ref.
CP1.4-127-045	Melcor Corp.a	72 <sup>b</sup>	75 <sup>b</sup>	40 × 40 × 3.8	[34]
CP1.4-127-045L	•	72	65	$40 \times 40 \times 3.3$	[105]
CP1.4-127-06L	Melcor Corp.	51.4	67	$40\times40\times3.8$	[49,67,96]
CP1.4-7-06L	Melcor Corp.	2.8	68	$10 \times 10 \times 3.8$	[106]
CP2-127-06	Melcor Corp.	120	68	$62 \times 62 \times 4.6$	[76]
CP2-127-06L	Melcor Corp.	120	67	$62\times62\times4.6$	[47,68,83,87]
HT8-12-40	Melcor Corp.	72	67	$40\times40\times3.5$	[76]
PT4-12-40	Melcor Corp.	32	67	$40\times40\times4.1$	[105]
TEC1-12706	HB Corp.	50	66	$40\times40\times3.8$	[46,107]
TEC1-12708	HB Corp.	71	66	$40\times40\times3.5$	[108,28]
TEC1-6308	HB Corp.	37.4	67	$40\times20\times3.8$	[109]
6L	Marlow Ind.	50	66	$40\times40\times3.9$	[75,88]
DT12-4	Marlow Ind.	36	66	$30\times30\times3.3$	[51]
UT8-12-40-RTV	Ultra TEC Series	72	_	_	[103]
TB-127-1.4-1.2	Kryotherm Corp.	75	70	$40\times40\times3.5$	[4]
TB-127-1.4-1.5	Kryotherm Corp.	60	70	$40\times40\times3.9$	[79]
TB-199-2.0-0.9	Kryotherm Corp.	310	69	$62\times62\times3.2$	[110]
TECA 980-127	TECA Corp.	83.2	72	$15.7\times15.7\times1.3$	[110]
9500/127/085B	Ferrotec Corp.	80	72	$40\times40\times4$	[111]
HM3930	Acetec Co.	16.7	69	$30\times30\times4.7$	[101]
CP10-127-05	Laird Tech.	34.3	67	$30\times30\times3.2$	[35]

<sup>&</sup>lt;sup>a</sup> Melcor Corporation has been acquired by the Laird Group PLC ("Laird") and its

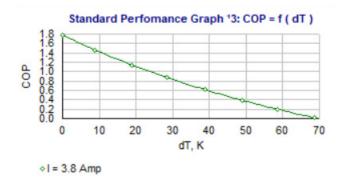
Figure 15: Summary of commercially available thermoelectric modules from published literature. Source: D. Zhao et al. 2014.

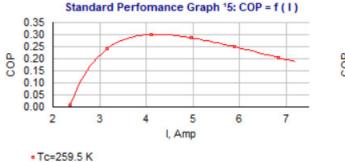
products have adopted the name of the new company [112].  $^b$   $Q_{\rm max}$  and  $\Delta T_{\rm max}$  are evaluated by manufacturers at hot side temperature 297 K or 300 K.

#### 2.8. COP – Coefficient of Performance

The coefficient of performance is an important number for the sizing of the system and determination of the overall efficiency.

The following graphs are provided by "Kryotherm" and display the COP in relation to dT [K], I [A] and U[V] for the module "FROST-74". As we can observe, the COP is directly dependent on the temperature difference (dT) and also the electrical power in the circuit. The values of COP vary between 0 and 1.8 for the particular module and it decreases when dT increases.





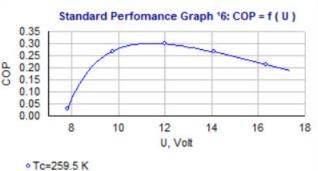


Figure 16: COP=f(dT) Figure 17: COP=f(I) Figure 18: COP=f(U)

Standard performance graphs for TEM FROST-74 by 'Kryotherm'

By various experimental tests authors have

The difficulty to define an average COP has been reported also by

#### 2.9. Façade integration

By utilizing a TE unit on a façade system, the main function principle is the use of solar energy, which is converted to electrical voltage through a PV panel (on the external skin of the building). Subsequently, the TE generator by using the DC current created, creates a temperature difference on the two opposite plates. The excessive heat on the hot side is disposed on a heat sink, while the cold side is cooling down the indoor area of the building. The Figure 19 illustrates the concept clearly.

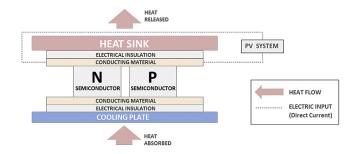


Figure 19: Functioning scheme of a thermoelectric cooling module.

Source: Prieto et al. (2017)

other ceramic face when DC curr

A thermoelectric module "pumps" heat from one ceramic face to the other ceramic face when DC current is applied. Unlike the compressor in a standard refrigeration system that pumps Freon, thermoelectric modules use electrons to transfer heat. Thermoelectric modules can also work in reverse, generating DC current (power) if one side is hot and the other is cold. The voltage and current generated in the circuit depends on many factors including the materials' inherent ability to conduct electricity and produce a voltage given a temperature difference.

As far as the TEM façade integration is concerned, it is currently in a R&D phase, so no commercial products are available. However, there is significant research and experimenting towards prospective façade integration. Several authors have carried out experiments by building prototypes and measuring the performance of a thermoelectric system.

More specifically, Z. Liu et al. (2015) and M. Ibanez-Puy et al. (2015) describe the concept of air-based and solid-based types of TE facade integration, while they have tested the performance on prototype model. X. Xu et al. (2007), (2008) describes the application with water being the main heat transfer medium and also has performed measured test on a prototype.

What is important to consider in these references is the arrangement and the components used for the construction of the prototypes. The materials are also important mainly due to their heat transfer properties.

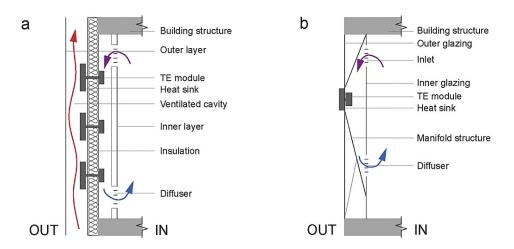


Figure 20: Air-based facade types, source: Prieto et al. (2017) based on information by Liu et al. (2015) and Ibanez-Puy et al. (2015).

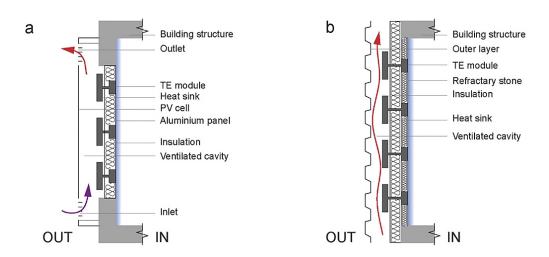


Figure 21: Solid-based facade types, source: Prieto et al. (2017) based on information by Liu et al (2015) and Ibanez-Puy et al. (2015).

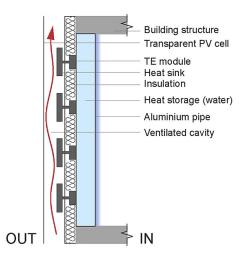


Figure 22: Water-based facade types, source: Prieto et al. (2017) based on information by Xu et al. (2007), (2008).

#### **Up-scaling potential**

The thermoelectric modules in the market currently have small scale applications, mainly for electronic circuits, so it is expected that the size of the modules be small. On average a square TEM has dimensions 40mm\*40mm - 62mm\*62mm.

On the other hand, an application on facade has a different scale and the question of the up-scaling potential is very reasonable. Interesting is the large-scale application of Peltier modules "Thermagy" developed by company RGS. The application deals with the conversion of waste heat  $(700^{\circ} - 1200^{\circ} \text{ C})$  into usable energy. This is the reverse function which is described by the Seebeck effect.

The thermoelectric technology allows for both functions and possible heating or cooling function according to the direction of the DC current. Therefore, it can be claimed that a similar large-scale module could be used in HVAC application for cooling or heating.

There is currently a performance beinh carried out in TATA steel, but unfortunately there is no technical information available in order to use such modules into the facade integration.





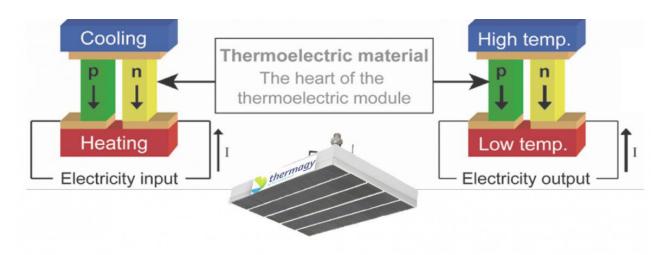


Figure 23: Functional scheme of "Thermagy" heat module developed by RGS company for large-scale applications. Test on TATA steel. Source: http://www.rgsdevelopment.nl/

PHOTOVOLTAIC TECHNOLOGY

# 3. Photovoltaic Technology

#### 3.1. General Information and BiPVs

Photovoltaics is a technology whereby sunshine is converted into electricity through the use of semiconductor technologies through the photovoltaic effect. Photovoltaic (PV) power is one of the most promising renewable energy technologies. It is estimated that just one hour of solar energy is consumed by humans in one year. Photovoltaics are solid-state devices that simply make electricity out of sunlight, silently and with little to no maintenance, no pollution and no significant depletion of material resources.

There is a big interest in the building of integrated photovoltaics (known as BiPV), where the PV elements are integral to the building, often servicing as the exterior weathering skin. The additional benefits of the BiPV are the following:

- The building itself becomes the PV support structure.
- · System electrical interface is easy just connect to a distribution panel.
- BiPV components displace conventional building materials and labour, reducing the net installed cost of the PV system.
- · On site generation of electricity offsets imported and often more carbon-intensive energy.
- Architecturally elegant, well-integrated systems will increase market acceptance.
- BiPV systems provide the building owners with a highly visible public expression of their environmental commitment.

Efficiency in photovoltaic solar panels is measured by the ability of a panel to convert sunlight into usable energy for consumption. The incident radiation flux could be better be described as the amount of sunlight that hits the earth's surface in W/m<sup>2</sup>.

#### **Space requirement**

To produce the same amount of electric energy, very different amounts of envelope surfaces are needed, depending on technology efficiencies and area orientations. As the efficiencies can range from 5% to almost 20%, the space occupied by a system, for the same orientation, can vary up to a 4 to 1 proportion.

A useful formula to quickly estimate the space required (Sr) to install 1KWp of PV, depending on the PV efficiency (eff), follows:

Sr [m<sup>2</sup>]=1/eff

#### 3.2. Available PV Technologies

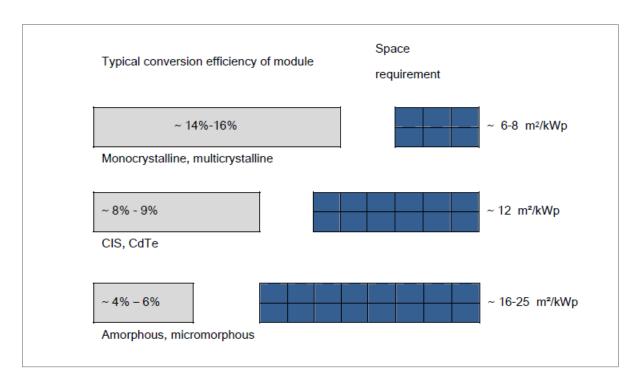


Figure 24: How the efficiency of the modules influences the space required.

Source: Munari Probst et al. © SUPSI, ISAAC- www.bipv.ch

#### Wafer based crystalline silicon cells

Monocrystalline cells (sc-Si), Multicrystalline cells (mc-Si) Solar cells made from crystalline silicon continue to account for about 85% of the cells used worldwide. Crystalline silicon cells (C-Si) are subdivided in two main categories:

#### MONOCRYSTALLINE CELLS

Monocrystalline cells are produced from silicon wafers; these wafers are extracted from a square block of single crystal silicon, by cutting slices of approximately 0.2 mm thick. This produces square cells of 100 to 150 mm sides with a homogeneous structure and a dark blue / blackish color appearance.

#### MULTICRYSTALLINE CELLS

For multicrystalline cells, the melted silicon is cast into square ingots where it solidifies into a multitude of crystals with different orientations (frost-like structure), which gives the cells their spotted and shiny surface.

To collect the electricity, very thin silver contacts are applied on the front of the cells, while a back contact is applied at the rear. Finally an anti-reflection coating is applied to enhance the light capture properties.

The efficiency of monocrystalline cells is currently the highest available on the market, ranging approximately from 17% to 22%, while multicrystalline cells are around 11% to 17%. To become a usable product, crystalline cells are electrically wired together and encapsulated into a substrate and a front covering material to create a solar module. The module can be provided with a frame, in order to improve its mechanical resistance. If it is kept unframed, the module is also called a "solar laminate".

#### Thin-film cells (second generation)





Figure 25: Mono- and poly- crystalline cells Source: Munari Probst et al.

Thin-film solar cells (also called "second generation" solar cells) and their contact are deposited directly on large area substrates, such as glass panels, stainless steel or polymers (square metresized and bigger) or foils (several hundred meters long).

Thin films can be seen as a microscopically thin layer of "disordered" photovoltaic material that gives the module surface a more homogeneous appearance.

With respect to wafer based crystalline technology, thin-film PV has a low-cost potential because its manufacture requires only a small amount of material, and is suited to fully integrate processing and high throughputs. Furthermore, the production process requires less energy than in the case of crystalline technology, since thin films are deposited at quite low temperatures (200 to 500°C vs about 1400°C for c-Si) and they can tolerate higher impurities than crystalline, thus needing less expensive purification of raw materials.

Thin-film solar cells are usually categorized according to the photovoltaic material used, the three main technologies being

- · Amorphous silicon (a-Si),
- · Copper Indium Gallium Selenide (CIS or CIGS) and
- Cadmium Telluride (CdTe).

The most common material is amorphous silicon. The production of amorphous or micromorphous silicon has undergone the most development (and this is why it is more diffuse than the other two thin film technologies) while the cadmium-telluride promises the lowest production costs and copper-indium-gallium diselenide achieves the highest conversion efficiencies (the new record value for flexible CIGS solar cells was reached in May 2011, by the EMPA laboratory, about 18.7% and nearly closes the "efficiency gap" to solar cells based on polycrystalline silicon wafers or CIGS thin film cells on glass).

Thin-film modules can be subdivided in three main categories, depending on the substrate that is used; in particular: glass, metal or polymeric material. In relation to the substrate material, thin film PV modules exist also in flexible and lightweight forms, as well as opaque or semitransparent.

Modules general surface appearances range from brown/orange to purple and black, with parallel lines more or less marked.

While for standard amorphous silicon cells the efficiency lies among 4% to 8%, some manufacturers produce modules with combined cells (multijunctions), reaching efficiencies around 10%. CIGS cells can reach 12%.





Figure 26: Amorphous silicon cell and module. Source: Munari Probst et al.

#### **Emerging and novel PV technologies (third generation)**

The category "Emerging" is used for those technologies which have passed the "proof-of-concept" phase, or could be considered as mid-term options compared with the two main established solar cell technologies (crystalline Si and thin-film solar cells). The category "Novel" will be used for developments and ideas which can lead to potentially disruptive technologies, but where there is not yet clarity on practically achievable conversion efficiencies or structure cost. Sometimes they are called also "third generation" cells.

Among the emerging PV technologies, organic solar cells play an important role. In fact, organic solar cells have already been subject of R&D for a long time, because they offer the prospect of very low cost active layer material, low-cost substrates, low energy input and easy up-scaling.

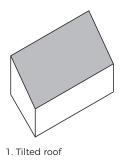
For this technology the active layer, at least partially, consists of an organic dye and small, volatile organic molecules or polymers suitable for liquid processing. Within 'organic solar cells', two technology branches can be distinguished. The first one is the hybrid approach, in which organic solar cells retain an inorganic component. The other one is the full-organic approach, with organic cells and organic substrates. The main challenges for both approaches are related to the efficiency and stability improvement, and the development of an adapted manufacturing technology.

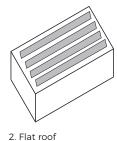
Dye-sensitized solar cells are an interesting example of the hybrid approach. They use an inorganic nano-structured substrate (titanium dioxide nano-particles), covered with a molecular dye that uses an artificial photosynthesis process to generate electricity. New polymer cells are also appearing in the market. The main advantage of these cells is a much lower cost than crystalline or thin film ones, but due to their low efficiency and durability (up to now) they are not yet considered competitive in the market. Their efficiencies range from 4% up to 10%.

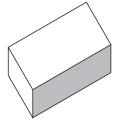
# 3.3. Facade integration/application possibilities

Among plenty of possibilities, the most basic Integration techniques are the following:

- Sloped roof
- Flat roof
- Façade applications
- Shading system







3. 90 facade

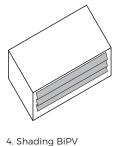


Figure 28: Possible configurations for BiPVs. Source: Prasad D. et al., own representation

On Figure 27 are summarized the annual data for averaged radiation incident for equator-pointed surfaces. The data are considering the area of Athens and can be used for solar system applications.

# Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m²/day)

											`		
Lat 37.9 Lon 23.73	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
SSE HRZ	2.14	2.88	4.00	5.37	6.43	7.46	7.36	6.62	5.21	3.44	2.18	1.73	4.57
K	0.45	0.46	0.49	0.54	0.57	0.64	0.65	0.64	0.60	0.51	0.42	0.40	0.53
Diffuse	0.89	1.19	1.58	1.92	2.13	2.00	1.89	1.68	1.48	1.27	0.98	0.81	1.49
Direct	3.32	3.72	4.46	5.60	6.60	8.26	8.31	7.79	6.49	4.48	3.02	2.59	5.40
Tilt 0	2.12	2.80	3.96	5.34	6.39	7.40	7.31	6.59	5.13	3.41	2.15	1.72	4.53
Tilt 22	2.91	3.49	4.53	5.63	6.34	7.13	7.13	6.80	5.80	4.21	2.82	2.37	4.94
Tilt 37	3.27	3.75	4.65	5.48	5.91	6.49	6.55	6.50	5.88	4.49	3.11	2.66	4.90
Tilt 52	3.45	3.81	4.53	5.05	5.19	5.52	5.64	5.86	5.65	4.53	3.23	2.82	4.61
Tilt 90	3.06	3.08	3.26	3.07	2.72	2.58	2.69	3.23	3.80	3.58	2.78	2.53	3.03
OPT	3.47	3.81	4.65	5.63	6.45	7.41	7.34	6.82	5.89	4.54	3.24	2.84	5.18
OPT ANG	59.0	49.0	37.0	21.0	9.00	4.00	6.00	17.0	33.0	47.0	55.0	60.0	33.0

## 3.4. Prospective development of PVs

On Figure 29, we can see individual predictions for many of the technologies we have introduced above. These predictions are made for a fixed module size (60 cells with dimensions of 156 mm x 156 mm). In terms of efficiency, this is equivalent to:

Approximately 20% for the low-end technologies (such as p-type multi-crystalline Al-BSF), up from about 17% today.

Approximately 26% for the high-end technologies (such as n-type monocrystalline IBC), up from about 21% today. This means that in 2027, an average premium module will be able to convert more than a quarter of all incident solar energy to electricity.

If these predictions prove to be correct, the result will be a very significant increase (roughly 20%, relative) on today's product. This will be a remarkable example of continued innovation for an industry, which, already more than 60 years old, is already very mature.

(https://cleantechnica.com/2017/08/15/efficient-will-solar-pv-future-10-year-predictions-industry/)

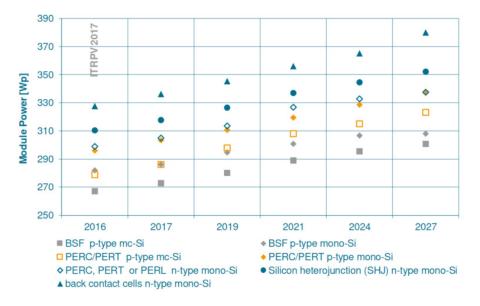


Figure 29: Most recent industry data (2016) and projections for the power of a module constructed from 60 cells with dimensions of 156 mm x 156 mm. Source: 2017 International Technology Roadmap for Photovoltaics

Last but not least, regarding the future possibilities according to NREL:

#### **III-V Multijunction Solar Cells**

The efficiency and concentration of III-V multijunction solar cells can be highly leveraged to reduce the cost of high-concentration photovoltaic systems. We are recognized for the invention, development, and technology transfer of a range of key device architectures, most recently including the inverted metamorphic multijunction (IMM) solar cell. In this device architecture, a metamorphic solar cell uses a compositionally graded buffer to incorporate nearly perfect single-crystal layers with different crystal lattice parameters. With this architecture, we have demonstrated ~46% efficiency with a four-junction IMM cell. We are extending the concept to five- and six-junction IMM solar cell devices that have the potential to exceed 50% efficiency at high concentrations. (https://www.nrel.gov/pv/high-efficiency-crystalline-photovoltaics.html)

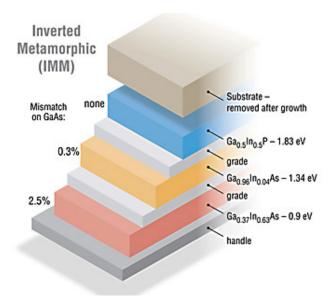


Figure 30: In the IMM cell, high-performance subcells are realized by: (1) inverting the usual growth order, growing mismatched cells last, (2) engineering a transparent buffer layer to mitigate dislocations, and (3) removing the primary substrate/attachment to the secondary "handle."

Source: NREL,

Classification	Efficiency	Area	Voc	Jsc	Fill Factor	Test Centre	Description
	(%)	(cm <sup>2</sup> )	(V)	(mA/cm <sup>2</sup> )	(%)	(date)	
III-V Multijunctions							
5 junction cell (bonded)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2- terminal[23]
(2.17/1.68/1.40/1.06/0.73	≥V)						
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27 <sup>a</sup>	86.7	AIST (2/13)	Sharp, 2 term. [24]
GaInP/GaAs(monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18 <sup>b</sup>	87.7	NREL (1/16)	Alta Devices, 2 term.[25]
Multijunctions with c-Si							
GalnP/GaAs/Si (mech. stack)	35.9 ± 0.5 °	1.002 (da)	2.52/0.681	13.6/11.0 <sup>d</sup>	87.5/78.5	NREL (2/17)	NREL/CSEM/EPFL, 4-term.[26]
GalnP/GaAs/Si (wafer bonded)	31.3 ± 1.1 °	3.981 (ap)	3.046	11.7 <sup>d</sup>	87.5	FhG-ISE (3/17)	Fraunhofer ISE, 2- term.[27]
GalnP/GaAs/Si (monolithic)	19.7 ± 0.7 <sup>c</sup>	3.943 (ap)	2.323	10.0 <sup>e</sup>	84.3	FhG-ISE (8/16)	Fraunhofer ISE[28]
GaAs/Si (mech. stack)	32.8 ± 0.5 <sup>c</sup>	1.003 (da)	1.09/0.683	28.9/11.1 <sup>d</sup>	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term.[26]
Perovskite/Si (monolithic)	23.6 ± 0.6 <sup>f</sup>	0.990 (ap)	1.651	18.09 <sup>e</sup>	79.0	NREL (8/16)	Stanford/ASU[29]
GalnP/GalnAs/Ge; Si(spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina 4-term.[30]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin- film)	14.0 ± 0.4 <sup>g, c</sup>	1.045 (da)	1.922	9.94 <sup>e</sup>	73.4	AIST (5/16)	AIST[31]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4% <sup>g, c</sup>	1.000(da)	1.342	13.45 <sup>h</sup>	70.2	AIST (10/14)	AIST[15, 32]

Abbreviations: a-Si, amorphous silicon/hydrogen alloy; nc-Si, nanocrystalline or microcrystalline silicon; (ap), aperture area; (t), total area; (da), designated illumination area; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; AIST, Japanese National Institute of Advanced Industrial Science and Technology.

Figure 31: Confirmed multiple - junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Source: http://onlinelibrary.wiley.com/doi/10.1002/pip.2909/full

<sup>°</sup>Spectral response and current-voltage curve reported in version 42 of these tables.

 $<sup>^{</sup>b}$  Spectral response and current-voltage curve reported in version 48 of these tables.

<sup>&</sup>lt;sup>c</sup>Not measured at an external laboratory.

 $<sup>^</sup>d$ Spectral response and current-voltage curve reported in the present version of these tables.

 $<sup>^{\</sup>rm e}\text{Spectral}$  response and current-voltage curve reported in version 49 of these tables.

<sup>&</sup>lt;sup>f</sup>Not stabilized, initial efficiency. Sasaki et al[24] reviews the stability of similar devices.

 $<sup>{}^</sup>g\mathrm{Stabilized}$  by 1000 hours exposure to 1 sunlight at 50°C.

<sup>&</sup>lt;sup>h</sup>Spectral responses and current-voltage curve reported in version 45 of these tables.

CLIMATE



# 4. Climate

# 4.1. Climate of Greece - Mediterranean climate

The climate of Greece is characterized as Mediterranean according to the Köppen-Geiger-Pohl climate classification system. Greece belongs to the Cs category and more specifically to the Csa sub-category, whose characteristics are given on the following table:

Descri	ption	of C- cl	imatic types according to the modified Köppen-Geiger scheme
Letter	symbo	l	
1st	2nd	3rd	criterion
С			temperature of warmest month greater than or equal to 10 °C, and temperature of coldest month less than 18 °C but greater than -3 °C
	S		precipitation in driest month of summer half of the year (months April-September) is less than 30 mm and less than one-third of the wettest month of the winter half (October-March)
	W		precipitation in driest month of the winter half of the year less than one-tenth of the amount in the wettest month of the summer half
	f		precipitation more evenly distributed throughout year; criteria for neither 's' nor 'w' satisfied
		а	temperature of warmest month 22 °C or above
		b	temperature of each of four warmest months 10 $^{\circ}\text{C}$ or above but warmest month less than 22 $^{\circ}\text{C}$
		С	temperature of one to three months 10 $^{\circ}\text{C}$ or above but warmest month less than 22 $^{\circ}\text{C}$

Figure 32: Description of C- climatic types according to the modified Köppen-Geiger scheme.

Source: Encyclopaedia Britannica.

Retrieved from: https://www.britannica.com/science/Mediterranean-climate

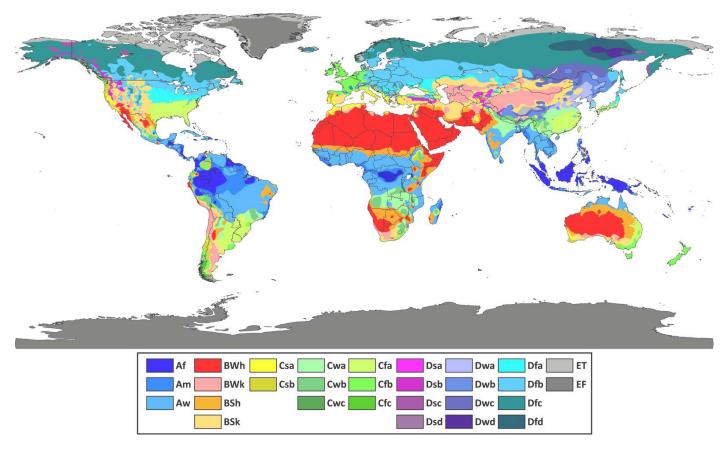


Figure 33: "Köppen climate classification map". Photo. Encyclopædia Britannica Online. Web 28/05/2017.

Source: <a href="https://www.britannica.com/science/Mediterranean-climate?oasmld=206711">https://www.britannica.com/science/Mediterranean-climate?oasmld=206711</a>>

Greece is situated at the most southeastern part of Europe, located between the 34° and 42° parallel N., with a meridional extent from 19° to 28° E. and borders the Aegean Sea, the Ionian Sea and the East Mediterranean Sea.

The climate in Greece is typical of the Mediterranean climate: mild and rainy winters, relatively warm and dry summers and, generally, extended periods of sunshine throughout most of the year. A great variety of climate subtypes, always within the Mediterranean climate frame, are encountered in several regions of Greece. This is due to the influence of topography (great mountain chains along the central part and other mountainous bodies) on the air masses coming from the moisture sources of the central Mediterranean Sea.

Thus the weather in Greece varies from the dry climate of Attiki (Athens' greater area) and East Greece in general, to the wet climate of Northern and Western Greece.

In climatological terms, the year can be broadly subdivided into two main seasons: The cold and rainy period lasting from mid-October until the end of March, and the warm and dry season lasting from April until September.

During the first period the coldest months are January and February, with, a mean minimum temperature ranging, on average, between 5-10 degrees Celsius near the coasts and 0-5 Celsius over the mainland, with lower values (generally below freezing) over the northern part of the country.

Long stretches of consecutive rainy days are infrequent in Greece, even during the winter, and the sky does not remain cloudy for more than a few days in a row, as it does in other regions of the world. During the warm and dry period the weather is usually stable, the sky is clear, the sun is bright and there is generally no rainfall. There are, however, infrequent and brief intervals of rapid rain or thunderstorms chiefly over mainland areas.

The warmest period occurs during the last ten days of July and the first ten days of August, when the mean

maximum temperature lies between 29.0 and 35.0 degrees Celsius. During the warm period the high temperatures are tempered by fresh sea breezes in the coastal areas of the country and from the north winds, known as 'Etesian', blowing mainly in the Aegean.

On the following. (Figure 34), is shown a map of solar irradiation in Greece showing the potential of PV panels placed to their optimum inclination. We can observe that the vast majority of Greek mainland and islands would be suitable for placement of PV panels.

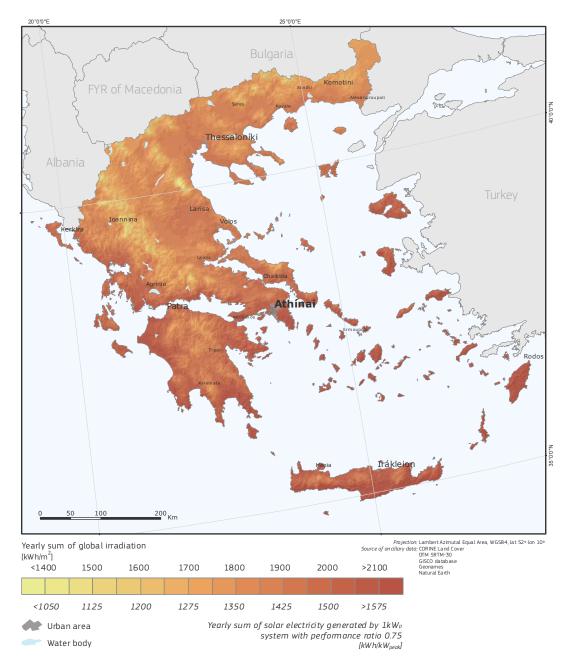


Figure 34: Global irradiation and solar electricity potential. Optimally-inclined photovoltaic modules.

Authors: Thomas Huld, Irene Pinedo-Pascua. European Commision - Joint Research Centre Institute for Energy and Transport, Renewable Energy Unit PVGIS.

Source: http://re.jrc.ec.europa.eu/pvgis/cmaps/eu\_cmsaf\_opt/G\_opt\_GR.pdf

## 4.2. Climate profile of Athens

In more detail, we are going to study the specific climate characteristics of Athens. The most significant data are summarized on the following table.

MONTHLY MEANS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ост	NOV	DEC	
Global Horiz Radiation (Avg Hourly)	213	267	338	394	441	512	525	493	443	321	215	192	Wh/sq.m
Direct Normal Radiation (Avg Hourly)	253	240	282	310	341	452	496	459	451	299	198	216	Wh/sq.m
Diffuse Radiation (Avg Hourly)	112	149	170	187	190	168	150	159	148	152	127	109	Wh/sq.m
Global Horiz Radiation (Max Hourly)	543	668	874	924	974	997	984	956	845	736	548	478	Wh/sq.m
Direct Normal Radiation (Max Hourly)	868	911	942	910	916	895	886	886	870	788	805	843	Wh/sq.m
Diffuse Radiation (Max Hourly)	257	354	432	470	569	489	432	488	419	363	292	266	Wh/sq.m
Global Horiz Radiation (Avg Daily Total)	2067	2814	4011	5143	6215	7479	7529	6626	5420	3522	2141	1809	Wh/sq.m
Direct Normal Radiation (Avg Daily Total)	2447	2525	3356	4047	4817	6596	7109	6170	5504	3273	1967	2039	Wh/sq.m
Diffuse Radiation (Avg Daily Total)	1094	1574	2008	2447	2681	2458	2161	2133	1818	1671	1262	1032	Wh/sq.m
Global Horiz Illumination (Avg Hourly)	23079	29029	36842	43039	48400	55910	57713	54067	48395	35062	23518	20857	lux
Direct Normal Illumination (Avg Hourly)	22796	22481	27187	30008	33037	43986	48379	44004	43333	28027	17875	19394	lux
Dry Bulb Temperature (Avg Monthly)	10	9	11	15	19	24	27	27	23	19	14	10	degrees C
Dew Point Temperature (Avg Monthly)	4	3	5	7	11	12	15	15	14	12	9	5	degrees C
Relative Humidity (Avg Monthly)	67	67	65	60	62	50	50	51	56	65	71	68	percent
Wind Direction (Monthly Mode)	0	0	0	0	200	0	70	0	0	20	0	0	degrees
Wind Speed (Avg Monthly)	3	3	3	2	2	3	3	2	3	3	3	2	m/s
Ground Temperature (Avg Monthly of 3 Depths)	11	12	13	15	19	22	23	22	21	18	15	12	degrees C

Figure 35: Weather Data Summary - monthly means. Location: Athens, Latitude/ Longitude: 37.9° North, 23,73° East. Data Source: IWEC Data, 167160 WMO Station Number. Source: Climate Consultant 6.0

The prevailing wind throughout the year is mainly north - northeast, while there are significant peak values of southern and western winds, which are in average warmer in temperature. The average wind speed is about 6.5 m/s. The second wind wheel gives a more analytic overview of the prevailing winds during the hot summer periods. The North and Southwest winds prevail lasting for longer hours and being hotter in temperature.

The sun shading charts gather information about the hourly temperature throughout the year, separated from June 21st till December 21st and from December 21st till June 21st. We observe that approximately in the period May-October the temperature surpasses the comfort zone and therefore shading is needed. Shading would be necessary for 1889 hours in total of the year, while sun would be needed for 2415 hours. Within the comfort zone there are 806 hours, in which shading would be of help. 5110 hours with sunlight in total.

To sum up the overall results are as follows:

### o WARM/HOT >24°C

(SHADE NEEDED) 1889 Hours Exposed out of 5110 0 Hours Shaded (SHADE HELPS)

806 Hours Exposed out of 5110 0 Hours Shaded o COOL/COLD <20°C

(SUN NEEDED)
2415 Hours Exposed out of 5110
0 Hours Shaded

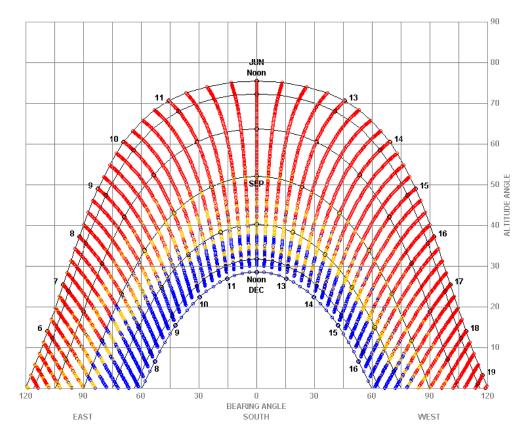


Figure 36: Sun shading chart June 21st to December 21st. Source: Climate Consultant 6.0

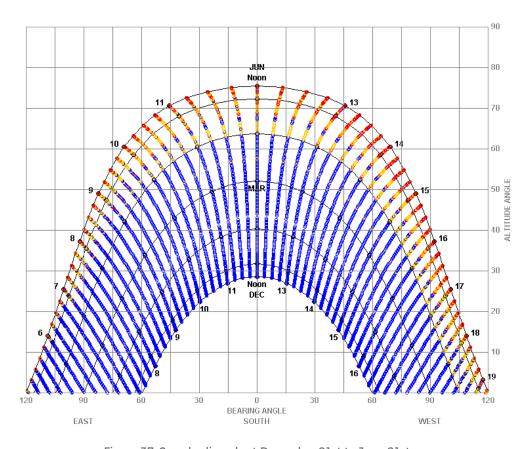


Figure 37: Sun shading chart December 21st to June 21st. Source: Climate Consultant 6.0

### **LEGEND**

### o WARM/HOT >24°C (SHADE NEEDED)

### 1494 Hours Exposed 0 Hours Shaded

(SHADE HELPS) 413 Hours Exposed 0 Hours Shaded

### o COOL/COLD <20°C (SUN NEEDED)

# 691 Hours Exposed 0 Hours Shaded

### **LEGEND**

### o WARM/HOT >24°C (SHADE NEEDED) 395 Hours Exposed 0 Hours Shaded

(SHADE HELPS) 393 Hours Exposed 0 Hours Shaded

### o COOL/COLD <20°C (SUN NEEDED) 1724 Hours Exposed 0 Hours Shaded

The temperature ranges from 2° - 35° C on annual basis, with the summer months being primarily above the comfort zone while winter months are substantially below, which can be seen on Figure 42.

On the psychrometric diagram (Figure 40) it is clearly depicted the comfort zone with the green color, which represents 13% of the total. The need for improvement is therefore evident and with the appropriate approach it is possible to improve the indoor condition as it is shown on the psychrometric diagram.

The sky cover range is higher during the winter period and significantly lower in the summer period (Figure 43).

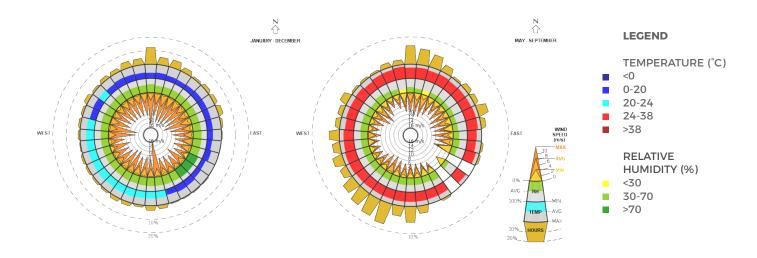


Figure 38: Wind wheel, annual average temperature, relative humidity, speed and duration.

Figure 39: Wind wheel May-September

Source: Climate Consultant 6.0

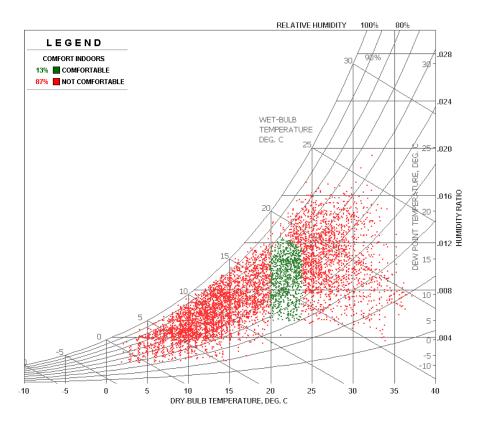


Figure 40: Psychrometric chart. Indoor Comfort display.

Source: Climate Consultant 6.0

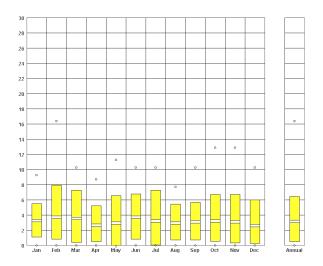


Figure 41: Wind velocity range. Source: Climate Consultant 6.0

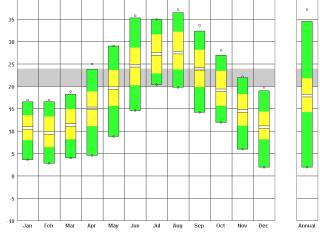


Figure 42: Temperature range. Source: Climate Consultant 6.0





LEGEND

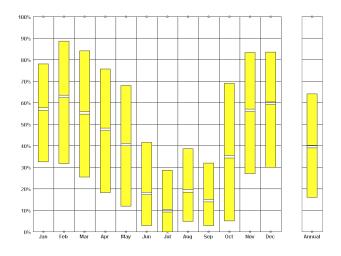


Figure 43: Sky cover range. Source: Climate Consultant 6.0

### LEGEND



### 4.3. Urban Heat Island Effect

The urban heat island effect appears in the large, dense cities. It is observed mainly during the summer and happens due to concentration of heat in the buildings, the roads and the lack of greenery.

Normally, the solar irradiation during summer days charges the buildings with heat, which is stored in their mass. During the night the reverse procedure takes place: the rejection of the heat to the atmosphere.

However, due to the dense urban fabric of large cities, the few free spaces and the obstruction of free wind flow, the absorbed amount of heat cannot be rejected back to the atmosphere during the night. Thus, a big part of it is retained by the buildings is additively accumulated day by day, causing overheating conditions for the period when high temperatures prevail.

This phenomenon is called "heat island" effect and it causes unpleasant microclimatic conditions in the cities with high buildings. In the cities with lower buildings or in the countryside this phenomenon is not observed. There have been noticed differences in temperature up to 10-15° C between cities and nearby countryside. (Andreadaki E, 2006).

This phenomenon can be also noticed in Athens. Especially in the hot summer periods the temperature may vary significantly between the city center and the suburbs. Indeed, as it can be observed on the following map (Figure 45), the air temperature difference between the city centre and other areas can vary up to 10°C.

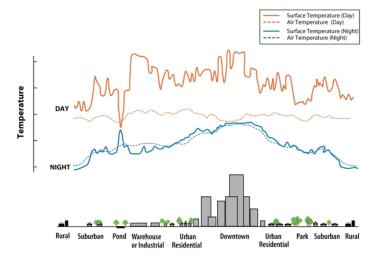


Figure 44: Visual representation of the urban heat island effect portraying the dT between urban and rural areas during day and night.

Source: https://peopleandtreesincities.wordpress.com/tag/usfs/

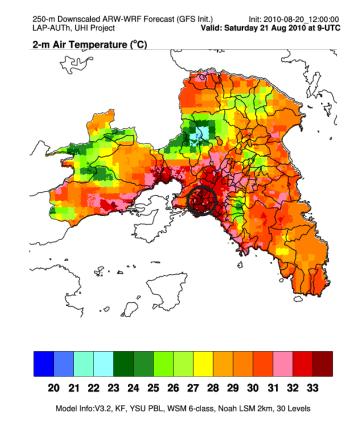


Figure 45: Map of Attica showing the thermal differences on 21/08/2010. The dT between city centre and certain areas is up to 10° C. City center is marked with black circle.

Source: AUTh - Aristotle University of Thessaloniki

#### **Collateral Positive Influence**

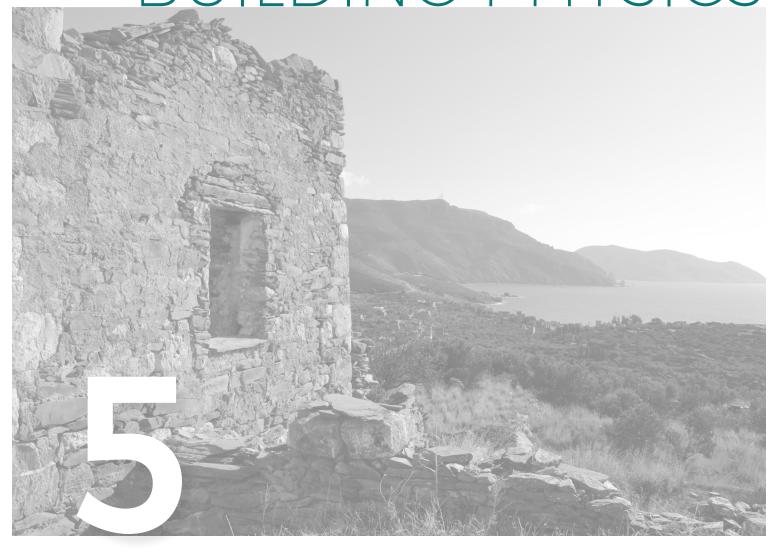
Beside its mostly negative effects, the urban heat island effect has some positive results. According to a survey conducted in London, the energy required to cover the cooling demands is 25% increased, contrary to the energy for heating, which Is 22% reduced. (Zisopoulou A et al.)

### Strategies to tackle the heat Island effect

According to the United States Environmental Protection Agency, the ways and technologies to confront the urban heat island effect are the following:

- · Green spaces: They reduce the air temperature and the surface temperature through shading and respiration.
- Green roofs: They reduce the air temperature and the surface temperature through shading and respiration, as well as the interior temperature resulting in less energy demands for cooling
- Cool materials on roofs and exterior surfaces of buildings and urban spaces. The materials with high reflectance properties result in reduced thermal energy absorbtion. (Zisopoulou A. et al.)

BUILDING PHYSICS



# 5. Building Physics

# 5.1. Principles for heating, cooling, ventilation and lighting in Mediterranean climate condition

This paragraph will handle in general the principles of bioclimatic design. Objective of the bioclimatic design is, in brief, the minimization of heat losses, the maximization of solar gain, protection against wind during winter and the minimization of solar gain, the protection against solar irradiation and the utilization of natural cooling processes during summer.

The bioclimatic design refers to all architectural scales, from the urban scale until the building detailing scale and involves a variety of systems. In the following, there will be briefly discussed the principles and the systems of bioclimatic design.

### **Principles**

- Topography Location: determine the maximization of solar gain and wind (protection in winter and usage of cool breezes in summer) orientation, ground inclination, obstacles
- · Shape of the building: determines the heat exchange with the environment
- · Interior spaces configuration
- Building skin: the building components and materials affect the energy performance of the building (thermal insulation, avoid thermal bridges, materials with high heat capacity, window frames with low heat conducting coefficient, use of sun shading)
- · Openings: appropriate orientation and size for optimum ventilation, lighting, solar gain

### **Systems (Passive Systems)**

- Solar heating systems: systems which utilize the solar power for heating. According to the positioning of the collection and storage elements they are distinguished into:
  - Direct solar gain
- Indirect solar gain: thermal storage, thermal walls, Trombe walls, thermal mass, water walls, solar space etc.
  - Isolated solar gain
- Natural ventilation and cooling systems: Cross and Stack ventilation occur due to pressure difference or due to temperature difference. Passive ventilation involves wind, water or the ground as heat sinks.
   Direct or indirect evaporative cooling, night cooling and ventilation, ground cooling.
- · Natural lighting: vertical openings and skylights, atria, light selves, appropriate glazing.

# 5.2. Vernacular Architecture

The Greek traditional architecture is as versatile as the Greek landscape and local climate conditions are. The people have been always taking measures to protect themselves against the elements of nature and have been adjusting them in order to meet their needs. In spite of some differentiations according to each specific region, many practices and techniques remain common throughout the whole country. In the following there have been summarized the most basic principles.

	heating	cooling	ventil.	light
Small and few openings on the northern sides while big and many in the southern sides of the buildings	•	•	•	•
Use of natural ventilation: Cross ventilation and stack ventilation via windows			•	
Use of direct solar gain	•			
Window blinds: movable insulation or/and shading system in addition to minimization of heat gain in summer and minimization of heat loss in winter	•	•		•
Timber interior walls, floors and ceilings for faster heating of the inner space and minimization of air condensation	•			
Prolonged roof for better protection of walls and openings against rain (winter) and sun (summer)		•		
Exterior walls made of stone with thickness 0.50-1.00m: thermal mass	•	•		
Fireplace: additional heat source	•			
Use of local materials: durability in time and energy saving (stone, wood, earth, lime)	•	•		
White or light color painting on the exterior walls: minimize heat gain		•		
Semi-outdoor spaces (covered terraces, balconies)		•		•
Use of soil thermal mass: semi-underground houses	•	•		
open-surface evaporative cooling (ponds, springs etc)				











46 47

48

49 50

Figure 46: Hatzigianni Mexi Mansion, in Spetses, with semi-open-air spaces. (Floros 2014)

Figure 47: Semi - buried buildings in Oia, Sadorini Island. (Floros 2014)

Figure 48: Naousa traditional settlement in Paros Island. (Floros 2014)

Figure 49: Mansion in Kastoria, Northern Greece. (https://goo.gl/YR4oU4)

Figure 50: Traditional House in Ipiros, Northern Greece. (https://goo.gl/sjr5c1)

# 5.3. Indoor Environmental Comfort

### **Aspects of Indoor Comfort**

There are four basic environmental factors in the indoor environment (see Figure 3.1) that directly influence the perception of that indoor environment through the senses, but also have an effect on the physical and mental state (comfort and health) of occupants:

- 1. thermal comfort or indoor climate, comprising parameters such as moisture, air velocity and temperature;
- 2. visual or lighting quality, determined by view, illuminance, luminance ratios, reflection and other parameters;
- 3. indoor air quality: a complex phenomenon comprising odor, indoor air pollution, fresh air supply, etc.;
- 4. acoustical quality, influenced by outside and indoor noise, as well as vibrations.

In addition, ergonomics, such as the dimensions and sizes of the space, tools, furniture, etc, play an important role in total body perception. (Bluyssen 2009)

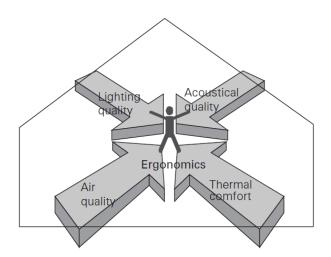


Figure 51: Basic environmental factors in an indoor space.

Source: Bluyssen 2009

### **Thermal Comfort Models**

While some existing standards specify only one level of comfort, such as ASHRAE 55 (ASHRAE, 2004a), others, such as ISO EN 7730 (ISO, 2005), CR 1752 (CEN, 1998) and EN15251 (CEN, 2005), recommend three categories, as shown in Figure 52.

Each category prescribes a maximum predicted percentage of dissatisfied (PPD) for the body as a whole and for each of the four types of local discomfort. The three categories in Figure 52 apply to spaces where people are exposed to the same thermal environment. For a given conditioned space there exists an optimum operative temperature corresponding to PMV = 0, depending upon the activity and the clothing of the occupants. The number of dissatisfied people in Figure 53 is not additive. Some of the same people experiencing general thermal comfort (PMV-PPD) may be the same as the people experiencing local thermal discomfort. Figure 53 provides examples of recommended operative temperatures in some typical spaces.

For local discomfort parameters, ISO 7730 (ISO, 2005), ASHRAE 55 (ASHRAE, 2004a) and EN15251 (EN, 2005) give similar recommendations (Figure 54 - Figure 57 on page 57).

For adaptive comfort (mainly in naturally ventilated buildings), ASHRAE (2004a) recommends the ranges found in Figure 56 on page 57 and CEN (2005) recommends the ranges found in Figure 58 on page 57, in which a running weekly mean outdoor temperature is used instead of a monthly average.

Category	Thermal state of	the body as a who	le	Local discomfort Percentage of dissatisfied due to:				
	Predicted percentage of dissatisfied (PPD) (%)	Predicted mean vote (PMV)	Draught (DR) (%)	Vertical air temperature difference (%)	Warm or cool floor (%)	Radiant asymmetry (%)		
A	<6	-0.2 <pmv<+0.2< td=""><td>&lt;15</td><td>&lt;3</td><td>&lt;10</td><td>&lt;5</td></pmv<+0.2<>	<15	<3	<10	<5		
В	<10	-0.5 <pmv<+0.5< td=""><td>&lt;20</td><td>&lt;5</td><td>&lt;10</td><td>&lt;5</td></pmv<+0.5<>	<20	<5	<10	<5		
C	<15	-0.7 <pmv<+0.7< td=""><td>&lt;25</td><td>&lt;10</td><td>&lt;15</td><td>&lt;10</td></pmv<+0.7<>	<25	<10	<15	<10		

Source: CEN (2005)

Figure 52: Three categories of thermal comfort. Source: Bluyssen 2009

Type of Building/ space	Clothing		Activity	Category		erative erature	Mean air velocity	
	Cooling season (summer) clo	Heating season (winter) clo	met	met	Cooling season (summer) °C	Heating season (winter) °C	Cooling season (summer) ms <sup>-1</sup>	Heating season (winter) ms <sup>-1</sup>
Office	0.5	1.0	1.2	A	24.5 ± 0.5	22.0 ± 1.0	0.18	0.15
				В	24.5 ± 1.5	$22.0 \pm 2.0$	0.22	0.18
				C	24.5 ± 2.5	$22.0 \pm 3.0$	0.25	0.21
Cafeteria/	0.5	1.0	1.4	A	$23.5 \pm 1.0$	$20.0 \pm 1.0$	0.16	0.13
restaurant				В	$23.5 \pm 2.0$	$20.0 \pm 2.5$	0.20	0.16
				C	$23.5 \pm 2.5$	$20.0 \pm 3.5$	0.24	0.19
Department	0.5	1.0	1.6	A	$23.0 \pm 1.0$	19.0 ± 1.5	0.16	0.13
store	-			В	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15
				C	23.0 ± 3.0	19.0 ± 4.0	0.23	0.18

Source: CEN (2005)

Figure 53: Example criteria for operative temperature and mean air velocity for typical spaces. Rh is 60% for summer and 40% for winter. Source: Bluyssen 2009

Category	Vertical air temperature difference (°C)
A	<2
В	<3
C	<4

Source: ASHRAE (2004a), CEN (2005), ISO (2005)

Figure 54: Vertical air temperature difference between head and ankles. Source: Bluyssen 2009

Category	Range of surface temperature of the floor (°C)
A	19–29
В	19-29
C	17–31

Source: ASHRAE (2004a), CEN (2005), ISO (2005)

Figure 55: Range of floor temperature for the three categories of the thermal environment.

Source: Bluyssen 2009

Category	Radiant temperature asymmetry (°C)							
	Warm ceiling	Cool wall	Cool ceiling	Warm wall				
A	< 5	< 10	< 14	< 23				
В	< 5	< 10	< 14	< 23				
C	< 7	< 13	< 18	< 35				

Source: ASHRAE (2004a), CEN (2005), ISO (2005)

Figure 57: Radiant temperature assymetry for th three categories of the thermal environment - valid for low-ceiling spaces.

Source: Bluyssen 2009

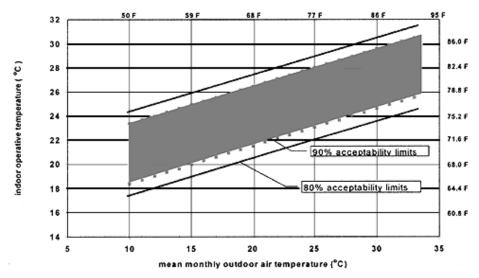


Figure 56: Acceptable operative temperature ranges for naturally conditioned spaces according to ASHRAE 55-2004: Range is shown for different climatic areas. Source: ANSI/ASHRAE Standard 55-2004, p. 10.

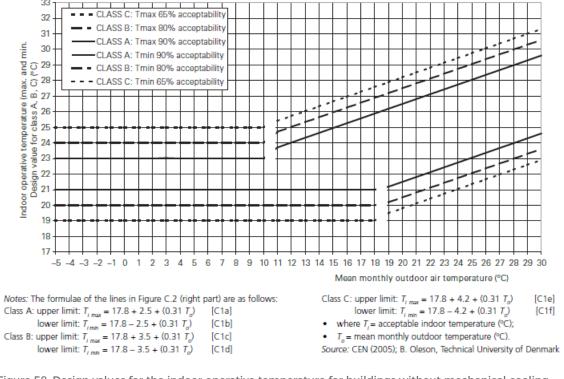
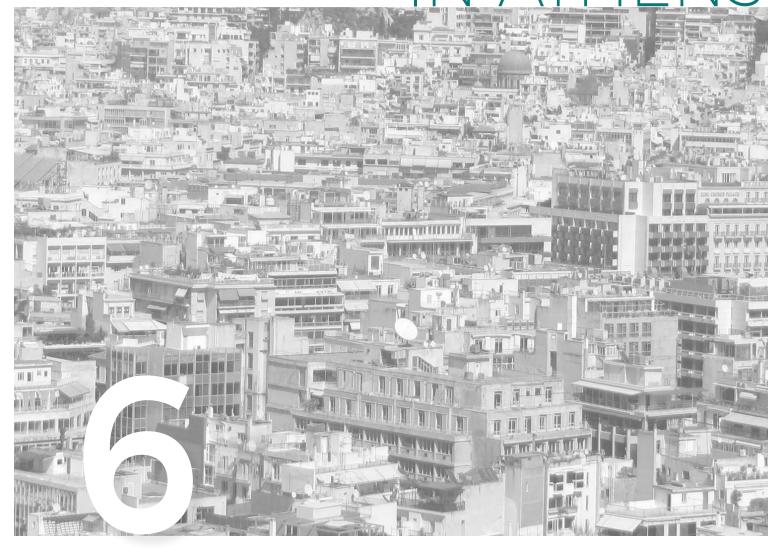


Figure 58: Design values for the indoor operative temperature for buildings without mechanical cooling systems. Source: Bluyssen 2009

# OFFICE BUILDINGS IN ATHENS



# 6. Office Buildings in Athens

### 6.1. General Information and Statistics

In this chapter are examined the existing office buildings in Athens in regard to their number and position in the city, statistic information about the number of floors and an estimation on the current energy demand.

Firstly, the office (along with commercial use) buildings constitute the 2nd bigger category in uses after the residential. There are approximately 9500 buildings. Out of those, the vast majority as it can be seen on Figure 63, have been constructed prior to 1980. There is no collective information concerning any renovations, but in general they are significantly aged.

Many of the office buildings are situated within the hyperlocal center of the city, which is shown on Figure 62. In this area the building coefficient is 5.4 in most regions and 4.3 in small area. Comparing this info with the graph on Figure 61, we conclude that there are many multi-storey buildings.

In the current phase of the research, the data which have been collected aim to give an overview on the current situation and on the available building stock that will be the main point of the further design task.

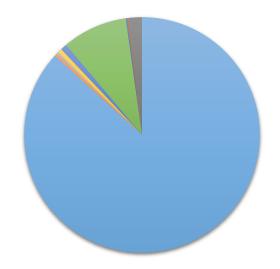


Figure 59: Number of buildings per type within the central administrative sector of Athens.

Data source: Hellenic Statistic Service 2011, own representation

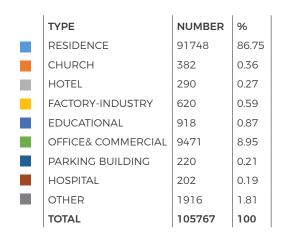




Figure 60: Typical office building energy consumption.

Source: US Energy Information Administration's 2003, own representation

FUNCTION	%
Heating & Cooling	43
Ventilation	7
Lighting	21
Refrigeration & Cooking	9
Electronics	3
Water Heating	8
Other	9
Refrigeration & Cooking Electronics	9

2.500					
2.000				_	
1.500		_			
1.000					
500	-				٠.
0	Ground floor only (G)	G + 1 floor	G + 2 floors	G + 3-5 floors	G + 6 and more floo

Figure 61: Number of floors information for single and mixed use buildings in the central sector of Athens. Graph showing number of buildings.

Data source: Hellenic Statistic Service 2011, own

representation

Single	use
Mixed	use

CENTRAL SECTOR OF ATHENS	SINGLE USE	MIXED USE
Ground floor only (G)	2290	60
G + 1 floor	1299	572
G + 2 floors	899	331
G + 3-5 floors	1833	601
G + 6 and more floors	1140	446
TOTAL	7461	2010

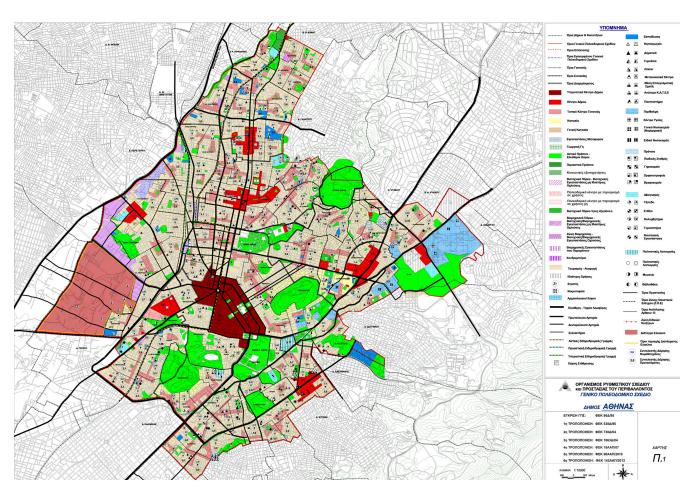


Figure 62: General Urban Plan of Athens (Central Sector-Municipality of Athens), 1988, last adaptation in 2012. In dark red color is displayed the hyperlocal center of Athens, which is the region where most of offices are located. Source:

Organization for the Master Plan and Environmental Protection of Athens

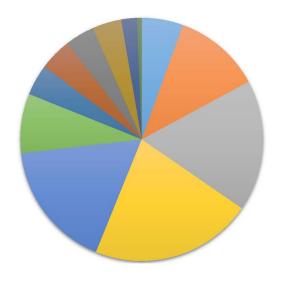


Figure 63: Number of office and commercial use buildings in central sector according to year of construction.

Source: Hellenic Statistic Service 2011.

CENTRAL SECTOR	SINGLE USE	MIXED USE
before 1919	481	43
1919 - 1945	891	208
1946 - 1950	1127	526
1961 - 1970	1528	514
1971 - 1980	1265	347
1981 - 1985	614	135
1986 - 1990	334	58
1991 - 1995	349	58
1996 - 2000	333	37
2001 - 2005	323	43
2006 and after	164	34
under construction	52	7
TOTAL	7461	2010

# 6.2. Overview of façades of office buildings in Athens

As main part of the field research during May 2017, there have been collected photographs and information from the most representative façade types which can be encountered at the center and in some regions of the north suburbs today.

Aim is to create understanding of the typical characteristics of office buildings in Athens and out of these observations define the 'typical office building' where the simulation and design will take place. Also, it aims to explore the trends in façade design of the most recent buildings and possible implementation of solar cooling or passive technologies.

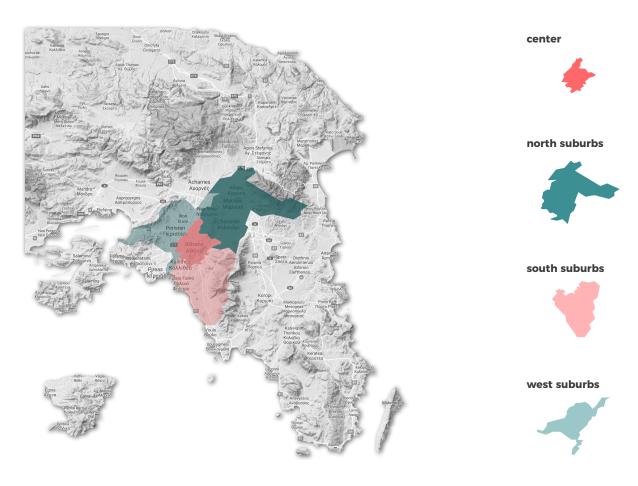


Figure 64: Region of Attiki and the City of Athens with its suburbs.

Map source: Google Maps, own adaptation

There have been examined 25 cases, which gather the most representative categories of buildings in terms of typology, building age, style, construction type and façade construction. The majority of the buildings is located in the center of the city, as this area consists the business, commercial as well as cultural center of Athens, as indicated on the Central Urban Plan of Athens in paragraph 6.1.

Of course, this sample is not an exhaustive source of information, but the selection has been carefully made, based on observations, previous knowledge and the long-term experience as a resident of Athens. Subsequently, it can be presumed that the sample is very representative and can lead to safe conclusions

concerning the typical office building of Athens.

On the last pages of this chapter can be found the tables with collective summary of the building facades (Figure 65 on page 67) and the building data (Figure 66 on page 68).

One type of buildings share the common characteristic that the facade is organized with windows, adopting a neoclassical style. The window to wall ratio (WWR) varies between 0.18 and 0.46, which are the lowest values. Construction material may be stone for the first floors, but considering the fact that some of them have been built later on, concrete may have been used too.

Another category with several types are buildings of the 1970-1990 and little or no information is known about the construction, so these conclusions are based on the observation. In general they have larger glass surfaces compared to the previous ones, so the WWR is bigger, varying between 0.35 and 0.55 with one exception 0.68 (building 13).

In most examples it is evident that the construction is rather old, neither properly maintained nor cleaned and moreover the external air-conditioning units occupy big part of the exterior surface with an inelegant result. In some of the examples the presence of ventilation (?) grills is visible at the exterior.

Other type with the largest WWR varying between 0.84-1.00 are the fully glazed facades with no or small presence of other material. While there are several of those in the center of the city, a lot of them are located along the Kifisias Avenue, major axis leading to the North suburbs. Along the years these type of facades have been the major complain of pedestrians and drivers because of glaring, strong reflections and heat concentration, contributing largely to the urban heat island effect. In some occasions the problem has been faced with very minor interventions but in most cases it remains.

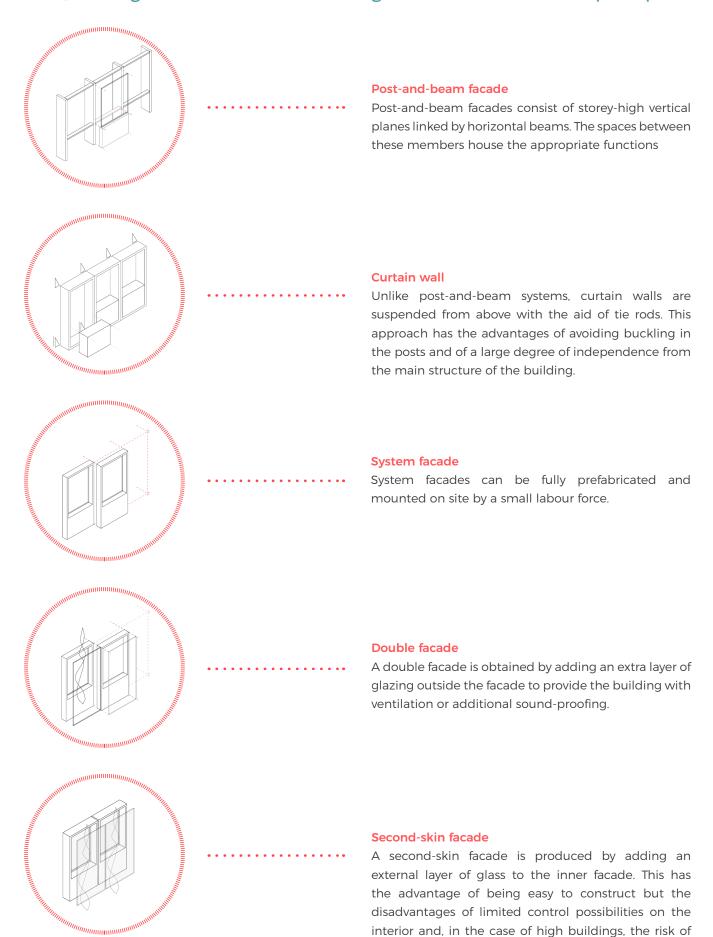
Very few buildings have adopted already some sustainable strategies (Building 3, 23 and 25) in small or great extent. In principle these are contemporary constructions.

# 6.3. Building Index

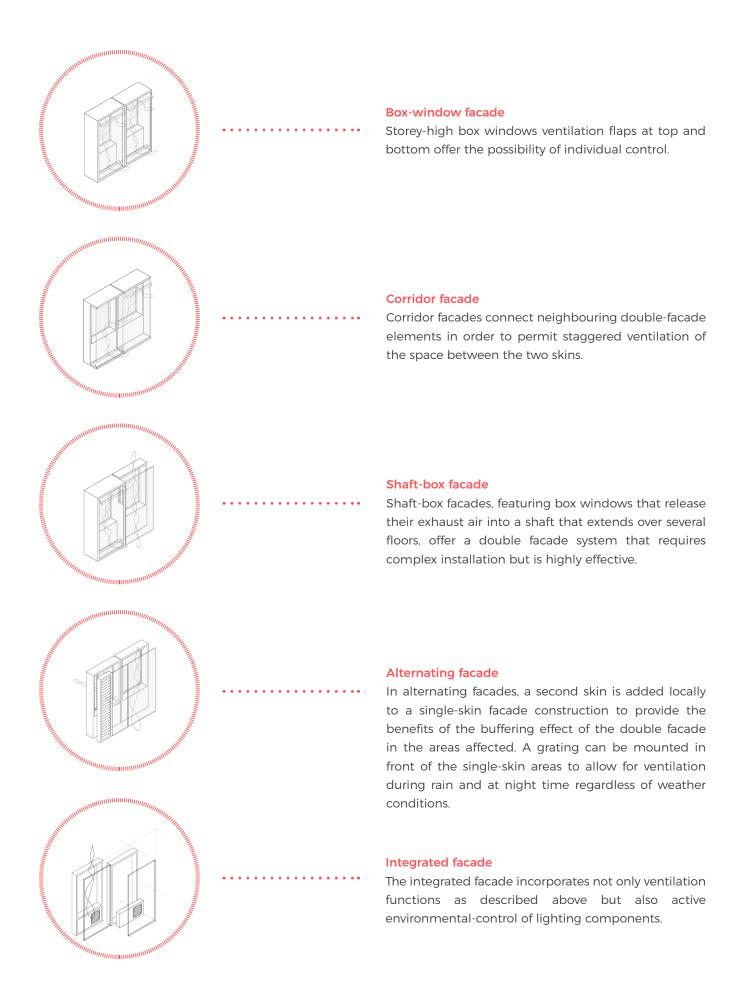
The case studies include the following 25 buildings which are located in the center and north suburbs of Athens. The full panorama with photographs and basic information about each building is to be found in Appendix I.



# 6.4. Categorization criteria according to facade construction principles



overheating.



Schemes and descriptions from: Knaack, U., Klein, T., & Bilow, M. (2014). "Façades: principles of construction". Retrieved from http://ebookcentral.proquest.com, on 2017-09-26.

# 6.5. Summary office facades



Figure 65: Collective table of the examined facades.

The red lines indicate the facade unit, according to which is calculated the WWR.

	Façade grid (m)		WWR	Façade type	Total height	Number of	Building	Building	Dimensions	
					(m)	floors	year/ period	System		
	Height	Width							width	depth
Building 1	4,0	-	0,46	0,46 solid	36	6	1981	attached	09	22
Building 2	3,7	1,8		0,49 beam façade	33	6	1975	attached	34	24
Building 3	3,4	1	0,47	curtain wall	31	6	2013	attached	27	32,5
Building 4	4,0	3,6		0,19 solid	20	2	1844	attached	28,5	32
Building 5	5,8	ı	0,21	0,21 solid	23	7	1840	attached	50	40
Building 6	5,7	2,5		0,46 solid	34	9	1933	attached	80	50
Building 7	6,2	1	0,18	0,18 solid	31	2	1933	attached	80	50
Building 8	3,2	1,5		0,26 curtain wall	32	10	0261~	attached	15	22
Building 9	3,2	3,6		0,45 curtain wall	32	10	0261~	attached	43	22
Building 10	2,9	1,2		0,26 post and beam	26	6	0261~	attached	30	19
Building 11	3,2	1,8	0,53	curtain wall	32	10	0261~	attached	15	25
Building 12	3,4	1,2	0,35	curtain wall	34	6	0261~	attached	61	25
Building 13	3,4	4,2	0,68	post façade	34	10	0261~	attached	18	20
Building 14	3,1	6'0	0,51	parapet	31	10	0261~	attached	35,7	17
Building 15	3,3	3,5	0,55	curtain wall	33	10	0261~	attached	77	71
Building 16	3,2	2,7		0,50 double skin	32	10	0/61~	attached	26	45
Building 17	3,1	1,2	0,51	post and beam	31	10	0161~	attached	20	37
Building 18	3,9	-	1,00	1,00 curtain wall	27	7	01970	attached	20	18
Building 19	3,4	-	0,84	0,84 curtain wall	31	6	~1970	attached	22	17
Building 20	4,0	2	1,00	1,00 curtain wall	80	20	1980	free	09	30
Building 21	3,4	1,6		1,00 curtain wall	34	10	~1970	attached	15,2	34,8
Building 22	3,6	7		0,44 curtain wall	32	6	0261~	attached	27,7	35
Building 23	5,3	-	0,44	0,44 post and beam	30	6	2008	attached	13	15
Building 24	3,2	6,0	0,53	curtain wall	68	21	1975	free	64	30
Building 25	4,3	1,2		0,50 curtain wall	30	7	2005	free	100	44
AVERAGE	3,8		0,51		34,3	9,5			37,9	28,9

Figure 66: Comparative data table of the buildings analyzed, with facade grid, WWR, Facade type, height, number of floors and year of construction.

# 6.6. Final scheme per facade category

CURTAIN WALL	WINDOW FACADE	POST AND BEAM FACADE	DOUBLE FACADE

# 6.7. Defining the 'Typical office building of Athens'

Following the field research and analysis of the case studies, the typical characteristics of an office building were defined and summarized on the following scheme.

As next step, one of the examined buildings has been analyzed into more detail and the following pages contain the basic facade drawings. This building will be used as reference for the application of the design and the final evaluation. A second case was also analyzed, which can be found in "APPENDIX II - BUILDING 12 - DRAWINGS" on page 164.

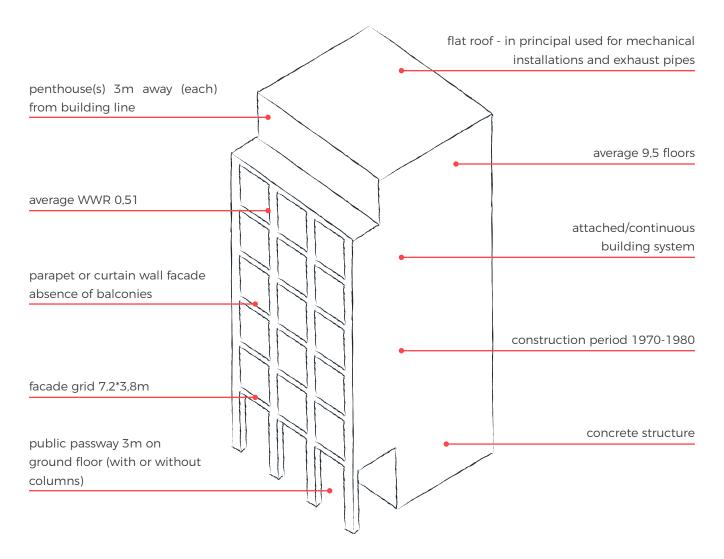


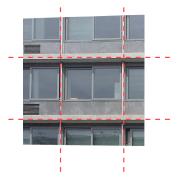
Figure 67: Schematical representation of the typical characteristics of office building according to the field research and analysis.

# 6.8. Drawings of Current Situation

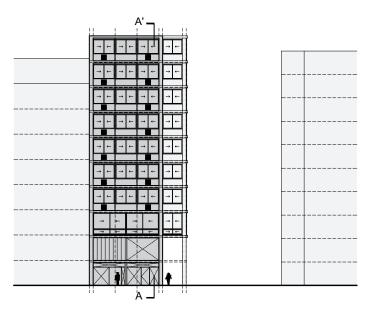


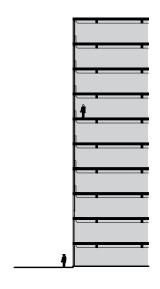
Figure 68: Building 15, Ermou and Nikis str. SSW street view

Facade grid	Height	3.30
	Width	2,70
WWR	0.55	
Facade type	window elements w parapet	
Structure type	concrete	
Total building height	33m	
Number of floors	10	
Year	unknown	
Materials	concrete, marble, glass	





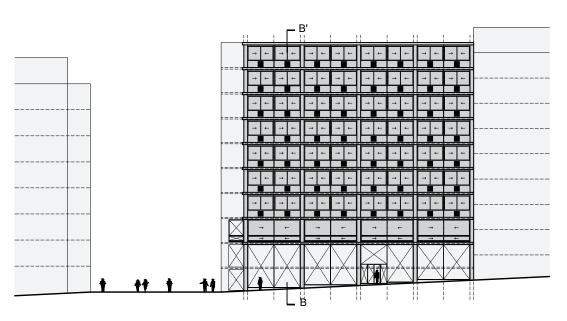


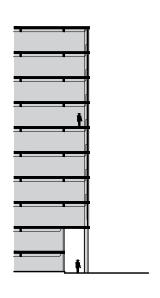


### SECTION A-A'

### SOUTH ELEVATION - ERMOU STR.

Facade Length = 9.70m
Facade Height = 33.00m
Total Building Height = 33.00m
Facade Grid: Height = 3.30m
Width = 2.90m
Columns = 0.50m



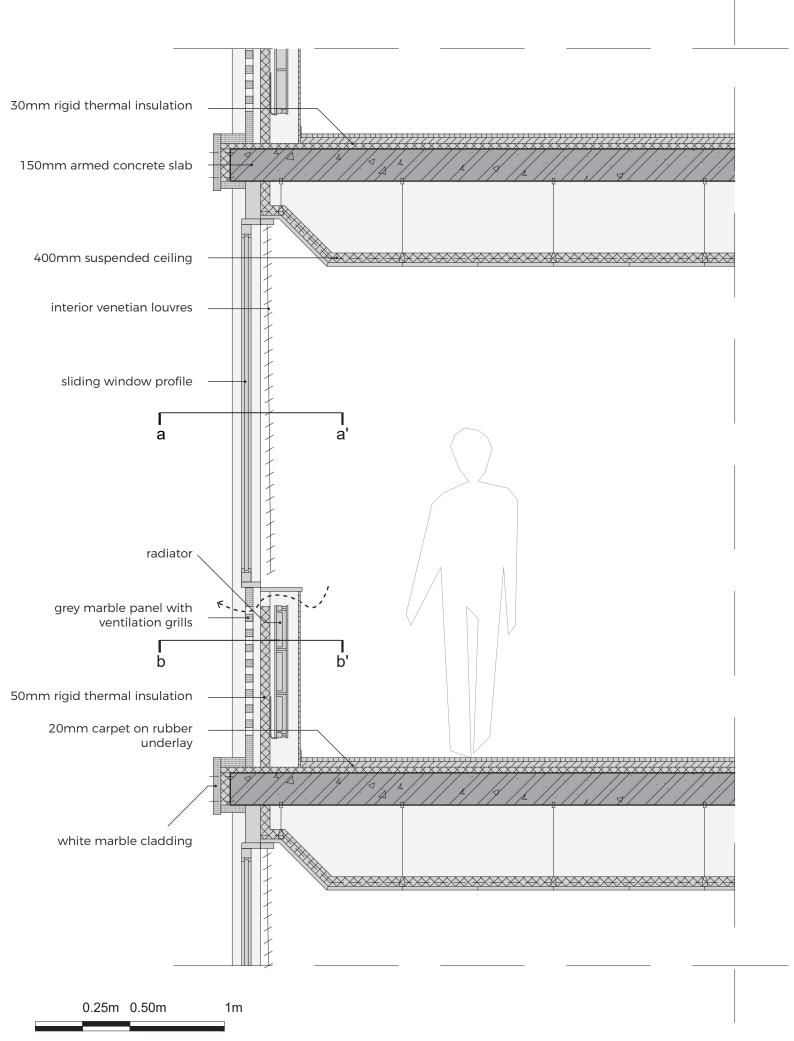


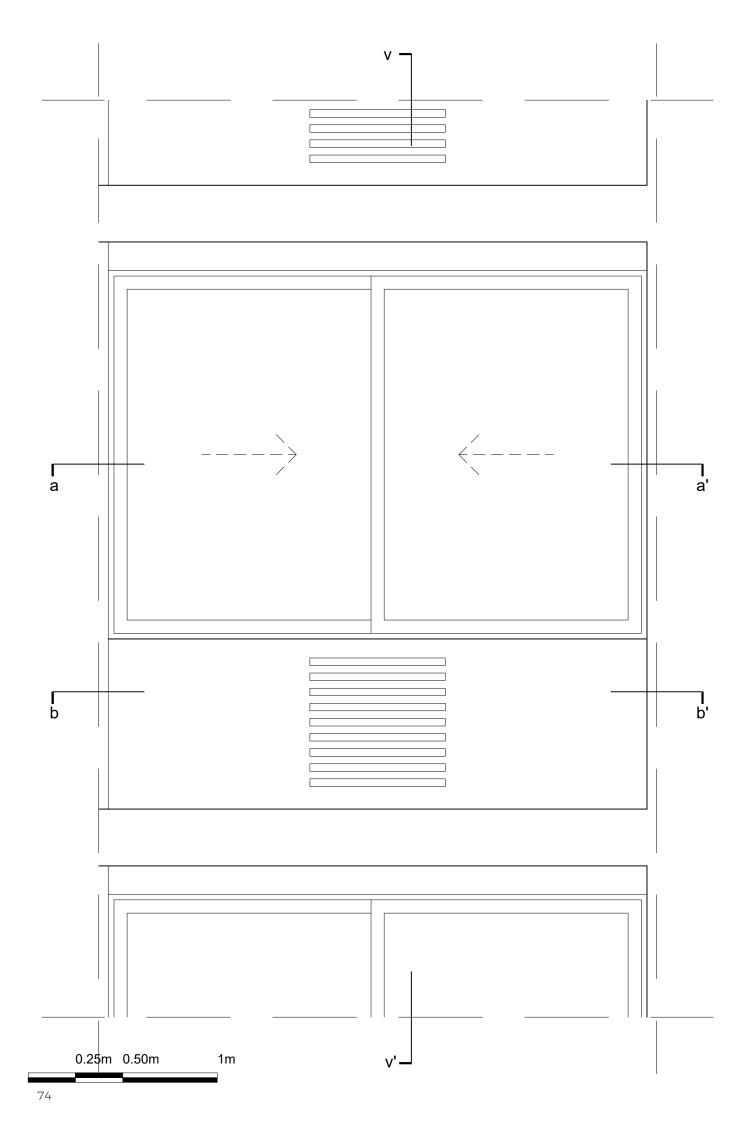
EAST ELEVATION - NIKIS STR.

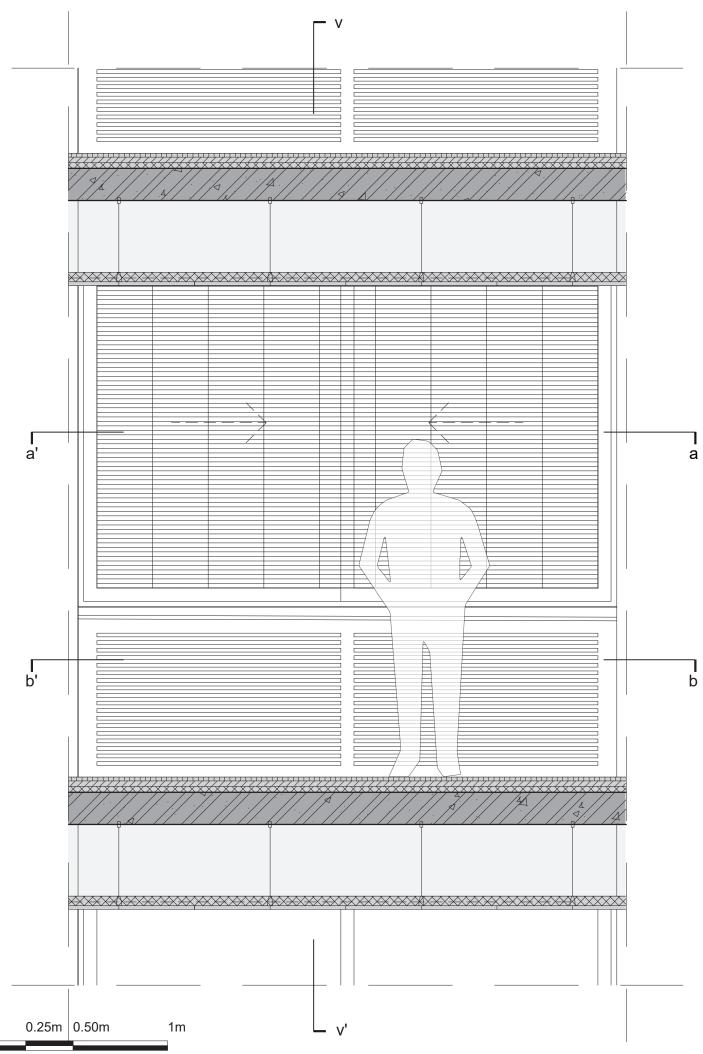
Facade Length = 30.40m
Facade Height = 31.40 - 33.00m
Total Building Height = 31.40 - 33.00m
Facade Grid: Height = 3.30m
Width = 3.50m
Columns = 0.50m

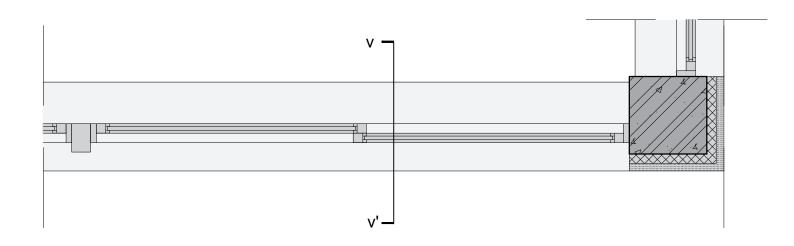
SECTION B-B'

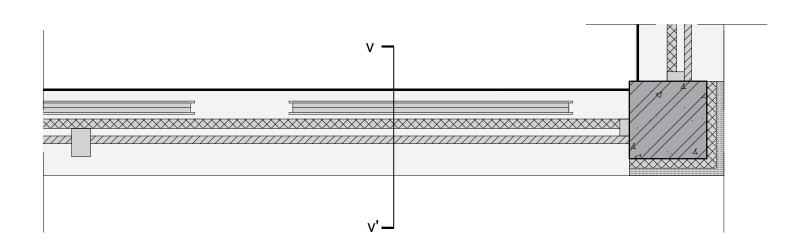






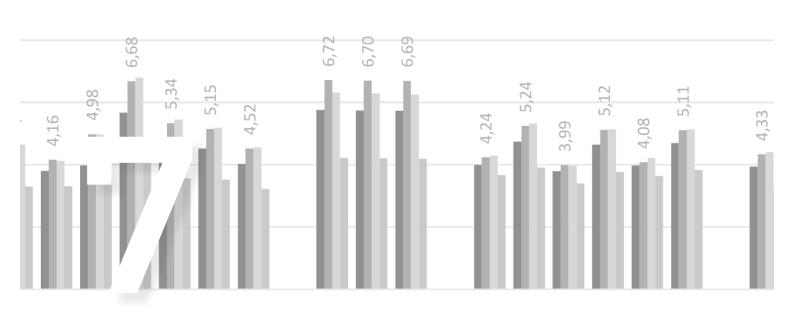






# CALCULATIONS

# COOLING LOAD (KWH/M2) SUMMER DESIGN WEEK



## 7. Calculations (Design Builder)

### 7.1. Method Description

#### Phase 1 - Scenario 0

As a next step after the field research and analysis of the 25 office building cases studies, a typical model-construction has been assumed in order to proceed to the study. Object of the research was to start with a building case having the typical construction and minimum or no passive strategies applied. This initial case (to be called Scenario 0) has been the basis for the further Scenarios. The criteria for the examined scenarios have been selected according to the research on Vernacular Bioclimatic Strategies as described in chapter 5. The software used was the Design Builder, version 5.0.3.007. More information regarding the model and the settings used follows in paragraph 7.2.

#### Phase 2 - Scenarios 1.-. 2.-. 3.-. 4.-

During this phase, the scenario 0 has been used always as a reference and on each scenario there has been changed only one parameter. The various scenarios, as mentioned previously, regard the most important bioclimatic strategies that are also used traditionally in vernacular architecture and are relevant to the case of an office building.

More specifically, these strategies are:

- Glazing Type (Scenario 1.0)
- Night Ventilation Concept (Scenario 2.0)
- Sun Shading Application (Scenario 3.0)
- Window to Wall Ratio WWR (Scenario 4.0)

For each strategy there have been examined various parameters in order to explore and get the best potential from each case. The full list of the examined scenarios as well as the numerical results are presented on the next table.









Figure 69: The parameters for the passive evaluation: 1-Glazing type, 2-night ventilation schedule, 3-sun shading, 4-WWR

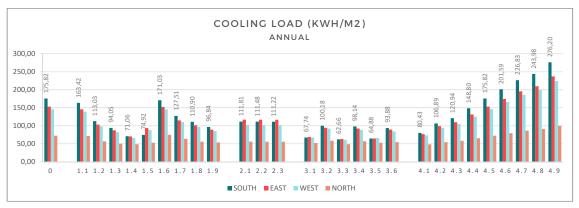
The simulation with the same settings has been carried out for all orientations (south, east, west and north).

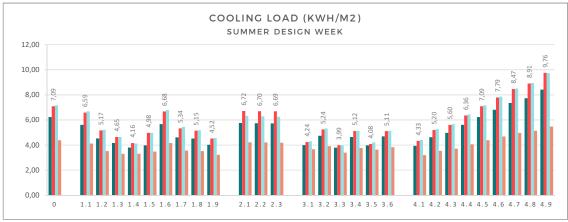
From each scenario and orientation there have been gathered data about the respective:

- Cooling Loads [kWh/m2] ANNUAL SIMULATION
- Cooling Loads [kWh/m2] DESIGN SUMMER WEEK SIMULATION (hottest summer week according to the weather file)
- Design Capacity [kW] DESIGN SUMMER DAY SIMULATION (hottest summer day according to the weather file)

Again, it is important to emphasize, that every scenario is based on Scenario 0 and only one parameter is altered, which is the characteristic for each scenario.

The results are summarized on the following graphs.





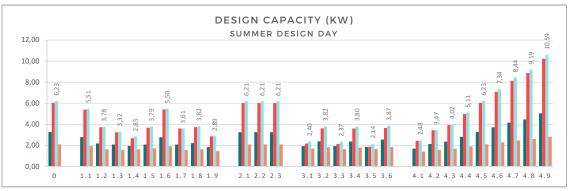


Figure 70: Graphs displaying the Cooling Load (annual and for summer design week) and Design Capacity (for Summer design day)

		TIOS	SOLITH ORIENTATION	N		FAST ORIENTATION	NC	>	WEST ORIENTATION	NO		NORTH ORIENTATION	
		Contract to the Contract Contr		Property (IAM)	Annual Control	1	Contract Countries (1980)	And the state of	7	And Constitution	Control of the Control		Catal Catal
	A Sana no	ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY ANNUAL SIMULATION WEEK	DESIGN SUMMER WEEK	DESIGN SUMMER DAY
Scenario	0 No passive strategies	175,82	6,23	3,28	153,06	2,09	6,05	146,09	71,7	6,23	72,63	4,38	2,11
Scenario	1.0 Glazing Type												
	1.1 dbl clear 6mm/6mm Air	163,42	5,61	2,80	145,76	6,59	5,40		69'9	5,51	71,69	4,13	1,94
	1.2 dbl LoE Clr 6mm/6mm Air	113,03	4,53	2,20	103,14			98,45					1,64
	1.3 dbl LoE Tint 6mm/6mm Air	94,05	4,17	2,09	87,48	4,65			4,65			3,30	1,59
	1.4 dbl Ref Clr 6mm/6mm Air	71,06	3,80	1,97	70,67	4,16				2,85			1,65
	1.5 dbl Ref Tint 6mm/6mm Air	74,92	3,97	2,09	93,76								1,74
	1.6 dbl Clr 6mm/13mm Argon	171,03	5,67	2,78	152,25			(-1					1,93
	1.7 dbl LoE Clr 6mm/13mm Argon	127,51	4,61	2,09	115,15	5,34	3,61		5,45		63,92		1,58
	1.8 dbl Ref Clr 6mm/6mm Argon	110,90	4,52	2,23	101,61	5,15			5,19				1,65
	1.9 dbl LoE Tint 6mm/13 Argon	96,84	4,02	1,85	68'68	4,52	2,88		4,56			3,22	1,47
Scenario	2.0 Night Ventilation												
	2.1 schedule a: n=5/hour	111,81	5,76	3,27	117,26	6,72	6,03		6,32	6,21		4,22	2,10
	2.2 schedule a: n=6/hour	111,48	5,74	3,27	116,89	0,70	6,03	102,03	6,29	6,21	55,83	4,21	2,10
	2.3 schedule a: n=7/hour	111,22	5,73	3,27	116,57	69'9			6,26			4,19	2,10
Scenario	3.0 Shading												
	3.1 external - slats - solar	67,74	4,00	1,94	68,72								1,72
	3.2 internal - slats - solar	100,18	4,74	2,40	94,75		3,64						1,83
	3.3 external - slats - always on	99'29	3,79	1,94	63,47			96'09					1,66
	3.4 internal -slats - always on	98,14	4,65	2,39	92,52	5,12	3,61		5,14	3,80	52,05	3,76	1,81
	3.5 ext - roll med opaque - solar	64,88	3,97	1,87	65,04	4,08	1,90	66,13	4,22		53,20		1,67
	3.6 el/chromic - refl - switchable	93,88	4,70	2,57	89,34	5,11	3,66	84,64	5,14	3,87		3,83	1,86
scenario	4.0 WWR												
	<b>4.1</b> WWR = 15%	80,43	3,94	1,71	76,71								1,42
	<b>4.2</b> WWR = 25%	106,89	4,63	2,14	99,05								1,60
	<b>4.3</b> WWR = 30%	120,94	4,97	2,37	109,95	5,60	3,95			4,02		3,72	1,70
	<b>4.4</b> WWR = 40%	148,80	5,61	2,83	131,31								1,91
	<b>4.5</b> WWR = 50% (scenario 0)	175,82	6,23	3,28	153,06	7,09	90'9		7,17		72,63	4,38	2,11
	<b>4.6</b> WWR = 60%	201,59	6,81	3,73	174,40	62,7			7,86	7,34			2,30
	<b>4.7</b> WWR = 70%	226,83	7,36	4,17	195,41	8,47	8,15		8,51			4,96	2,49
	<b>4.8</b> WWR = 80%	243,98	7,73	4,48	209,85	8,91				9,19	91,14		2,61
	<b>4.9</b> WWR = 90%	276,20	8,42	50'5			1						2,84

Figure 71: Table with the numerical results of Design Builder simulations per orientation. Displaying: 1-Annual cooling loads, 2-summer design week cooling loads, 3-summer design day capacity

## 7.2. Design Builder Model and Settings

#### Model

The research on the office facades in the center of Athens has led to some general observations, which will be used in order to proceed to the next step, namely to the simulation of the typical office space. There hase been selected one case, which bear the most common typological characteristics of office buildings in Athens. It is a building placed between other similar buildings in an attached building system. Total height is considered to be around 38 meters/10 floors, according to the average building height found on the field research.

We can notice certain urban design rules, which are applied in high-rise buildings in the center of Athens according to the existing legislation. This is, on the one hand, the public passway of 3 meters on the ground floor and on the other hand, the design of the penthouses, which above a certain height have a setback of 3 meters away from the building line, resulting into the depicted form. These strategies aim to provide a pedestrian-friendly urban context in terms of more convenient walking, protection from weather conditions and less visual obstacles.

In the following, there will be presented the details of the initial settings (scenario 0) of the simulation. The software used for the purposed of the dynamic simulation of the typical case is the Design Builder version 5.0.3.007. For practical issues the simulations emphasize on a characteristic office space, which is located on 7th floor (shown on figures above). This particular office is selected because of its position at the middle of the façade and its position not directly under the first penthouse.

All the sizes, numbers and constructions are based on a typical-standard office building located in the city of Athens, as derived from the previous analysis.

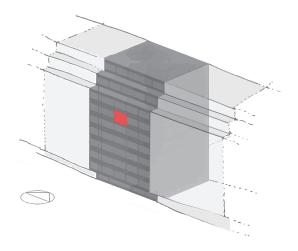
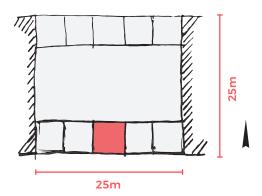


Figure 72: The simulation model in Design Builder. The test office is shown in red color.



5*5 m
22.95 m <sup>2</sup>
all
25 m
50%
3.8 m
7th (out of 10)
625 m <sup>2</sup>

#### **Settings**

LOCATION: Athens, Greece

LATITUDE: 37.9° LONGITUDE: 23.73°

LOCATION TEMPLATE: ATHINAI AP HELLINIKO\*

ASHRAE CLIMATE ZONE: 3A

OUTPUT INTERVALS FOR REPORTING: MONTHLY AND ANNUAL, DAILY

SUMMER DESIGN WEEK: 3 AUGUST - 9 AUGUST

SUMMER DESIGN DAY: 15 JULY

WINTER DESIGN WEEK: 17 FEBRUARY - 23 FEBRUARY

WINTER DESIGN DAY: 21 FEBRUARY

#### **ACTIVITY**

Occupancy density: 0.1 people/m2

Metabolic activity: Light office work/Standing/Walking

Cooling setpoint temperature: 26°C

Cooling setback: 28°C

Office equipment gain: 11.77 W/m2 Lighting target illuminance: 400lux

#### CONSTRUCTION

External Walls: Wall exterior Athens typical (6-layer construction; outermost layer: 20mm plaster – 100mm brick layer – 50mm air cavity – 50mm rigid thermal insulation extruded polystyrene

- 100mm brick layer - 20mm plaster: innermost layer)

U-value external Wall section: 0.482 W/m2K (Design Builder calculation)

Internal Partitions: 2\*12mm plasterboard leaves with 25mm glass wool in cavity

Internal Floor: 12mm carpet on 12mm rubber underlay

Airtightness/Infiltration: 0.2 ac/h (on 24/7)

#### **OPENINGS**

Glazing Type - external windows: Single Clear 6mm

WWR: 50% Shading: NO

#### LIGHTING

General Lighting: ON

Normalized Power Density: 3 W/m2 - 100lux

Luminaire Type: Suspended Working place height: 0.80m

#### **HVAC**

Template for HVAC: Fan Coil Unit (4-pipe), air cooled

Mechanical Ventilation: ON (min fresh air - sum per person)

Heating: OFF Cooling: ON

Fuel for cooling: Electricity from grid Cooling System Seasonal COP: 1

Notes: This project is focusing on a solar cooling façade module, heating is not examined and thus has been turned off for the simulations.

The cooling at this moment is turned on and the COP is set to 1, because this way the output cooling load will be indicative of the actual energy consumption of this construction. At this point the kind of the cooling system is not important as long as COP=1.

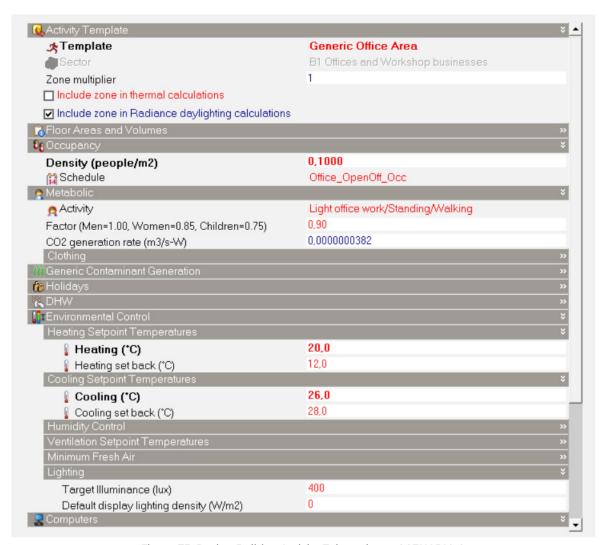


Figure 73: Design Builder, Activity Tab settings - SCENARIO 0

Template	Project glazing template	
External Windows		
	Sgl Clr 6mm	
Layout	Preferred height 1.5m, 50% glazed	
Dimensions		
Туре	3-Preferred height	
Window to wall %	50,00	
Window height (m)	1,50	
Window spacing (m)	5,00	
Sill height (m)	0,80	
Reveal		
Frame and Dividers		
Shading		
☐ Window shading		
■ Local shading		
Airflow Control Windows		
Free Aperture		
Internal Windows		
Sloped Roof Windows/Skylights		
Doors		

Figure 74: Design Builder, Glazing Tab settings - SCENARIO 0

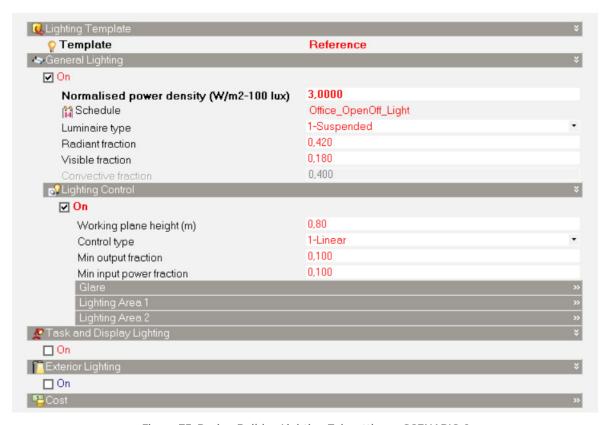


Figure 75: Design Builder, Lighting Tab settings - SCENARIO 0

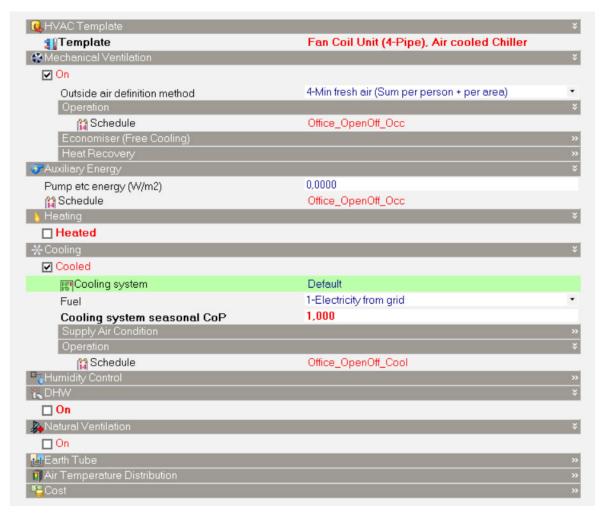


Figure 76: Design Builder, HVAC Tab settings - SCENARIO 0

## 7.3. Results and Evaluation

#### Discussion of the results

After the examination of various scenarios we can make some first observations and draw some first conclusions which will assist to proceed to the passive optimization step.

- All implemented passive strategies provide with improved situations. The only exceptions are those with the higher WWR scenarios, where this is logical, considering that there is single 6mm glazing and also the glazed area increases, leading to higher solar gains.

#### Scenario 1.0 (Glazing Type):

- Reflective clear glazing is the best in terms of cooling loads and design capacity
- Glazing with LowE coating presents also very improved performance
- Tint in glazing has improved the performance
- Argon filling does not give better values than air filling

#### Scenario 2.0 (Glazing Type):

- The scenario of night ventilation leads to small improvement of the results compared to the other strategies
- More changes per hour have very minor effects on the results

#### Scenario 3.0 (Shading Type):

- External shading is more effective in all cases compared to internal shading
- Solar controlled dynamic shading leads to higher cooling loads than static shading always on
- Slats and roll type of shading give similar results

#### Scenario 4.0 (WWR):

- The smaller WWR, the lower cooling loads.

## 7.4. Passive Optimization – Phase 3

#### **Description**

Following the examination of the various scenarios which have been presented, a passive optimization took place with the aim to find the optimum combination of strategies that could be applied to the case study. As it seemed logical, the scenarios with the best results during phase 2 have been examined initially and also some of the "second best strategies". The following table presents the various scenarios. In each case a combination from all 4 strategies has been applied. Only exception is scenario B, which is identical with scenario A, only without night ventilation. From the results we can see that the absence of night ventilation leads to higher annual cooling loads, so for this reason it is considered for all further cases.

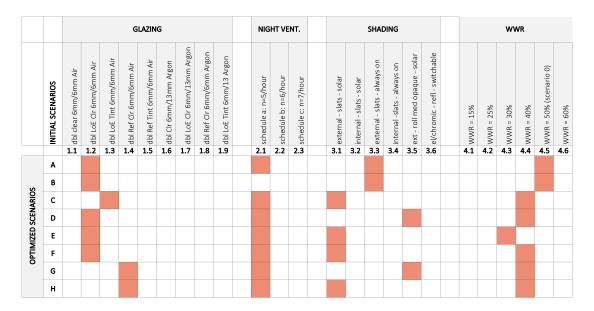


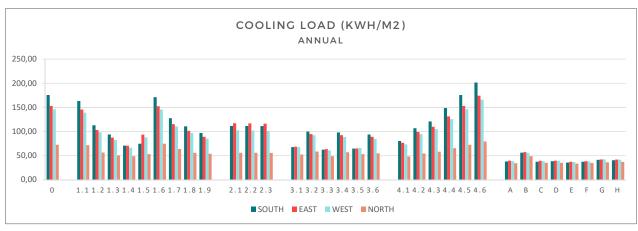
Figure 77: Optimization Index

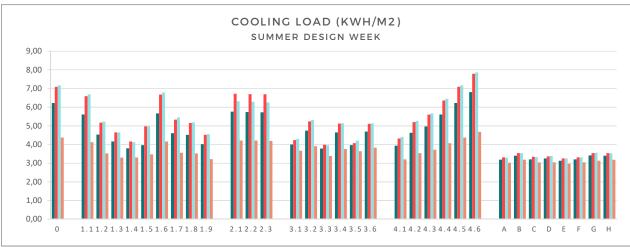


Figure 78: Further parameter for the passive evaluation: lighting loads

As the purpose of this step was to end up to the least optimum passive solutions, the criteria for the analysis have been expanded also to the annual lighting loads and also the summer design day cooling load. Also, a fifth orientation case has been simulated for north with no shading, because in a real situation there is no direct sunlight reaching the north for the case of Greece, so sun shading is unnecessary.

The results are the following:





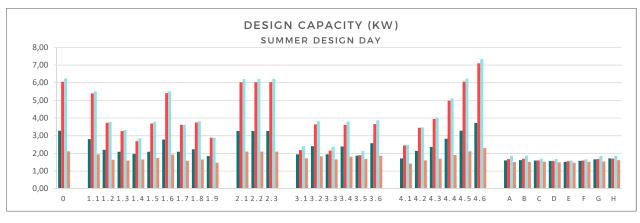


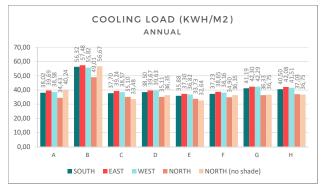
Figure 79: Comparative graphs for initial scenarios and passive optimization. It is obvious that all optimized scenarios A-H provide with significantly improved results. Scenarios 4.7-4.9 have been excluded from this representation.

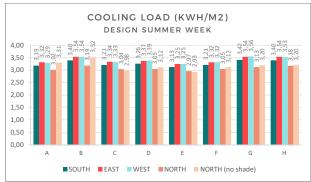
				so	UTH ORIENTATIO	ON			E	AST ORIENTATION	ON	
		Strategy	Cooling loads (kW	'h/m2)		Design Capacity (kW)	Lighting Loads (kWh/m2)	Cooling loads (l	«Wh/m2)		Design Capacity (kW)	Lighting Loads (kWh/m2)
			ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY	ANNUAL	ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY	ANNUAL
PASSIVE OF	TIMIZA	TION										
Scenario	Α	1.2 + 2.1 + 3.3 + 4.5	38,02	3,19	0,53	1,60	15,27	39,69	3,32	0,57	1,68	17,66
	В	1.2 + 3.3 + 4.5	56,32	3,40	0,57	1,61	15,33	57,48	3,54	0,62	1,69	17,73
	С	1.3 + 2.1 + 3.1 + 4.4	37,70	3,21	0,53	1,59	19,54	39,24	3,34	0,56	1,60	20,39
	D	1.2 + 2.1 + 3.5 + 4.4	38,50	3,26	0,53	1,56	23,38	39,67	3,37	0,56	1,56	23,20
	E	1.2 + 2.1 + 3.1 + 4.3	35,88	3,13	0,51	1,52	22,26	37,30	3,25	0,54	1,55	21,99
	F	1.2 + 2.1 + 3.1 + 4.4	37,23	3,21	0,53	1,58	19,31	38,65	3,32	0,55	1,59	19,27
	G	1.4 + 2.1 + 3.5 + 4.4	41,19	3,42	0,56	1,66	28,73	42,30	3,54	0,60	1,67	28,83
	Н	1.4 + 2.1 + 3.1 + 4.4	40,50	3,40	0,56	1,71	26,98	42,08	3,54	0,60	1,70	27,11

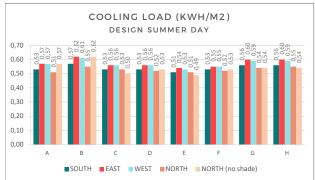
				WE	ST ORIENTATIO	N			NOI	RTH ORIENTATIO	)N	
		Strategy	Cooling loads (	kWh/m2)		Design Capacity (kW)	Lighting Loads (kWh/m2)	Cooling loads (k	Wh/m2)		Design Capacity (kW)	Lighting Loads (kWh/m2)
			ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY	ANNUAL	ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY	ANNUAL
PASSIVE OP	TIMIZA	TION										
Scenario	A	1.2 + 2.1 + 3.3 + 4.5	38,58	3,29	0,57	1,86	17,94	34,43	3,02	0,51	1,51	22,29
	В	1.2 + 3.3 + 4.5	55,82	3,54	0,61	1,87	18,02	49,01	3,19	0,55	1,52	22,38
	С	1.3 + 2.1 + 3.1 + 4.4	38,57	3,33	0,56	1,69	20,17	35,10	3,04	0,53	1,53	21,35
	D	1.2 + 2.1 + 3.5 + 4.4	39,63	3,39	0,56	1,67	22,84	35,11	3,05	0,52	1,49	21,51
	E	1.2 + 2.1 + 3.1 + 4.3	36,82	3,25	0,53	1,59	21,63	33,73	2,97	0,51	1,47	20,35
	F	1.2 + 2.1 + 3.1 + 4.4	38,16	3,32	0,55	1,66	18,97	34,90	3,05	0,52	1,52	18,35
	G	1.4 + 2.1 + 3.5 + 4.4	42,29	3,56	0,59	1,84	28,40	36,33	3,13	0,54	1,54	27,14
	Н	1.4 + 2.1 + 3.1 + 4.4	41,51	3,53	0,59	1,86	26,71	37,03	3,18	0,55	1,61	25,72

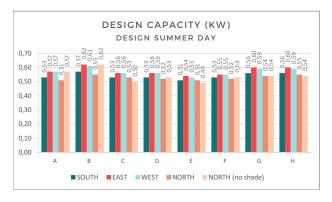
				NORTH O	RIENTATION* (N	O SHADE)	
		Strategy	Cooling loads (k)	Wh/m2)		Design Capacity (kW)	Lighting Loads (kWh/m2)
			ANNUAL	DESIGN SUMMER WEEK	DESIGN SUMMER DAY	DESIGN SUMMER DAY	ANNUAL
PASSIVE OP	TIMIZA	TION					
Scenario	A	1.2 + 2.1 + 3.3 + 4.5	40,24	3,31	0,57	1,64	7,84
	В	1.2 + 3.3 + 4.5	56,67	3,52	0,62	1,64	7,86
	С	1.3 + 2.1 + 3.1 + 4.4	33,48	2,98	0,50	1,48	11,01
	D	1.2 + 2.1 + 3.5 + 4.4	36,35	3,12	0,53	1,52	8,50
	E	1.2 + 2.1 + 3.1 + 4.3	32,64	2,93	0,49	1,41	9,33
	F	1.2 + 2.1 + 3.1 + 4.4	36,35	3,12	0,53	1,52	8,50
	G	1.4 + 2.1 + 3.5 + 4.4	36,75	3,20	0,54	1,59	13,80
	н	1.4 + 2.1 + 3.1 + 4.4	36,75	3,20	0,54	1,59	13,80

Figure 80: Numerical output from passive optimization.









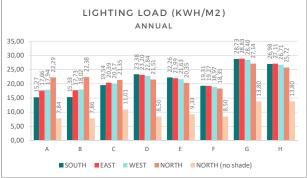


Figure 81: Graphs of scenarios A-H (passive optimization)

#### **Discussion - Evaluation**

It would be practically impossible to cross-check every possible combination of the 27 scenarios in order to find the best, so the optimized scenarios are based on selection of the best results of the second phase of the analysis.

As we saw, the implementation of night ventilation by itself does not contribute significantly to the situation, but in combination with other strategies leads to better results.

There are materials, such as those with high reflectivity, which can play a significant role in the urban heat island effect, although we cannot directly measure these impacts. Reflective glazing is crossed out of the concept for this reason. Besides, as it was shown in scenarios G and H, in combination to the other strategies it displays worse values for cooling loads and lighting loads.

The variation NORTH without shading is proved to be far more efficient in terms of lighting loads, so it is confirmed that can be used.

Scenario B (no night ventilation) is rejected due to the increased annual values compared to other scenarios. Scenarios 4.6 - 4.9 are rejected due to their much raised cooling loads. Scenarios 4.1 - 4.2 are also rejected because very low WWR will impact the visual quality of the office space and the indoor comfort level in terms of light. Also, it is estimated that they would lead to high lighting loads.

#### Final / Optimal scenario - Phase 4

In this final phase the Scenario F is selected as the optimum scenario.

#### **SCENARIO F**

Glazing: double Low-E Clear 6mm/6mm Air

Night ventilation: n=5per hour

Shading: external slats solar

WWR: 40%

In fact, the difference between scenarios C, D, E and F present small differences and would be almost equally efficient. Also, as it is evident from the passive optimization (phase 3) the sunshading is better if placed on the exterior side and is solar responsive. The distinction between slats and roll is not so important now, as the results are very similar after the simulations. It could be therefore a design choice later on. Lastly, the scenarios C and F have tiny difference in all simulations, but F has a slightly better performance, thus it is selected as the optimum scenario.

Note: In this paragraph the Cooling and Heating Loads are represented as factors of the heat balance equation, so the Cooling appears with negative sign.

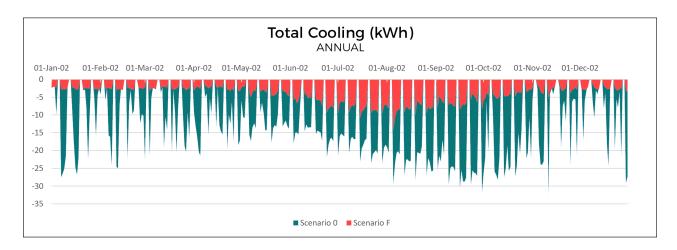


Figure 82: Total Cooling Loads for Scenario 0 (initial) and Scenario F (final) - ANNUAL REPRESENTATION

Data: Design Builder

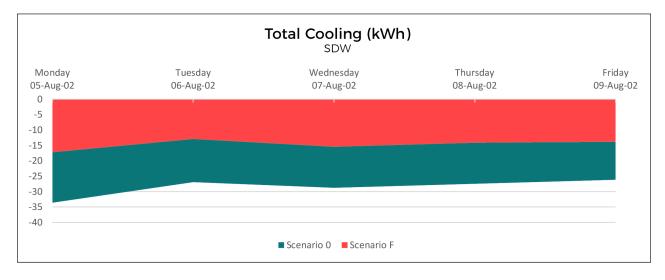


Figure 83: Total Cooling Loads for Scenario 0 (initial) and Scenario F (final) - SUMMER DESIGN WEEK REPRESENTATION
Data: Design Builder

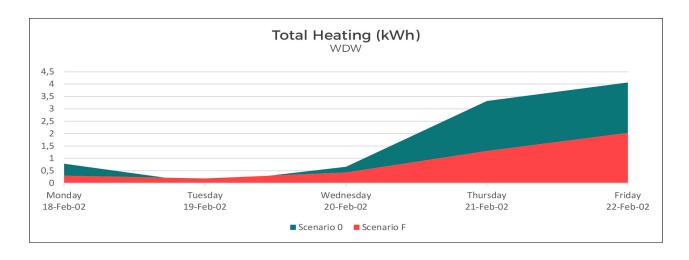


Figure 84: Total Heating Loads for Scenario 0 (initial) and Scenario F (final) - WINTER DESIGN WEEK REPRESENTATION

Data: Design Builder

## 7.5. Hand Calculations

#### Stationary heat balance calculation (without thermal mass)

As a next step after the simulations with Design Builder, some basic hand calculations are done in order to determine the cooling demand. The heat balance equation describes the heat transfer relations. The model follows the simulation settings of Design Builder and more specifically the scenario 0. It is also considered that there are adjacent office rooms with similar conditions, so there is no transmission between those. Transmission occurs only between the room and the external environment through the façade. The heat flows might have positive or negative sign depending on their direction inwards or outwards.

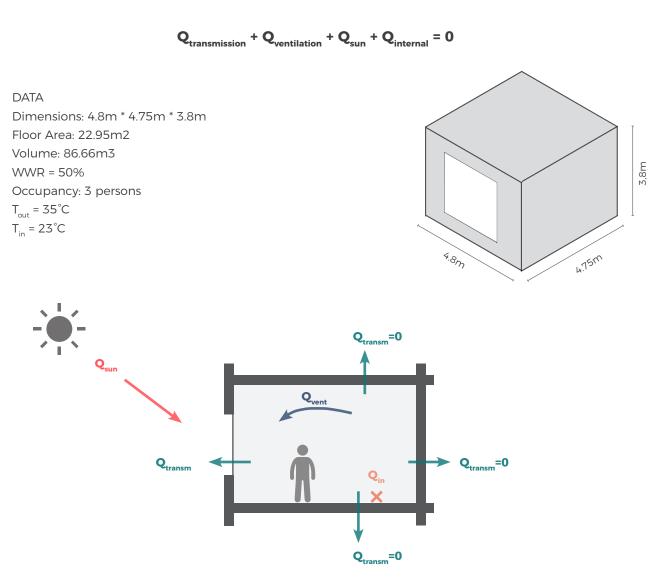


Figure 85: Heat flows of the heat balance equation

• 
$$\mathbf{Q}_{intern}$$
 =  $\mathbf{Q}_{people}$  +  $\mathbf{Q}_{lights}$  +  $\mathbf{Q}_{equipment}$  = 130 \* 3 + 3 \* 22.95 + 11.77 \* 22.95 = 390 + 68.85 + 270.12 = 728.97 W

• 
$$Q_{sun}$$
 =  $W_{sun}$  \* Area<sub>glass</sub> = 400 \* 3.8 \* 4.8 \* 0.5 = 3648 W

• 
$$\mathbf{Q}_{\text{ventilation}}$$
 =  $\rho$  \* c \* n \* V \*  $\Delta$ T \* 3600<sup>-1</sup> = (1200 \* 5 \* 86.66 \* 12) / 3600 = 6239520 / 3600 = 1733.2 W

• 
$$\mathbf{Q_{transmission}} = \sum_{i} U_{i} * A_{i} * \Delta T = U_{wall} * A_{wall} + U_{glass} * A_{glass} = 0.482 * 9.5 + 6.1 * 9.5 = 62.529 W$$

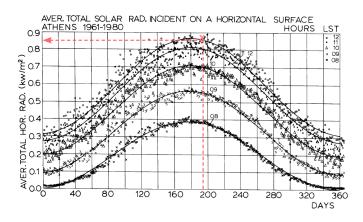
#### **Determination of W**<sub>sun</sub>

The amount of energy that comes from the sun is dependent mainly on two factors: the geographical location and the angle of the incidence. Sky cover range is also important, but is also arbitrary and cannot be taken into account in the calculations.

For this case is required the value of W for a vertical surface oriented towards the south for the location of Athens. Since this information is not directly available neither from literature nor from Design Builder, some estimations have been made in order to consider an approximate value.

Starting from the total solar radiation incidence on horizontal surface (retrieved from Figure 86) ~850kW/m2 and total direct radiation (retrieved from Figure 87) ~1000kW/m2, it is assumed that the total radiation incidence on a vertical surface should be significantly lower due to the height of the sun in summer (75°). Also, as reference we can use the W value for Netherlands ~700kW/m2 (retrieved from Figure 88). The W value for Greece should be also lower than this value, considering that the solar incidence is different in the two countries.

Therefore, an approximate value would be reasonable to vary between 400kW/m2 and 500kW/m2. For the static calculations W=400kW/m2 will be used.



1.0 duect radiation (kM/m/m) 0.8 due to 1.0 duect radiation (kM/m/m) 0.0 duect radiation (kM/m/m) 0.0 duect radiation (kM/m/m) 0.0 duect radiation (kM/m) 0.

Figure 86: Calculated yearly variation of the average total solar irradiation on a horizontal surface in Athens for every hour from 08:00 to 12:00 hrs LST. Design summer day (July 15=Day 196) is marked on the diagram.

Source: D. Kouremenos et al, 1985.

Figure 87: Solar direct radiation intensity in W/m<sup>2</sup> throughout the day (Day 196=July 15). Latitude: 38° North, Athens. Absense of clouds. Source: http://www.pveducation.org/pvcdrom/calculation-of-solar-insolation

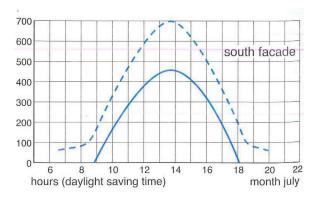
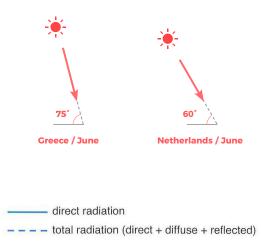


Figure 88: Solar radiation intensity on the vertical plane in W/m² through out the day (July). Location: Netherlands. Source: v. d. Linden et al, 2013.



#### Calculation of T<sub>in</sub> after 5 hours (with thermal mass)

For the same room as examined previously, a calculation of the final reached temperature will be shown.

DATA

Dimensions: 4.8m \* 4.75m \* 3.8m

Floor Area: 22.95m2 Volume: 86.66m3 WWR = 50%

Occupancy: 3 persons

 $T_e = 35^{\circ}C$   $T_{in} = 23^{\circ}C$ t = 5 hours

n (ventilation) = 5 / hour Floor material: concrete

$$T_i = T_e + \frac{W}{H} (1 - e^{\frac{-H}{M}t})$$

 $\textbf{H} = \textbf{H}_{\text{transmission}} + \textbf{H}_{\text{ventilation}} = \sum_{i=1}^{n} U_{i}A_{i} + \text{npcV}/3600 = U_{\text{wall}} + U_{\text{glass}} + U_{\text{glass}} + S*1200\text{V}/3600 = 0.428*9.5 + 6.1*9.5 + 5*1200*86.66/3600 = 4.579 + 57.95 + 144.43 = 206.96$ 

 $\mathbf{M} = \mathbf{M}_{material} + \mathbf{M}_{air} = \rho_{mat} * C_{mat} * length * width * spec.thickness + <math>\rho_{air} * c_{air} * V_{air} = 2400 * 0.75 * 22.95 * 0.1 + 1200*86.66 = 4131 + 104 = 4235$ 

$$W = Q_{intern} + Q_{sun} = 728.97 + 400 * 19 = 729 + 7600 = 8329$$

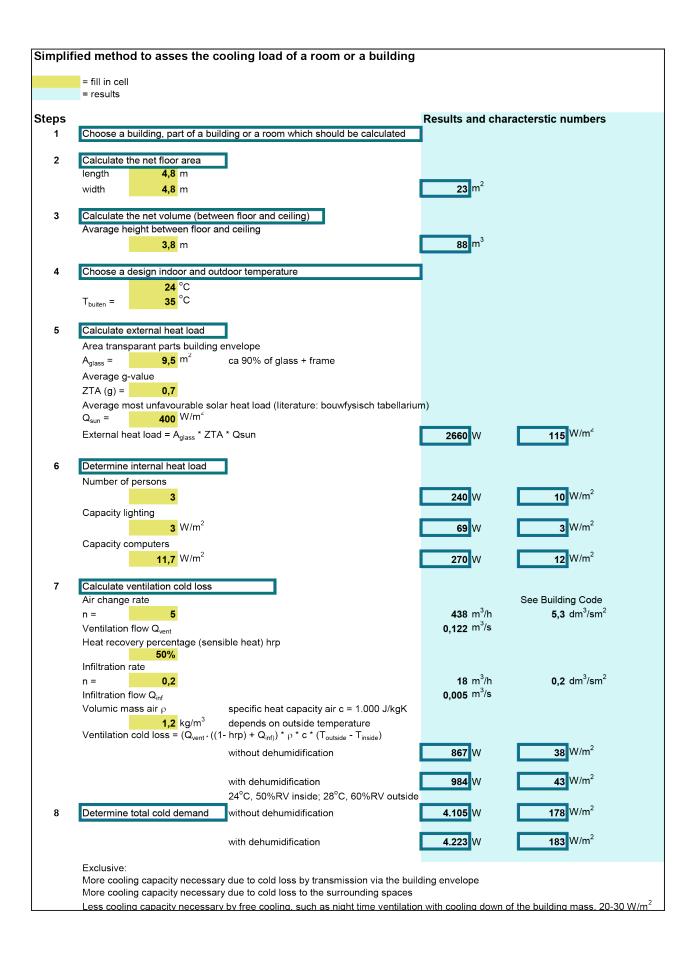
so, according to the initial equation:

$$T = 35 + (8329/206.96)^* (1 - e^{(-206.96'5)/4235}) = 35 + 40.24^* (1 - e^{-0.24}) = 35 + 40.24^* 0.22 = 43.9^{\circ}C$$

After 5 hours of sunshine the temperature will rise to 43.9°C. This is of course a high temperature which cannot be accepted for an occupied space such as an office room. However, since this calculation is made according to Scenario 0, it is expected to be high. A lower temperature is expected for scenario F, but this calculation is noy possible because the W value with external sunshading is not known.

#### **Simplified Calculation Formula**

Another method to calculate the cooling loads of a certain office space is given by the following formula. The numeric input is kept same to the possible degree as in Design Builder.



## 7.6. System Sizing

#### **COOLING APPLICATION**

The system size can be calculated by taking into consideration the efficiency of the PVs and subsequently the COP of TEs. As the efficiency of the PV is influenced by the orientation and tilt, the monthly averaged radiation incident (r) is also included in the calculation. (Figure 89).

The efficiency of PVs and the COP of TEs have been discussed on previous chapters regarding the average and the future potential. Also, analytic schemes showing the function of the system can be found on paragraph 8.2 on page 105. In the following calculations there will be presented the different results according to the average available modules and also the most promising future numbers according to literature and manufacturers.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tilt 90°	3,06	3,08	3,26	3,07	2,72	2,58	2,69	3,23	3,8	3,58	2,78	2,53

Figure 89: Monthly Averaged Radiation Incident On An Equator-Pointed Tilted Surface (kWh/m2/day). Emphasized are the values for February (winter design) and July (summer design). Source: NASA - https://goo.gl/AtwCpU

Area façade	3,8	5	19	m2
WWR	0,4			
Area glazing	19	0,4	7,6	
Area PV	19	0,6	11,4	
Area office	22,95	m2		
Cooling demand				
(SDD)	0,53	kWh/m2		
Total demand	12,16	kWh		

Figure 90: Calculation of Solar Outout and Total System Output for different  ${\rm eff}_{\rm PV}$  and  ${\rm COP}_{\rm TE}$ .

calculation	(1)				
eff PV	0,2				
COP TE	0,225				
Solar Outp	2,69	0,2	11,4	6,13	kWh
Total Syste	6,13	0,225	-	1,38	kWh/day
% of peak	-	-	-	11,35	%

calculation	(3)				
eff PV	0,35				
COP TE	0,225				
Solar Outp	2,69	0,35	11,4	10,73	kWh
Total Syste	10,73	0,225	-	2,41	kWh/day
% of peak	-	-	-	19,85	%

calculation	(5)				
eff PV	0,35				
COP TE	1,2				
Solar Outp	2,69	0,35	11,4	10,73	kWh
Total Syste	10,73	1,2	-	12,88	kWh/day
% of peak	-	-	-	105,89	%

calculation	1 (2)				
eff PV	0,2				
COP TE	0,8				
Solar Outp	2,69	0,2	11,4	6,13	kWh
Total Syste	6,13	0,8	-	4,91	kWh/day
% of peak	-	-	-	40,34	%

calculation	calculation (4)							
eff PV	0,35							
COP TE	0,8							
Solar Outp	2,69	0,35	11,4	10,73	kWh			
Total Syste	10,73	0,8	-	8,59	kWh/day			
% of peak	-	-	-	70,59	%			

calculation (6)						
eff PV	0,4					
COP TE	1,2					
Solar Outp	2,69	0,4	11,4	12,27	kWh	
Total Syste	12,27	1,2	-	14,72	kWh/day	
% of peak	-	-	-	121,02	%	

According to these calculations we can see the efficiency of the whole system and also check in relation to the passive optimization. This way, we know how much we have gained from the implementation of the thermoelectric cooling system.

Important factor is the orientation of the panels and also the different values of "r" throughout the year. For simplification reasons, the calculations do not contain dynamic input, they only show the potential maximum that can be achieved. As a possible further research topic, a dynamic/parametric model could be built to simulate other orientations and tilt of PV panels, but this exceeds the boundaries of the current project (eg Ladybug and Honeybee plugins of Grasshopper).

As it is shown on the calculation, this particular façade cooling system depends on two major factors, firstly the efficiency of PV and secondly the COP of TEs. With the development of the technologies and achievement of higher efficiencies it is certain that the overall efficiency can be achieved. The following chart will help compare the Cooling Loads as in Scenario 0, Scenario F, after the passive optimization and finally on the aforementioned calculations.

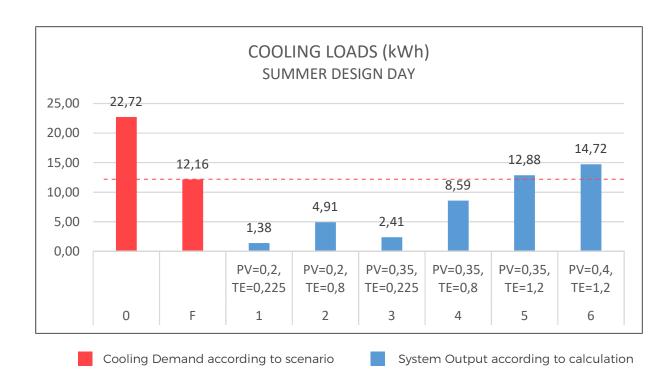


Figure 91: Comparative chart of Cooling Load on Summer Design Day (SDD) for initial case, passive optimization and final scenario. Simulation and calculation for south orientation.

#### **HEATING APPLICATION**

The calculation for the heating is similar, only this time we consider the peak heating demand (winter design day - 21 February and we use the "r" for February. Since the peak heating demand is considerably lower than cooling, the thermoelectric system can satisfy the demand and also produce excess.

The results are presented below.

Area façade	3,8	5	19	m2
WWR	0,4			
Area glazing	19	0,4	7,6	m2
Area PV	19	0,6	11,4	m2
Area office	22,95	m2		
Heating demand				
(WDD)	0,11	kWh/m2		
Total demand	2,52	kWh		

calculation (1)						
eff PV	0,2					
COP TE	0,225					
Solar Outp	3,08	0,2	11,4	7,02	kWh	
Total Syste	7,02	0,225	-	1,58	kWh/day	
% of peak	-	-	-	62,59	%	

calculation (3)						
eff PV	0,35					
COP TE	0,225					
Solar Outp	3,08	0,35	11,4	12,29	kWh	
Total Syste	12,29	0,225	-	2,77	kWh/day	
% of peak	-	-	-	109,53	%	

calculation	calculation (2)						
eff PV	0,2						
COP TE	0,8						
Solar Outp	3,08	0,2	11,4	7,02	kWh		
Total Syste	7,02	0,8	-	5,62	kWh/day		
% of peak	-	-	-	222,54	%		

calculation (4)						
eff PV	0,35					
COP TE	0,8					
Solar Outp	3,08	0,35	11,4	12,29	kWh	
Total Syste	12,29	0,8	-	9,83	kWh/day	
% of peak	-	-	-	389,44	%	

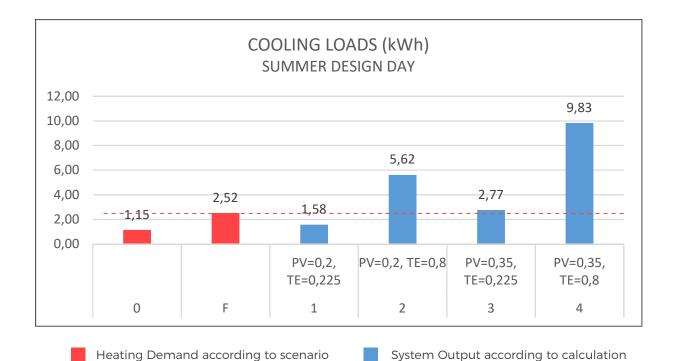


Figure 92: Comparative chart of Heating Load on Winter Design Day (WDD) for initial case, passive optimization and final scenario. Simulation and calculation for south orientation.

#### **Thermoelectric System Sizing**

The previous paragraphs describes the overall system efficiency according to the input of PVs. Since the available PV area is limited and also the presence of a window is essential, there is an upper limit as to how much energy the system can gain from the sun. However, as the fff describes, the façade cooling system can not only work independently, but it can also use energy from the building grid to supply the TEMs. For this reason, and also considering unlimited electrical power from the grid, it is prudent to base the thermoelectric sizing on the maximum design capacity as found on the Design Builder simulations.

Design Capacity (SDD) according to scenario 0: 3.28kW = 3280W

Design Capacity (SDD) according to scenario F: 1.60kW = 1600W (optimized)

TE Qc = 12.17W Area of module = 1600mm<sup>2</sup> = .0016m<sup>2</sup> 1600W/12.17W = **132 modules** 132 modules \* 0.0016m<sup>2</sup> = **0.21m<sup>2</sup>** 

TE Qc = 63W (average value) Area of module = 0.0016m<sup>2</sup> 1600W/63W = **26 modules** 26 modules \* 0.0016m<sup>2</sup> = **0.0416m<sup>2</sup>** 

Consequently, by using average performance modules, it is required to place 26 on the façade. Those should be distributed over the available facade area for better heating/cooling distribution.

Similar is the calculation according to the heating, but since the heating demands are much lower and also the solar radiation incident in winter is higher, the demands can be covered.

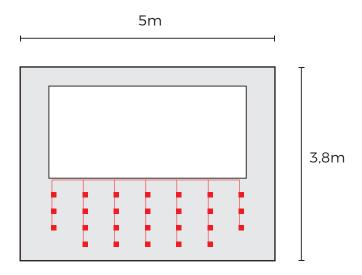


Figure 93: Exemplary positioning of 26 TE modules on facade 3.8\*5m with WWR 40%. Wired in parallel (7 threads) and in series.

DESIGN

mounting bracket for PV

ble cladding 40mm

water barrier

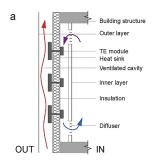
## 8. Design

## 8.1. Design Guidelines

Based on the studied literature there have been explored some design principles for the integration of thermoelectric cooling technology to the facade. There are three variations, based on the heat transfer medium: air-based, solid-based and water-based.

The following schemes are taken into account as guidelines for the development of the facade concept.

#### Air-based type



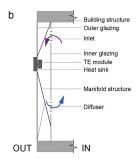
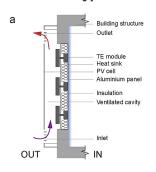


Figure 94: Air-based facade types, source: Prieto et al. (2017) based on information by Liu et al (2015) and Ibanez-Puy et al. (2015).

#### Solid-based type



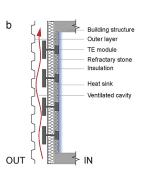


Figure 95: Solid-based facade types, source: Prieto et al. (2017) based on information by Liu et al (2015) and Ibanez-Puy et al. (2015).

#### Water-based type

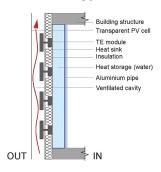


Figure 96: Water-based facade types, source: Prieto et al. (2017) based on information by Xu et al. (2007), (2008).





Figure 97: (left) Testing room model for performance test. Source: Xu et al. Figure 98: (right) Experimental setup for performance test. Source: Xu et al.

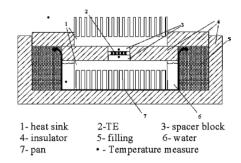
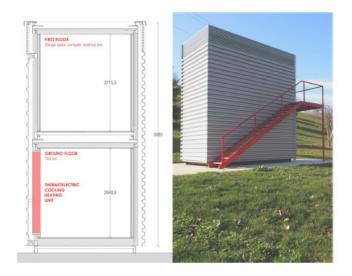


Figure 99: Sectional drawing of the setup for single TE unit. Source: Xu et al.



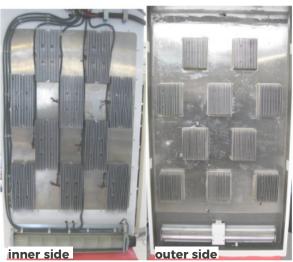


Figure 100: Construction section of the test cell. The thermoelectric unit is on the ground floor, while the auxiliary equipment is in the upper floor. Source: Ibanez 2017

Figure 101: Global disposal of the heat sinks and fans in the outer side and in the inner side of the thermoelectric unit.

Source: Ibanez 2017.

In all of the examined cases, crucial are two main factors: the thermal insulation and the heat transfer medium. The TEMs need to be thoroughly insulated from the environment in order to ensure that the heat flow happens only in the desired direction and through the foreseen media. The heat sinks play an important role in the heat dissipation and direction of the flow.

The heat transfer medium according to the categorization of Prieto et al (2017), presented on Figure 94 - Figure 96 on page 102, can be solid, air or water. Heat transfer through conduction is always preferable, therefore heat sinks are used for both the hot and the cold plate of the TE. Additional methods are used in order to forward the 'heat' to the desired place/area.

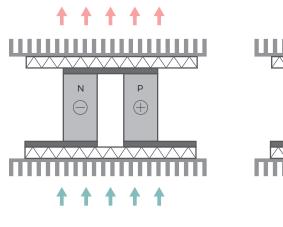
Furthermore, according to the experiment performed by Ibanez et al (2017), presented on Figure 100 and Figure 101 on page 103, it is advised to attach larger heat sinks on the cold plate, as the CoP of the TEMs tends to be lower when they perform in cooling function.

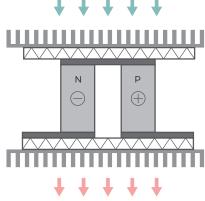
## 8.2. System Design

#### Thermoelectric arrangement and function

The following scheme summarizes the arrangement of a TE module and two heat sinks on both sides for facade integration.

The TEMs can be placed in array on the facade component in series or parallel. The electrical connection does not affect the efficiency of the modules (Lairdtech) but is important to ensure for optimum function and consider the possibility of failure of one TE.





Heat Sink

Electrical Insulation (Ceramic Plate) Electrical Conducting Material

P- and N-type Semiconductors

Electrical Conducting Material
Electrical Insulation (Ceramic Plate)
Heat Sink

HEAT ABSORPTION

**HEAT CONTRIBUTION** 

Figure 102: Schematic configuration of TE module and heat sinks for facade integration. The direction of the current can be regulated in order to set the direction of the heat flow and subsequently the application of heating or cooling.

Adapted from Ibanez et al 2017.

#### **Heat sink**

The heat sink plays an important role as it helps the remove excess heat and also absorb heat from the environment.

The most common heat sink materials are aluminium alloys. Aluminium alloy 1050A has one of the higher thermal conductivity values at 229 W/mK but is mechanically soft. Aluminium alloys 6060 and 6063 are commonly used, with thermal conductivity values of 166 and 201 W/mK, respectively. The values depend on the temper of the alloy.

Copper has around twice the conductivity of aluminium, but is three times as dense and, depending on the market, around four to six times more expensive than aluminium. Aluminium can be extruded, but copper cannot. Copper heat sinks are machined and skived. Another method of manufacture is to solder the fins into the heat sink base.

Diamond is another heat sink material, and its thermal conductivity of 2000 W/mK exceeds copper five-fold. Nowadays synthetic diamond is used as submounts for high-power integrated circuits and laser diodes.

Composite materials can also be used. Examples are a copper-tungsten pseudoalloy, AlSiC (silicon carbide in aluminium matrix), Dymalloy (diamond in copper-silver alloy matrix), and E-Material (beryllium oxide in beryllium matrix). Such materials are often used as substrates for chips, as their thermal expansion coefficient can be matched to ceramics and semiconductors. (ABL, 2016)

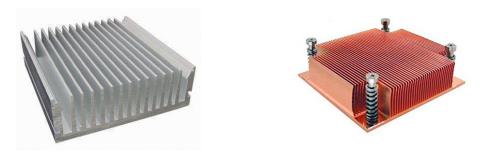


Figure 104: Aluminum extrusion heat sink profile (left), copper heat sink profile (right). Source: Google images

#### **Electrical arrangement**

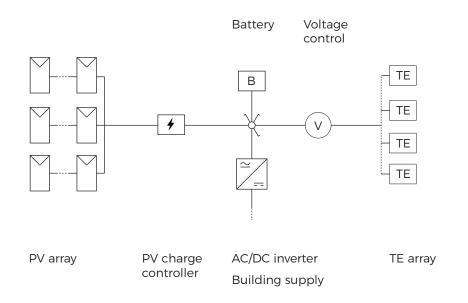


Figure 103: Electric circuit diagram showing the schematic system.

Sceme drawn by author, based on info from various sources. (Laird thermoel. handbook)

As it is shown on the scheme, the solar cooling system is autonomous and can function independently from the building electrical supply, but it can also use it for its benefit.

Primarily the PV array provides DC power which feeds the TEMs passing previously through a voltage control device. When excess power is generated but not immediately needed, it can be stored in the battery and used later on. Lastly, the AC supply of the building can also be used after being inverted to DC.

A three-wayswitch enables to control the power flow of the system according to the occasional needs. Connection in parallel for both PVs and TEs is preferred in order to minimize potential losses due to disfunctions or failures.

Going in more depth, we will examine the specific components of the system and how they are related to each other on the facade component. These components are: PV panels, TE modules, heat sink for heat rejection of the TE hot plate and a heat transfer medium for the cold plate.

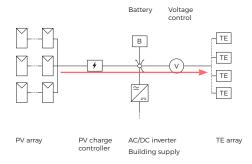


Figure 105: Primary power flow, from PVs directly to TEs

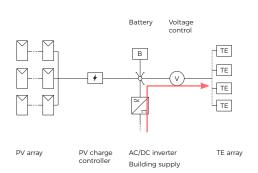


Figure 107: Alternative function, electricity from the building is used after being converted to DC. Can be useful to cover the peaks or during cloudy days.

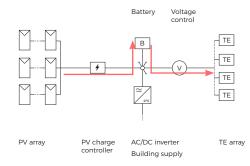


Figure 106: Alternative function, energy from PVs is stored in batteries and when needed fed to TEs

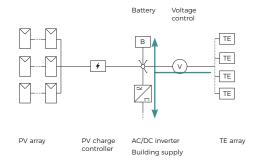


Figure 108: Potential reverse function, temperature difference created on TEs produces DC which is either stored in batteries or supplied to the building.

## 8.3. Condensation and internal surface problems

The thermoelectric module is a device with small dimensions (4-6cm square) and the  $\Delta T$  which is developed between the two ceramic plates can be up to 60°-70° C. It is to be expected that the cold plate might reach temperature of 0° or even lower and this can lead to condensation problems.

An average value of relative humidity is approximately 40% - 50% for an indoor room and also an average dry bulb temperature within the comfort zone is 25°C. For these conditions according to the psychrometric diagram on Figure 109, the dew point temperature varies between 10° and 14° C. However, when T <  $T_{DEW}$  and since  $T_{COLDPLATE}$  < 10° C, condensation will occur (v. d. Linden 2007).

#### Measures against condensation

It seems that condensation occurrence cannot be avoided on the cold side of the construction, as practically always will be  $T_{COLDPLATE} < T_{DEW}$ . In this case protective measures need to be considered to ensure the unobstructed function. Proper drainage needs to be designed, so that condensed moisture can be removed from the construction.

Furthermore, the low temperature that develops on the cold plate and cools the adjacent air is distributed over the room with the help of a ventilator attached to the bottom. This way the 'heat' is distributed by the forced air flow and also by radiation. In the small scale, the elongated fins on the cold plate allow for conduction.

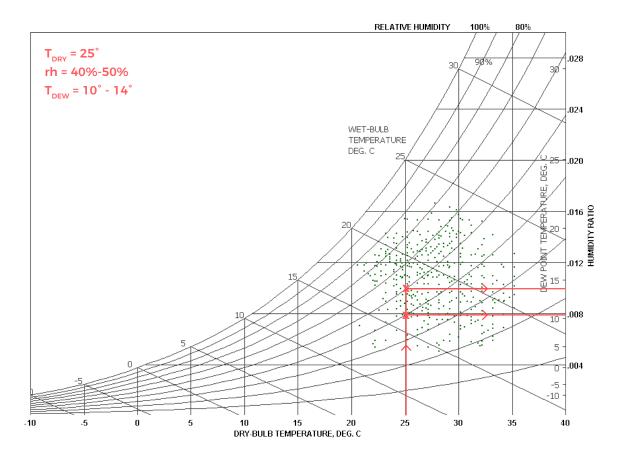


Figure 109: Psychrometric diagram. Comfortable conditions are represented with green dots. Display for dew point temperature with rh=40-50% and T<sub>DRV</sub>=25°C. Source: Climate Consultant 6.0

The temperature of the cold plate of the thermoelectric is not precisely known but according to the manufacturers' information, it can vary from -10°C to 10°C. The temperature is naturally very low and could be compared with the high heat which is developed on an old-fashioned light bulb. The dimensions and the watt-output of the two devices are similar, thus the perception of hot/cold feeling are also comparable.

According to the equation  $\mathbf{q} = \mathbf{A} * \alpha * \Delta \mathbf{T}$  with  $(\alpha = \mathbf{10} \ \mathbf{W/m^2K})$  the increase of the surface area can provide with a lower  $\Delta T$ , meaning that the 'heat' is more uniformly distributed so the risk of condensation is lower. The increase of the surface of the cold plate can be achieved with the attachement of vertical fins, functioning similarly to the heat sink of the hot plate. The fins of the cold plate will need to be bigger than those of the hot plate, as the COP of cooling has proved to be lower (Ibanez 2017).



# 8.4. Design Process

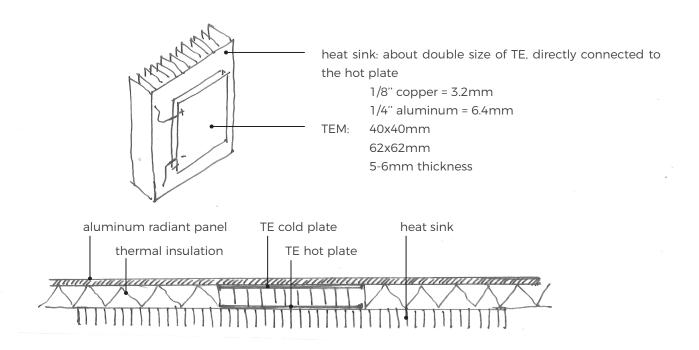


Figure 110: Horizontal Section - Step 1. Cold plate of TEM connected to aluminum radiant panel and hot plate connected directly to heat sink. Thermal insulation 6mm. Not sufficient.

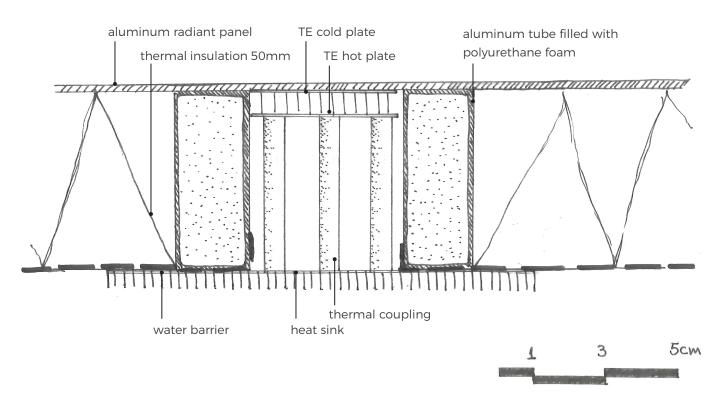


Figure 111: Horizontal Section - Step 2. Cold plate of TEM connected to aluminum radiant panel and hot plate coupled to heat sink. TE is mounted on aluminum tubes filled with thermal insulation. Rigid foam thermal insulation 50mm, water barrier. Multiple thermal bridges due to connections with tubes.

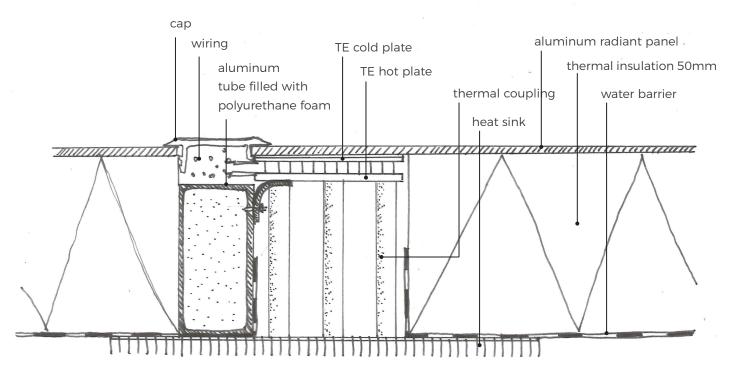


Figure 112: Horizontal Section - Step 3. Cold plate of TEM connected to aluminum radiant panel and hot plate coupled to heat sink. TE is mounted on one aluminum tube filled with thermal insulation. There is place for wiring and also a removable cap on the inner side for access. Rigid foam thermal insulation 50mm, water barrier. Thermal bridge due to connection to tube.

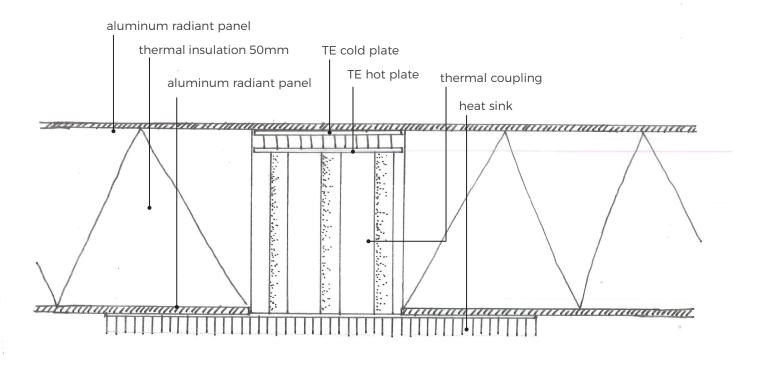


Figure 113: Horizontal Section - Step 4. Sandwich panel of two aluminum plates. Cold plate of TEM connected to aluminum radiant panel (inner side) and hot plate coupled to heat sink. Sandwich panel is being semi-penetrated for the placement of TEs. Self-supporting panel, simple construction. No thermal bridges due to connections. No place for wiring. Rigid foam thermal insulation 50mm.

5cm

The design at this point can demostrate the substantial principles. A last step is presented in the following sketch with an optimization that helps for better cooling distribution. Similarly to the hot plate, there are aluminum fins attached to the cold plate of the TEM. This way, the surface area is increased and the thermal energy can be more effectively transferred with conduction. Furthermore, a second panel is placed in distance from the cold plate fins to protect the facade construction.

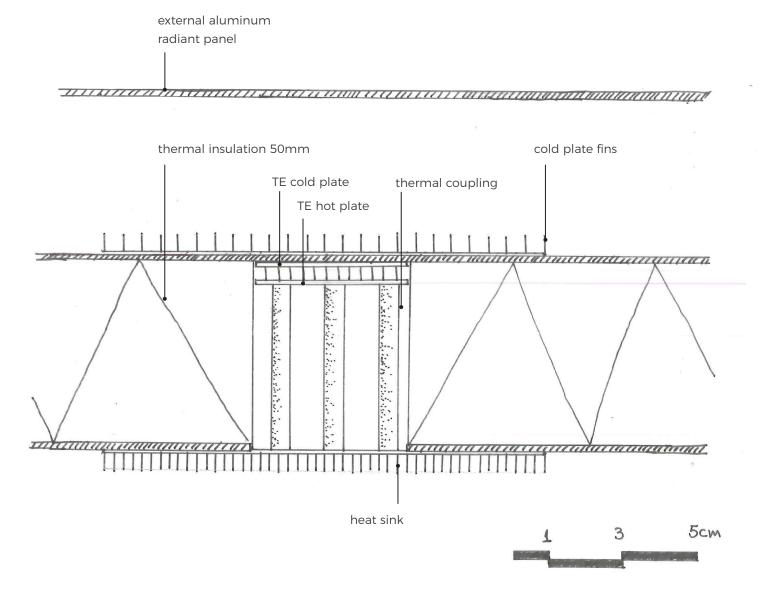


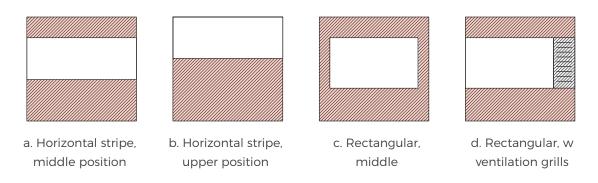
Figure 114: Improved section with fins on the cold plate and external aluminum radiant panel.

### 8.5. Architectural Possibilities

A rather interesting aspect of the integration of thermoelectrics on a facade component is the architectural possibilities that derive from it. For the development of a solar cooling facade certain aspects need to be taken into account, such as the PV panels' presence, thus a certain WWR needs to be considered. Furthermore for the following cases rectangular grid has been used and this is based on some specific characteristics of the typical buildings of Athens. Of course this does not exclude other arrangements as long as they comply to the certain solar-cooling requirements.

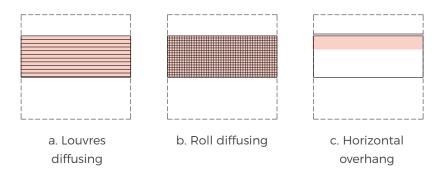
#### 1- MORPHOLOGY / GEOMETRY

For the following cases rectangular grid has been used and this is based on some specific characteristics of the typical buildings of Athens. Of course this does not exclude other arrangements as long as they comply to the certain solar-cooling requirements.



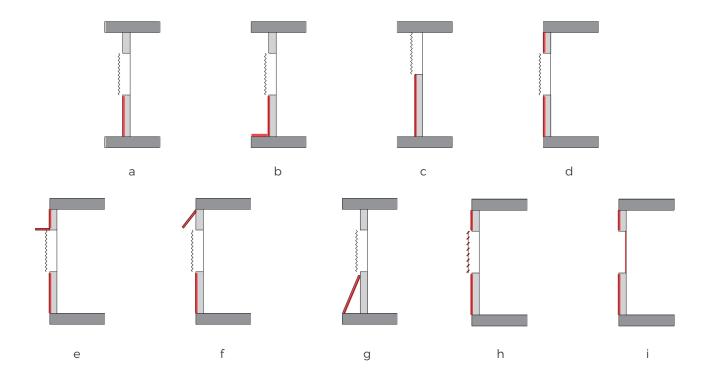
#### 2- SUN SHADING DEVICE

The sunshading device is absolutely essential. It is external in order to protect the glazing from the sunlight and according to the findings of the passive optimization, it is more efficient that it be dynamic/motorized. Important is also to be diffusing.



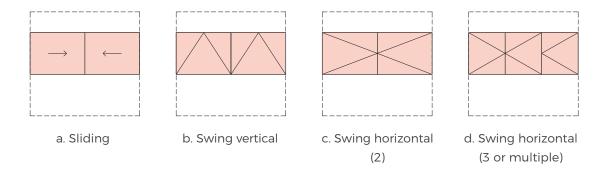
#### **3- SECTION (OFFSET & PV PLACEMENT)**

The distance of the facade from the building line is important as it determines the amount of sunlight that reaches the room. It is desired that PVs be exposed to solar light as much as possible throughout the daylight hours as much as possible. However, the glazed area must be shaded and protected from direct sunlight in order to minimize the solar gains/cooling demands. The placement of the PVs is critical for their performance during the different seasons and more specifically for summer; horizontal ones are more efficient than vertical and an inclination of 52° - 75° is optimum all year long and summer. Moreover, BIPV solutions such as solar cells on louvres or flexible and organic PVs can also offer some nice possibilities. Examples are given on Figure 115 - Figure 118 on page 115.



#### 4- TYPE OF OPENING

Sliding windows constitute a typical solution for many building, but the airtightness is not always sufficient. The swinging windows have better airtightness and also provide with a good ventilation solution. However, the horizontal swinging windows cannot be used in small spaces as their dimension and space requirement for operation makes them impractical. For those cases a smaller division is advisable, as of 4-d.



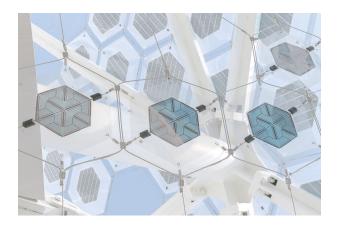




Figure 115: Organic photovoltaic applications by company "Opvius". These PV modules can give interesting results and work well in accordance with parametric and organic designs. Source: http://www.opvius.com.

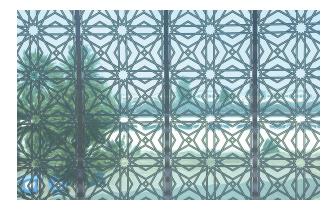


Figure 116: OPV nominated for renowned greentec award by company BELECTRIC. Source: http://www.opvius.com.



Figure 117: Vertical louvres with integrated PVs. The PVs are given shades of green and gold in order to integrate with the environment and appear as a 'living wall'.

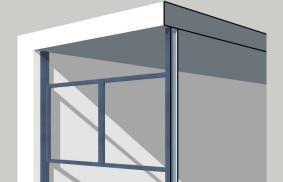
Source: http://www.cpre.org.uk



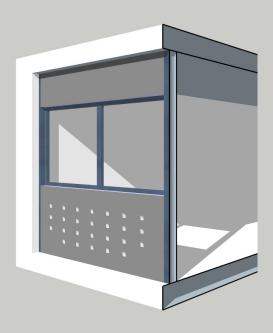
Figure 118: Application example of Amorphous silicon PV glass developed by company "ONYX solar". The efficiency varies between 3% to 7% depending on the design and is suitable also for overcast sky conditions. Source of image and information: https://www.onyxsolar.com

# 8.6. Final Design - Components

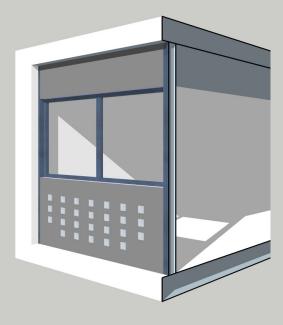
01- Frame structure



02- Composite panel perforated



03- TEMs & heat sinks & radiant panel

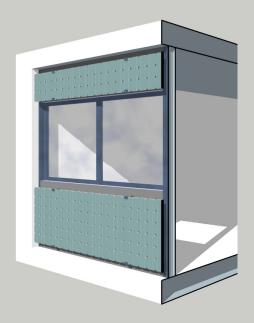


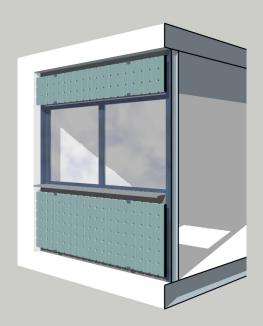
04- Mounting brackets for PVs



### 05- PV panels

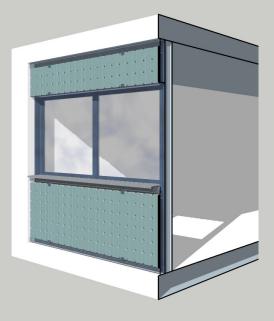
#### 06- Window sill

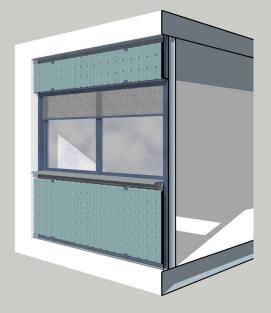




### 07- Ventilation grills

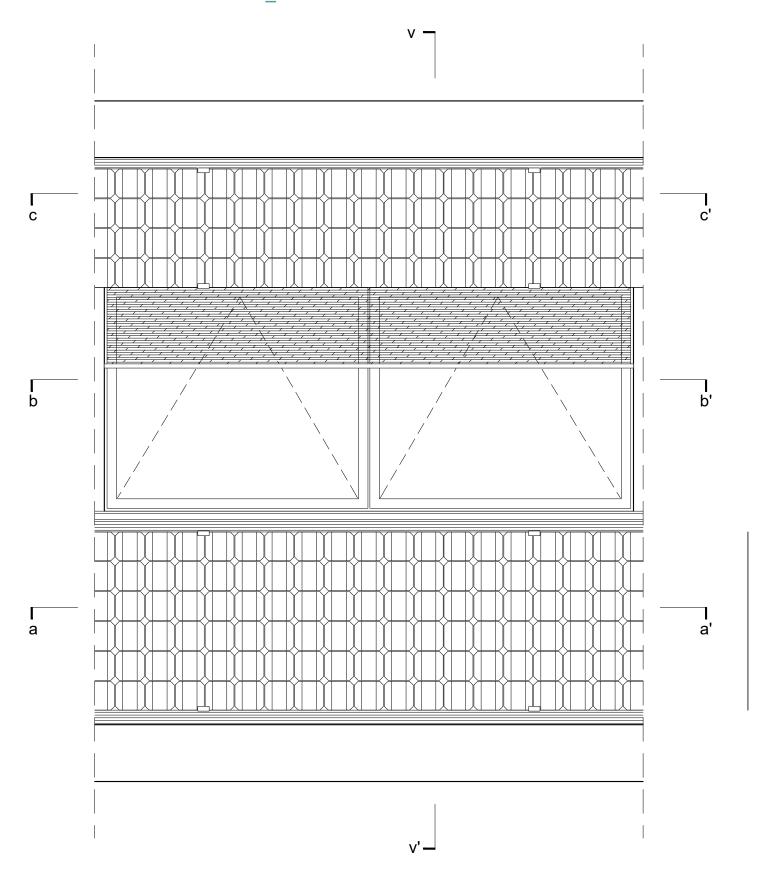
08- Sunshading roll



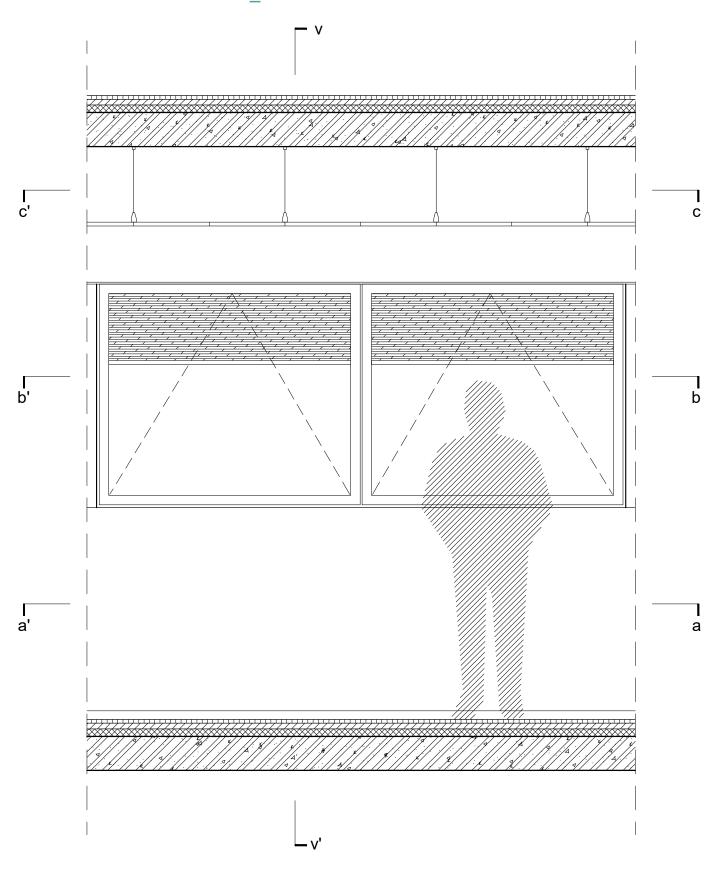


# VERTICAL SECTION \_ SCALE 1:20 ventilation grills c' С composite panel 140mm air cavity 90mm PV panel sunshading roll (diffusing) ..... b' b double clear Low-E glazing aluminum window frame 40\*50mm thermal coupling for TE TE module composite panel 140mm internal heat sink a' а external heat sink internal radiant panel ventilator PV panel mounting bracket for PV ventilation grills white marble cladding 40mm thermal insulation 60mm

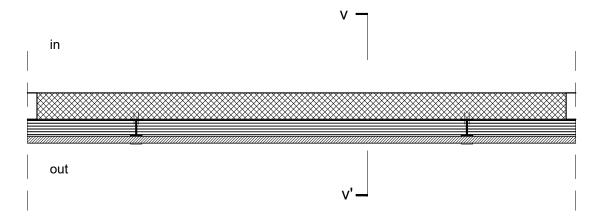
# EXTERIOR ELEVATION \_ SCALE 1:20



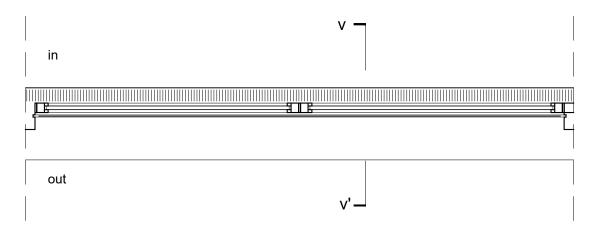
# INTERIOR ELEVATION \_ SCALE 1:20



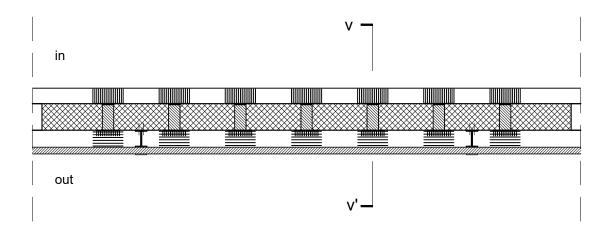
# HORIZONTAL SECTIONS \_ SCALE 1:20



**C-C'** 

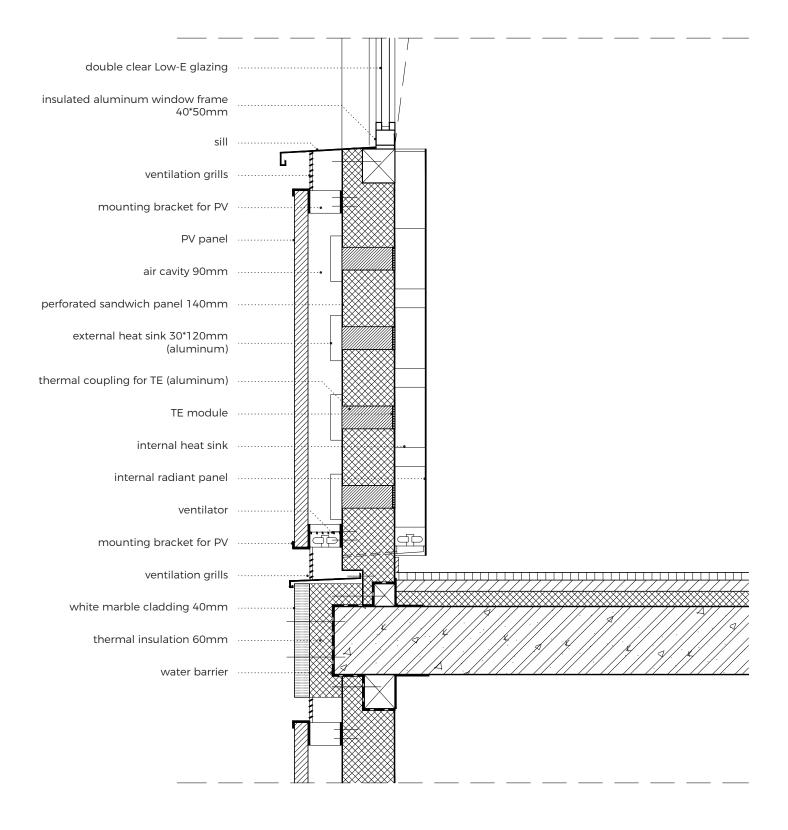


b-b'



a-a'

# VERTICAL DETAILED SECTION \_ SCALE 1:10



0.25m 0.50m 1m

# 8.7. Visualization

#### **OLD & NEW**



Figure 119: OLD / EXISTING FACADE

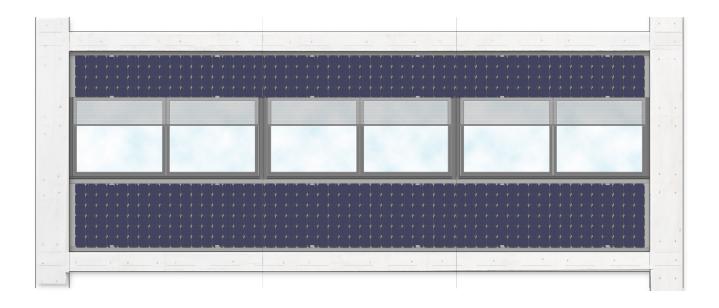


Figure 120: NEW FACADE





#### **INTERIORS**



# 8.8. Functional Schemes

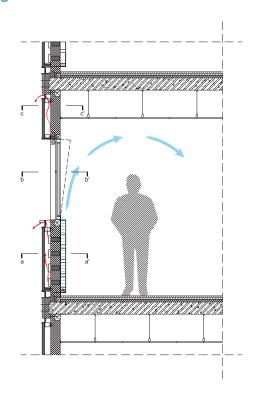


Figure 121: Diagram showing the function of the system. Radiant panel cools the nearby air and fans on the bottom of the cavity push the air into the room. Heat sinks reject heat in the cavity behind the PVs and a fan placed on the bottom of the cavity pushes the air upwards and out of the cavity. Ventilation helps the performance of PVs.

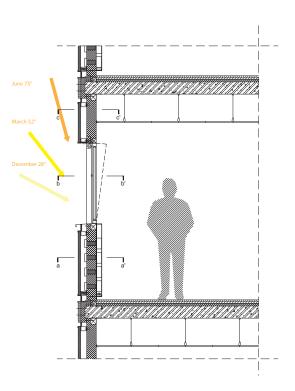


Figure 122: Solar geometry according to season. The placement of the facade on the edge of the building allows for maximum solar incidence throughout the year.

# DAYLIGHT STUDY

# 9. Daylight Study

# 9.1. Daylight Factor, Luminance and Illuminance

Daylight is a very important parameter when it comes to designing a façade module. The composition and the arrangement of the glazing panes is important and can influence the indoor visual comfort. For this reason, a short daylight study has been carried out in order to compare two cases with different geometry regarding the openings. Both models have WWR=40%; the first model has a single horizontal window, while the second one has two separate square windows. The model has been created and rendered with the VELUX Daylight Visualizer software.

#### **Initial models**

The settings used for both models are the following:

ORIENTATION: south
LOCATION: Athens
ROOM DIMENSIONS: 5x5m

FLOOR: Carpet, reflectance 0.656, roughness 0.05 EXTERNAL GROUND: Concrete, reflectance 0.4, roughness 0

CEILING: white paint (matte), reflectance 0.840, roughness 0.03 WALLS: white paint (matte), reflectance 0.840, roughness 0.03

WINDOW FRAMES: white

GLASS PANE: transmittance 78%

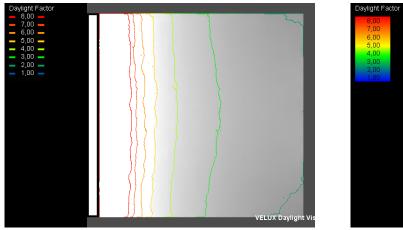
WINDOW SILL: 0.90m

FURNITURE: office desk grey
RENDER: July 21st, 12.00 hours

SKY: Intermediate

The visualizations include the (a) Daylight Factor, (b) Luminance, (c) Illuminance.

#### MODEL 1 - WWR = 40% - horizontal opening



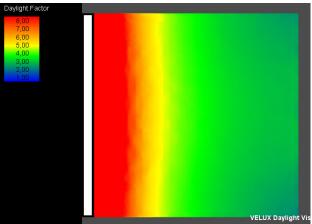


Figure 123: DAYLIGHT FACTOR, model 1, contours (left), false colors (right)



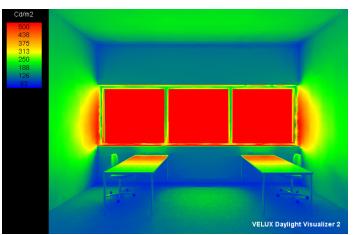


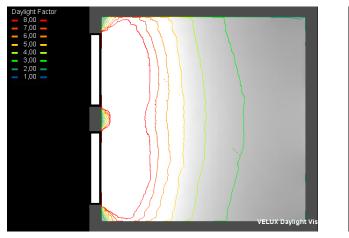
Figure 124: LUMINANCE, model 1, render (left), false colors (right)





Figure 125: ILLUMINANCE, model 1, render (left), false colors (right)

#### **MODEL 2 - WWR = 40% - square openings**



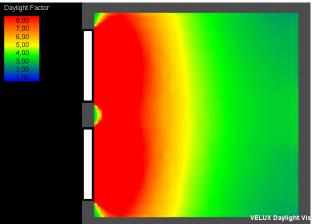


Figure 126: DAYLIGHT FACTOR, model 2, contours (left), false colors (right)



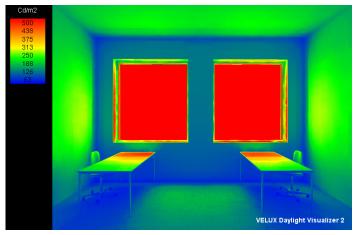


Figure 127: LUMINANCE, model 2, render (left), false colors (right)





Figure 128: ILLUMINANCE, model 2, render (left), false colors (right)

#### Discussion of the results

Three parameters have been visualized, the Daylight Factor (DF), the Luminance and the Illuminance.

Daylight Factor (DF): The DF is a measure which permits determination of the availability of daylight in a room. The higher the DF, the more daylight is available in the room. Rooms with an average DF of 2% or more can be considered daylit, but electrical lighting may still be needed to perform visual tasks. A room will appear strongly daylit when the average DF is above 5%, in which case electrical lighting will most likely not be used during daytime. (VELUX)

Luminance: Luminance is the measure of the amount of light reflected or emitted from a surface. It is typically expressed in  $cd/m^2$ .

Iluminance: Illuminance is the measure of the amount of light received on a surface. It is typically expressed in lux ( $Im/m^2$ ).

As it appears, the model 1 with horizontal opening provides with more distributed daylight inside the room than model 2. However, according to the DF, light will reach deeper into the room in model 2 than in model 1. In both cases though, DF is not lower than 2%, so the rooms can be considered mostly daylit, but artificial light may be necessary.

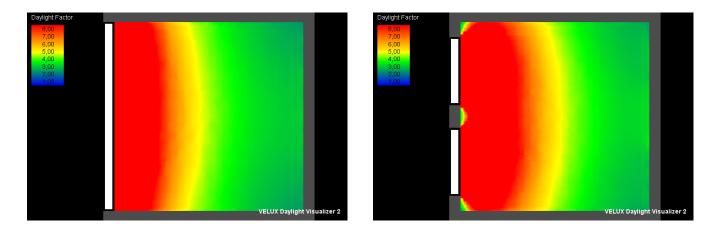


Figure 129: DF for altered window sill=1.20m. Model 1 (left), Model 2 (right).

#### **Alterations**

After a small alteration in the window sill height, we observe the following results:

In both cases the daylight can reach deeper, which is very rational as both rooms are south-oriented and the simulation takes place at 12.00 in July, when the sunbeams have a high inclination.

To sum up, it seems that the geometry of the opening influences the DF, namely the amount of available daylight into the room. Horizontal openings will provide with more uniform distribution of the light and lastly, higher positioning of the windows will also offer better light quality for the south orientation. The DF is in all points of the room higher than 3% (green), so according to VELUX, the room can be considered daylit.

### 9.2. Solar Geometry

The amount of daylight that reaches the offices heavily depends on the season of the year, because the solar position in the sky varies from summer to winter. According to the climate information that has been gathered, the angle is maximum on June 21st (75° south) and minimum on December 21st (28° south). Every intermediate season lies in-between, with spring and autumn being at 52° south.

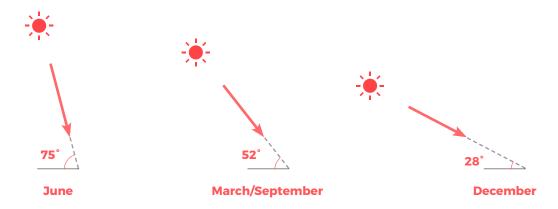


Figure 130: Solar incidence angle for summer, mid and winter season in Athens. Source: Figure 36 on page 45 and Figure 37 on page 45.

The presence of visual obstacles also impacts the incident sunlight, which is mostly important for the proper function of the PVs which are positioned on the facade. On Figure 131 has been examined the case study building under the influence of the cast shadow from the other building across the street. The solar anles are very vertical during summer and mid-seasons and there is no shadow on the facade. However, during wintertime we can see that about 50% of the south facade is shaded. This is of course not desirable and it means that only the 4 top floors have direct sunlight and thus, can be used for heat production. As it has been discussed previously, the heating demands of these offices are much lower than the cooling demands and also, the winter demand can be totally covered up to 200% and even more, depending on efficiency of PV panels and COP of TEs. For this reason it would be possible that heating demand of the 4 lower floors be covered by the excess production of the upper 4 floors. A back-up system can be also used.

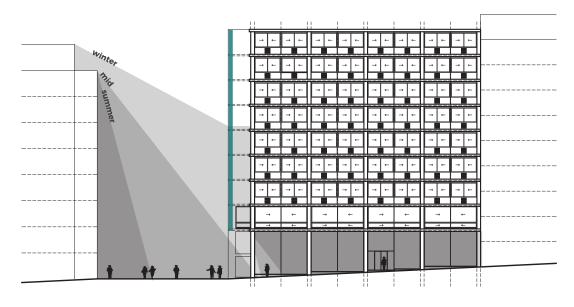


Figure 131: Solar incidence on the south facade of the case study building in Ermou str. for the whole year at 12.00 hours. Approximately 50% of the solar cooling facade (pointed out in blue) is shaded during wintertime.

### 9.3. Sun Shading Device

The sun shading device is of course essential and also plays crucial role in the amount of daylight that reaches the room. During the passive optimization phase it has been concluded that it needs to be external and dynamically responsive according to solar irradiance intensity.

Of course the possibilities are vast for sunshading devices. Important parameter to be considered is the light diffusion and the visibility factor. Objective is, eitherway to achieve uniformly distributed light into the room.

#### Louvres

Horizontal louvres are used for the south orientation and vertical louvres for the east and west orientation in order to achieve oprimum efficiency. The louvres are prominent to cast very sharp shadows under direct sunlight, so they should be carefully selected to be translucent of diffusing and also to cast overlapping shadows every season and every hour of the day. An advantage a louvre solution is that they can integrate PV cells. On the other hand, a disadvantage is that they block the view at a great degree.

#### Roll

A roll sunshading is a fabric with open weave structure. For external applications the products are treated with weather and resistant finishings. An advantage of a roll shading system compared to the louvre system is that it can block a certain amount of sunlight according to the density of the fibers and thus allow for view outwards.

As it has been discussed, the optimal sunshading is external and solar responsive. The operation is controlled by a pyranometer, as in Figure 133, which activates the sunshading when the solar irradiation exceeds a certain set limit.



Figure 133: Pynanometer. A device that measures solar irradiation. Source: Google images

# 10. Conclusions

This project shows the possibility of integration of passive design strategies along with active systems on the office building envelope for the Mediterranean climate condition. Location of the research is Athens, Greece. The generation of cooling is achieved through the façade by using a combination of PV (photovoltaic) and TE (thermoelectric) modules. In principle the PVs convert the solar energy into direct current which is supplied to the TEs. The TEs function as heat pumps, when DC is applied, a temperature difference is created on their plates and thus, cooling effect can be achieved.

## Answer to the research question and research sub-questions

#### Main research question

- How can a façade regulate the indoor temperature in an office building located in Athens by using bioclimatic strategies and thermoelectric technology in order to reduce the amount of energy needed for cooling?

Firstly, there need to be applied passive strategies; sun shading, double glazing with LoE coating, appropriate natural and mechanical ventilation and also as small as possible window to wall ratio in order to minimize thermal losses. Secondly, PV panels with high as possible efficiency should be selected and lastly, TE modules with good COP.

#### **Research sub-questions**

- What is the state-of-the art of PV and TE technology and what are the future potentials?

The PV technology is already mature. A typical monocrystalline silicon cell currently can achieve efficiency of 20%. In the future this is expected to increase up to 35%-40%.

The TE technology is in R&D phase for façade integration. The efficiency of thermoelectric modules depends highly on the technology of materials. The average current ZT (figure of merit) of the state-of-the-art available materials ( $\mathrm{Bi_2Te_3}$  - bismuth telluride and the  $\mathrm{Sb_2Te_3}$  - antimony telluride) is around 1.0. In order to be able to be compared with vapor-compression HVAC systems, there need to be achieved ZT values higher than 3.0.

- Which are the most distinctive climate characteristics that need to be considered and which passive design strategies can be applied to an office façade in Athens?

Which are the most distinctive climate characteristics that need to be considered in this design?

The solar irradiation is high all year long and also the sky coverage is low, so these two factors show that PV

application is feasible. High summer temperatures resulting in high cooling loads play significant role and also the heat island effect should be considered. Several strategies according to the traditional architecture examples can be applied. Protection from the summer sun, small openings and natural ventilation with thoughtful placing of the windows are the most crucial.

- To what extend can these building physics strategies be adequate for the achievement of indoor thermal comfort? (How far can we go with passive strategies?)

As it is shown during the passive optimization, the appropriate strategies can reduce cooling loads very drastically up to 50%-60% compared to a case with no measures taken.

- What is the typical office building in Athens?

A representative office building of Athens has the following characteristics: concrete structure, constructed 1970-1980, 10 floors in average, flat roof, built in an attached system. WWR is 50%, usually the façade is constructed with parapets or curtain wall and average floor height 3.8m. Morphologically, there is a public pass way on ground floor (with or without coluns) and penthouses, each one 3m away from the building line.

#### **Evaluation of Result**

#### **Performance**

The performance of the façade cooling system has been calculated and can cover approximately 40% of the peak design value in summer design day according to the commercially available products (PV and TE). As far as the winter heating demands are concerned, these can be covered 100%, as the calculation has shown.

#### Integration in urban context

The materials of the new proposal are very different to the old façade. PV panels have taken the place of the existing marble panels. Also external shading with slats has been introduced, which makes a big difference. The WWR has been decreased from 0.55 to 0.40. All in all, the new design has kept all the basic proportions, but used totally different materials.

In order to judge whether the proposal can integrate to the context or not, we should consider on the one hand the intervention on the building itself and on the other hand the connection to its surroundings. So, marble is strongly linked to the history and identity of Athens dating centuries back and consists the most characteristic material of the existing façade, which is replaced practically by PVs on the new design. This would really raise a question from point of architectural tradition but on the contrary, PVs contribute to a more sustainable solution for energy resource. As for the surroundings, the case study building is located on the largest commercial street of Athens, Ermou str, where many different buildings can be found. There are several neoclassical buildings but there are also many contemporary ones hosting offices. Under this scope, the proposed façade can not only stand among its context, but showcase this new and innovative concept on one of the most crowded places of the city.

#### Weaknesses

System depends highly on solar incidence. This is linked to a number of weaknesses. That means that solar panels, unless moving/tilting according to the sun path, will have limited daily hours of solar radiation. Also, the application in a dense urban web would be doubtful, as there might be places where sunlight cannot reach. What is more, cloudy days will also knock the system out.

Thermoelectric modules: with the current technology it is not possible to cover entirely the peak cooling demand.

### **Evaluation of Method**

Throughout the whole project the literature review has been systematic and eventually the focus has been given on areas that needed more information or required deeper understanding. The access on information did not encounter serious obstacles, apart from the part of TE technology. As the TEs are in R&D phase for façade integration, there are not many sources for information. Besides, the applications of TEs require complex calculations which are usually performed by trained engineers in the companies that specialize and merchandize them. Therefore, the calculations of system sizing were not simply at all, considering all the factors and have been based mostly on theoretical values/numbers provided by literature rather than commercial products.

Regarding the simulation software, Design Builder, it requires good familiarization in order to ensure the right settings are made so as to get the proper results. Unfortunately there have been several times that errors have occurred due to improper or incomplete settings and has been taken maximum care to fix them costing precious time. Of course every program of this kind requires full attention, but it should be acknowledged that it can provide with more detailed results than simple calculations can.

Lastly, the simulation and collection of data would have been far easier if computational methods were used. There are available methods and computer programs devoted to gather information regarding the solar envelopes generation and the solar collection calculations. This, however, requires a deep specialization and would go beyond the purposes of the current thesis. Nevertheless, for a complete application study on solar cooling facades, such methods should be considered.

### Recommendation for further Development

Areas that are worth exploring - researching, though, they are out of the scope of this project.

- · Computational approach/parametric simulation for solar collection calculation
- · Study for application on whole building, not only one office located by the façade
- Power generation under temperature difference (reverse process)
- Application on other types of buildings (eg residential)

# 11. Reflection

Name: Kalliopi Theodoraki

Student Number: 4517563

Graduation Topic: SOLAR - COOLING FAÇADES: An integrated façade design with thermoelectric

cooling systems for office buildings in Athens

1st Mentor: Tillmann Klein
2nd Mentor: Peter van den Engel
3rd Mentor: Alejandro Prieto Hoces

#### **Graduation process**

The graduation projects explores the application of a solar cooling façade system on an office building in Athens, Greece. It utilizes photovoltaic and thermoelectric modules with the purpose of transforming the solar power to DC current and subsequently to temperature difference, which is responsible for the cooling effect. The main focus is on Façade and Climate Design, which are two of the basic directions of the Building technology sustainable graduation studio. The graduation project deals extensively with research on PV, TE technology as well as the most outstanding climate characteristics and vernacular bioclimatic strategies in Greece. It also involves field research and passive optimization, which provide a solid case study for the development of the façade design concept.

The project involves a large part of research (literature review) on the various aspects that are important in order to answer the research question and sub-questions. The research itself could be abstractly separated into two parts: the location/context-related and the technology-related. While the location was very familiar to me and has been easy to access and retrieve the necessary information, the technology (PVs and TEs) has been a completely new field. Especially, the sources about the thermoelectrics are not at all related to HVAC applications, only with few exceptions. Also, the COP of the thermoelectric modules is dependent on a number of factors such as the  $\Delta T$  [ $^{\circ}$ K], the I [A] and the U [V] and this leads to a rather complex calculation of the system cooling capacity. During this part of research and optimization it felt that the progress was stumbling on such factors and not providing a good timing for the prompt start of the façade design. Moreover, the calculations of the system performance have been rather complicated as they involve not only the passive design strategies, but the PV and TE systems. Besides these, the whole 'route' has been interesting and challenging up to the end, where the final performance test was done in order to find out how well this system can cope with the cooling demands of the case study office building.

#### Relationship between research and design

Both research and design are strictly connected to the main research question "How can a façade regulate the indoor temperature in an office building located in Athens by using bioclimatic strategies and thermoelectric technology in order to reduce the amount of energy needed for cooling?" Big part of the research deals with identifying the most outstanding parameters for the design. Furthermore, the research provides a basis of technological knowledge, perception of environmental and topological context, cooling demands, all of which feed the design process.

#### **Societal impact**

Even though thermoelectric technology has been explored and used in multiple areas since the discovery of the Peltier effect in 1830's, it is currently on R&D stage regarding the façade integration. Within this scope, this project takes into consideration the specific characteristics of Athens as a location and provides with an applicable design product. It does not aim to exhaust all design possibilities, rather propose a more general component. Of course, it can be applicable in practice, but it could also be subject of further design.

Also, it is important to consider the current development of the technology, as it has a direct impact on the effectiveness of the cooling generation. It is estimated, according to literature, that in the future the involved technologies will be able to provide with higher COPs, so possibly the total cooling loads of an office building can be covered.

The proposed façade module is innovative in the sense that it integrates the thermoelectric technology, which is only in a developing phase. The whole system has the benefit of being low-maintenance, however if compared to similar technologies for cooling, it can only achieve partially same good results. For instance, the thermoelectric module system has limited cooling capacity compared to vapor-compression systems. For this reason we can claim that the design product is innovative, yet there is further space for future development.

#### **Sustainable development contribution**

The project contributes significantly to sustainable development. Mainly it addresses the problem of scarcity of the available energy resources and the imperative need for use renewable energy resources. This is achieved by using the solar energy as input and with the PV and TE modules it can eventually be used for cooling generation. Moreover, there are examined and applied several passive strategies, which lead to an optimum passive scenario. This is a very important step, as it can help reduce drastically the cooling loads in the hot period of the year only by means of passive design.

With the use of solar energy, a renewable energy resource, we achieve to minimize the use of any other non-renewable energy source (eg electricity generated from fossil fuels). Apart from being a legal requirement nowadays, the use of renewable energy resources is linked to plenty of beneficial environmental practices. Therefore, it is not only a necessity, but a moral statement to a more sustainable future.

As an intervention that focuses on the façade and climate design, it improves the indoor comfort (thermal and visual) and also signifies an important role on the daily working conditions of the people.

#### Relation to architecture and the built environment

The relation of the project to architecture and the built environment is very evident. The building envelope is the link between interior and exterior, acts like the skin of the building. It is the filter that plays both the separating and the linking role. It constructs the image of a building within its urban context and simultaneously it defines the indoor environment of the users.

Lastly, the building envelope is often connected to the problem of the urban heat island effect. Particularly in Athens this phenomenon is very intense and hardly solvable. This is also taken into consideration during the design process and confronted by using 'cool' materials with small heat capacity. The problem occurs naturally in a dense city like Athens and even though the proposed design will not be able to solve it, it contributes to a better level.

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- 3. VELUX Daylight Visualizer 2

# List of Figures

Figure 01: Share of renewable energy in gross final by 'Kryotherm' 28 energy consumption (%). Source: EUROSTAT 2017. Figure 19: Functioning scheme of a thermoelectric cooling module. Figure 02: Fractions of gross energy consumption Source: Prieto et al. (2017) 29 for 2013 (MWh). Source: Gaglia et al. Figure 22: Water-based facade types, source: Prieto et al. (2017) based on information by Xu et al. Figure 03: Energy consumption per building category. Office buildings constitute the 3rd higher (2007), (2008). 30 consumer. Source: https://goo.gl/Lw2AZM Figure 21: Solid-based facade types, source: Prieto Figure 04: Functional scheme of facade integration et al. (2017) based on information by Liu et al and energy flow 12 (2015) and Ibanez-Puy et al. (2015). Figure 05: Scheme of the boundary conditions: Figure 20: Air-based facade types, source: Prieto et Constraints al. (2017) based on information by Liu et al (2015) Figure 06: Geographical position of Athens in and Ibanez-Puy et al. (2015). Greece and extract with center, north, west and Figure 23: Functional scheme of "Thermagy" heat south suburbs. 13 module developed by RGS company for large-scale Figure 07: Work Flow Scheme applications. Test on TATA steel. Source: http://www. Figure 08: Research methodology in regard rgsdevelopment.nl/ to research part, objective, method and Figure 24: How the efficiency of the modules corresponding research sub-question. influences the space required. Figure 09: Time plan Source: Munari Probst et al. © SUPSI. ISAAC- www. Figure 10: Thermoelectic (TE) module 3D scheme. bipv.ch 34 Figure 25: Mono- and poly- crystalline cells Source: lairdtech.com 22 Figure 11: Second Law efficiency as a function of Source: Munari Probst et al. non-dimensional figure of merit (ZT). Source: Liu et Figure 26: Amorphous silicon cell and module. al. 201523 Source: Munari Probst et al. Figure 28: Possible configurations for BiPVs. Figure 12: Various types of commercially available thermoelectric modules. Source: Prasad D. et al., own representation From left to right: thermoelectric coolers for radio Figure 27: Monthly Averaged Radiation Incident On applications, standard single-stage thermoelectric An Equator-Pointed Tilted Surface (kWh/m2/day). coolers, multi-stage thermoelectric coolers, round Source: NASA - https://goo.gl/AtwCpU thermoelectrics. Source: http://kryothermtec.com Figure 29: Most recent industry data (2016) and projections for the power of a module constructed Figure 13: Scheme showing the heat flow between from 60 cells with dimensions of 156 mm x 156 the hot and the cold plate of a TEM mm. Source: 2017 International Technology Source: Ferrotec 26 Roadmap for Photovoltaics Figure 14: Cooling COP of a thermoelectric module Figure 31: Confirmed multiple - junction terrestrial under optimum electrical current with fixed hot cell and submodule efficiencies measured under side temperature of 300K. the global AM1.5 spectrum (1000 W/m2) at 25°C Source: D. Zhao et al. 2014 (IEC 60904-3: 2008, ASTM G-173-03 global). Figure 15: Summary of commercially available Source: http://onlinelibrary.wiley.com/doi/10.1002/ thermoelectric modules from published literature. pip.2909/full Source: D. Zhao et al. 2014. 27 Figure 30: In the IMM cell, high-performance Figure 16: COP=f(dT) subcells are realized by: (1) inverting the usual Figure 17: COP=f(I) 28 growth order, growing mismatched cells last, (2) Figure 18: COP=f(U) engineering a transparent buffer layer to mitigate

dislocations, and (3) removing the primary

Standard performance graphs for TEM FROST-74

substrate/attachment to the secondary "handle." differences on 21/08/2010. The dT between city Source: NREL, 39 centre and certain areas is up to 10° C. City center Figure 32: Description of C- climatic types is marked with black circle. Source: AUTh - Aristotle according to the modified Köppen-Geiger scheme. University of Thessaloniki Source: Encyclopaedia Britannica. Figure 46: Hatzigianni Mexi Mansion, in Spetses, Retrieved from: https://www.britannica.com/ with semi-open-air spaces. (Floros 2014) 54 science/Mediterranean-climate 41 Figure 47: Semi - buried buildings in Oia, Sadorini Figure 33: "Köppen climate classification map". Island. (Floros 2014) Photo. Encyclopædia Britannica Online. Web Figure 48: Naousa traditional settlement in Paros 28/05/2017. Island. (Floros 2014) 54 Source: <a href="https://www.britannica.com/science/">https://www.britannica.com/science/</a> Figure 49: Mansion in Kastoria, Northern Greece. (https://goo.gl/YR4oU4) 54 Mediterranean-climate?oasmld=206711> 42 Figure 34: Global irradiation and solar electricity Figure 50: Traditional House in Ipiros, Northern potential. Optimally-inclined photovoltaic modules. Greece. (https://goo.gl/sjr5c1) Figure 51: Basic environmental factors in an indoor Authors: Thomas Huld, Irene Pinedo-Pascua. European Commision - Joint Research Centre space. Institute for Energy and Transport, Renewable Source: Bluyssen 2009 55 Energy Unit PVGIS. Figure 54: Vertical air temperature difference Source: http://re.jrc.ec.europa.eu/pvgis/cmaps/eu\_ between head and ankles. Source: Bluyssen 2009 cmsaf opt/G opt GR.pdf Figure 52: Three categories of thermal comfort. Figure 35: Weather Data Summary - monthly means. Location: Athens, Latitude/Longitude: 37.9° Source: Bluyssen 2009 56 North, 23,73° East. Data Source: IWEC Data, 167160 Figure 53: Example criteria for operative WMO Station Number. Source: Climate Consultant temperature and mean air velocity for typical spaces. Rh is 60% for summer and 40% for winter. Figure 36: Sun shading chart June 21st to Source: Bluyssen 2009 56 December 21st. Figure 55: Range of floor temperature for the three Source: Climate Consultant 6.0 45 categories of the thermal environment. Figure 37: Sun shading chart December 21st to Source: Bluyssen 2009 56 June 21st. Figure 58: Design values for the indoor operative Source: Climate Consultant 6.0 45 temperature for buildings without mechanical Figure 38: Wind wheel, annual average cooling systems. Source: Bluyssen 2009 57 temperature, relative humidity, speed and Figure 57: Radiant temperature assymetry for th duration. three categories of the thermal environment - valid Figure 39: Wind wheel May-September for low-ceiling spaces. Source: Climate Consultant 6.0 46 Source: Bluyssen 2009 57 Figure 40: Psychrometric chart. Indoor Comfort Figure 56: Acceptable operative temperature display. ranges for naturally conditioned spaces according Source: Climate Consultant 6.0 46 to ASHRAE 55-2004: Range is shown for different Figure 41: Wind velocity range. climatic areas. Source: ANSI/ASHRAE Standard 55-Source: Climate Consultant 6.0 47 2004, p. 10. 57 Figure 43: Sky cover range. Figure 60: Typical office building energy Source: Climate Consultant 6.0 47 consumption. Figure 42: Temperature range. Source: US Energy Information Administration's Source: Climate Consultant 6.0 47 2003, own representation 60 Figure 44: Visual representation of the urban heat Figure 61: Number of floors information for single island effect portraying the dT between urban and and mixed use buildings in the central sector of rural areas during day and night. Athens. Graph showing number of buildings. Source: https://peopleandtreesincities.wordpress. Data source: Hellenic Statistic Service 2011, own com/tag/usfs/ 48 representation 60 Figure 59: Number of buildings per type within the Figure 45: Map of Attica showing the thermal

central administrative sector of Athens. evaluation: lighting loads 86 Data source: Hellenic Statistic Service 2011, own Figure 77: Optimization Index 86 representation 60 Figure 79: Comparative graphs for initial scenarios Figure 62: General Urban Plan of Athens and passive optimization. It is obvious that all (Central Sector-Municipality of Athens), 1988, optimized scenarios A-H provide with significantly last adaptation in 2012. In dark red color is improved results. Scenarios 4.7-4.9 have been displayed the hyperlocal center of Athens, which excluded from this representation. Figure 80: Numerical output from passive is the region where most of offices are located. Source: Organization for the Master Plan and optimization. 88 Environmental Protection of Athens Figure 81: Graphs of scenarios A-H (passive Figure 63: Number of office and commercial use optimization) 89 buildings in central sector according to year of Figure 82: Total Cooling Loads for Scenario 0 (initial) construction. and Scenario F (final) - ANNUAL REPRESENTATION Source: Hellenic Statistic Service 2011. 61 Data: Design Builder 91 Figure 83: Total Cooling Loads for Scenario 0 (initial) Figure 64: Region of Attiki and the City of Athens with its suburbs. and Scenario F (final) - SUMMER DESIGN WEEK Map source: Google Maps, own adaptation 62 REPRESENTATION Figure 65: Collective table of the examined facades. Data: Design Builder 91 The red lines indicate the facade unit, according to Figure 84: Total Heating Loads for Scenario 0 which is calculated the WWR. 67 (initial) and Scenario F (final) - WINTER DESIGN Figure 66: Comparative data table with facade grid, WEEK REPRESENTATION WWR, Facade type, height, number of floors and Data: Design Builder Figure 85: Sceme of heat flows of the heat balance year of construction. 68 Figure 67: Schematical representation of the 93 equation typical characteristics of office building according Figure 86: Calculated yearly variation of the average to the field research and analysis. total solar irradiation on a horizontal surface in Figure 68: Building 15, Ermou and Nikis str. SSW Athens for every hour from 08:00 to 12:00 hrs LST. Design summer day (July 15=Day 196) is marked street view Figure 69: The parameters for the passive on the diagram. evaluation: Source: D. Kouremenos et al, 1985. 1-Glazing type, 2-night ventilation schedule, 3-sun Figure 88: Solar radiation intensity on the vertical shading, 4-WWR 78 plane in W/m<sup>2</sup> through out the day (July). Location: Figure 70: Graphs displaying the Cooling Load Netherlands. Source: v. d. Linden et al, 2013. (annual and for summer design week) and Design Figure 87: Solar direct radiation intensity in W/m<sup>2</sup> Capacity (for Summer design day) throughout the day (July 15). Latitude: 38° North, Figure 71: Table with the numerical results of Athens. Absense of clouds. Source: http://www. Design Builder simulations per orientation. pveducation.org/pvcdrom/calculation-of-solar-Displaying: 1-Annual cooling loads, 2-summer insolation 94 design week cooling loads, 3-summer design day Figure 89: Monthly Averaged Radiation Incident On capacity 80 An Equator-Pointed Tilted Surface (kWh/m2/day). Figure 72: The simulation model in Design Builder. Emphasized are the values for February (winter The test office is shown in red color. design) and July (summer design). Source: NASA -Figure 73: Design Builder, Activity Tab settings https://goo.gl/AtwCpU 97 SCENARIO 0 Figure 90: Calculation of Solar Outout and Total Figure 74: Design Builder, Glazing Tab settings -System Output for different eff<sub>DV</sub> and COP<sub>TE</sub>. SCENARIO 0 Figure 91: Comparative chart of Cooling Load on Figure 75: Design Builder, Lighting Tab settings -Summer Design Day (SDD) for initial case, passive SCENARIO 0 optimization and final scenario. Simulation and Figure 76: Design Builder, HVAC Tab settings calculation for south orientation.98 Figure 92: Comparative chart of Heating Load on SCENARIO 0 84 Figure 78: Further parameter for the passive Winter Design Day (WDD) for initial case, passive

optimization and final scenario. Simulation and calculation for south orientation.99
Figure 93: Exemplary positioning of 26 TE modules on facade 3.8\*5m with WWR 40%.

Wired in parallel (7 threads) and in series. 100

Figure 94: Air-based facade types, source: Prieto et al. (2017) based on information by Liu et al (2015) and Ibanez-Puy et al. (2015). 102
Figure 95: Solid-based facade types, source: Prieto et al. (2017) based on information by Liu et al (2015) and Ibanez-Puy et al. (2015). 102
Figure 96: Water-based facade types, source: Prieto et al. (2017) based on information by Xu et al. (2007), (2008). 102

Figure 97: (left) Testing room model for performance test. Source: Xu et al. 103
Figure 98: (right) Experimental setup for performance test. Source: Xu et al. 103
Figure 100: Construction section of the test cell.
The thermoelectric unit can be found in the ground floor, while the auxiliary equipment is in the upper floor. Source: Ibanez 2017 103
Figure 101: Global disposal of the heat sinks and fans in the outer side and in the inner side of the thermoelectric unit. Source: Ibanez 2017.

Figure 99: Sectional drawing of the setup for single TE unit. Source: Xu et al. 103

Figure 102: Schematic configuration of TE module and heat sinks for facade integration. The direction of the current can be regulated in order to set the direction of the heat flow and subsequently the application of heating or cooling. Adapted from Ibanez et al 2017.

Figure 103: Electric circuit diagram showing the schematic system.

Sceme drawn by author, based on info from various sources. (Laird thermoel. handbook) 106

Figure 104: Aluminum extrusion heat sink profile (left), copper heat sink profile (right). Source: Google images 106

Figure 105: Primary power flow, from PVs directly to TEs 107

Figure 107: Alternative function, electricity from the building is used after being converted to DC. Can be useful to cover the peaks or during cloudy days. 107

Figure 106: Alternative function, energy from PVs is stored in batteries and when needed fed to TEs

107

Figure 108: Potential reverse function, temperature difference created on TEs produces DC which is either stored in batteries or supplied to the building.

Figure 109: Psychrometric diagram. Comfortable conditions are represented with green dots. Display for dew point temperature with rh=40-50% and  $T_{DRY}$ =25°C. Source: Climate Consultant 6.0 108

Figure 110: Horizontal Section - Step 1. Cold plate

of TEM connected to aluminum radiant panel and hot plate connected directly to heat sink. Thermal insulation 6mm. Not sufficient. 110
Figure 111: Horizontal Section - Step 2. Cold plate of TEM connected to aluminum radiant panel and hot plate coupled to heat sink. TE is mounted on aluminum tubes filled with thermal insulation. Rigid foam thermal insulation 50mm, water barrier. Multiple thermal bridges due to connections with tubes. 110

Figure 112: Horizontal Section - Step 3. Cold plate of TEM connected to aluminum radiant panel and hot plate coupled to heat sink. TE is mounted on one aluminum tube filled with thermal insulation. There is place for wiring and also a removable cap on the inner side for access. Rigid foam thermal insulation 50mm, water barrier. Thermal bridge due to connection to tube.

Figure 113: Horizontal Section - Step 4. Sandwich panel of two aluminum plates. Cold plate of TEM connected to aluminum radiant panel (inner side) and hot plate coupled to heat sink. Sandwich panel is being semi-penetrated for the placement of TEs. Self-supporting panel, simple construction. No thermal bridges due to connections. No place for wiring. Rigid foam thermal insulation 50mm.

Figure 114: Improved section with fins on the cold plate and external aluminum radiant panel. Thermal insul 100mm. 112

Figure 116: Organic photovoltaic applications by company "Opvius". These PV modules can give interesting results and work well in accordance with parametric and organic designs. Source: http://www.opvius.com. 115

Figure 117: OPV nominated for renowned greentec award by company BELECTRIC. Source: http://www.opvius.com. 115

Figure 119: Application example of Amorphous silicon PV glass developed by company "ONYX

solar". The efficiency varies between 3% to 7% depending on the design and is suitable also for overcast sky conditions. Source: https://www. onyxsolar.com 115

Figure 118: Vertical louvres with integrated PVs. The PVs are given shades of green and gold in order to integrate with the environment and appear as a 'living wall'. Source: http://www.cpre.org.uk

Figure 120: OLD / EXISTING FACADE

Figure 121: NEW FACADE 120

Figure 122: Diagram showing the function of the system. Radiant panel cools the nearby air and fans on the floor push the air into the room. Heat sinks reject heat in the cavity behind the PVs and a fan placed on the bottom of the cavity pushes the air upwards and out of the cavity. Ventilation also helps the performance of PVs. 121

Figure 123: Solar geometry according to season. The upper PV panels are entirely shaded during summer period, which is problematic and should be solved.

Figure 124: DAYLIGHT FACTOR, model 1, contours (left), false colors (right) 124

Figure 125: LUMINANCE, model 1, render (left).

false colors (right)

Figure 126: ILLUMINANCE, model 1, render (left),

false colors (right)

Figure 127: DAYLIGHT FACTOR, model 2, contours

(left), false colors (right) 125

Figure 128: LUMINANCE, model 2, render (left),

false colors (right) 125

Figure 129: ILLUMINANCE, model 2, render (left),

false colors (right) 125

Figure 130: DF for altered window sill=1.20m.

Model 1 (left), Model 2 (right). 126

Figure 131: Solar incidence angle for summer, mid and winter season in Athens. Source: Figure 36 on page 45 and Figure 37 on page45127. 127 Figure 132: Solar incidence on the south facade of the case study building in Ermou str. Approximately 50% of the solar cooling facade

(pointed out in blue) is shaded during wintertime.

Figure 133: Exemplary application of louvre (left) and roll (right) sun shading systems. Source: Google Images 128

Figure 134: Pynanometer. A device that measures solar irradiation. Source: Google images 128

# Appendices

APPENDIX I	OFFICE BUILDINGS CASE STUDIES	148
APPENDIX II	BUILDING 12 (EXISTING) - DRAWINGS	164
APPENDIX III	GENERAL URBAN PLAN OF ATHENS	170

### **APPENDIX I - OFFICE BUILDINGS CASE STUDIES**



# Building 1 Administrative building of Pireaus Bank in Athens, Stadiou

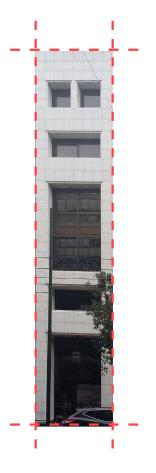


Facade grid	Height	4
	Width	-
WWR	0,46	
<b>Total building height</b> 36m		
Number of floors	9	
<b>Year</b> 1981		
Materials	concrete, marble, glass	
Architect	N. Valsamakis	
Description		

The building is designed with the scope of integration, not only to the nearby buildings, but also to the tradition of Athenian classicism. On ground level there is an arcade to provide with a more protected space for the pedestrians.

The facade is constructed with marble and glass surfaces, while the glass has a small setback from the exterior surface. The architectural design follows the neo-classical norms, while the top of the building is made entirely out of glass in order to remain visually 'silent'.







Building 2
Central building of Alpha Bank,
Stadiou & Korai

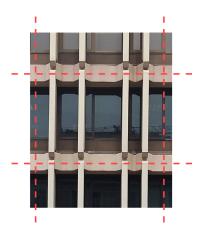
|--|

Facade grid	Height	3.7
	Width	0.6-1.8
WWR	0.49	
Facade type	beam facade	
Structure type	concrete	
Total building height	33m	
Number of floors	9	
Year	1975	
Materials	concrete, glass	
Architect	Sir B. Spence	
Description		

The building currently hosts offices of Alpha Bank and in the past it has been housing headquarters of other banks.

There are dense vertical shading panels on each facade. The lines of the top balconies coincide with the lines of adjoining neo-classical buildings.







Building 3 New building of TSMEDE offices, Parnassou

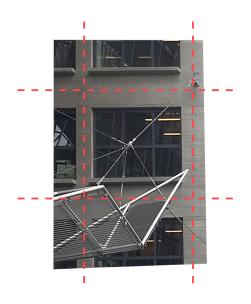
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Facade grid	Height	3.4
	Width	-
WWR	0.47	
Structure type	concrete	
Total building height	31m	
Number of floors	9	
Year	2013	
Materials	concrete, steel, glass	
Architect	OM Meletitiki	
Description		

The building currently hosts offices of Alpha Bank and in the past it has been housing headquarters of other banks.

The lines of the top balconies coincide with the lines of adjoining neo-classical buildings.



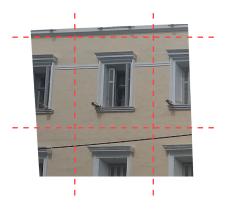




Building 4 Hellenic Navy Offices,

### I. Pararrigopoulou & Parnassou

Facade grid	Height 4	
	Width	3.6
WWR	0.19	
Total building height	20m	
Number of floors	5	
Year	1844	
Materials	concrete, stone, marble	

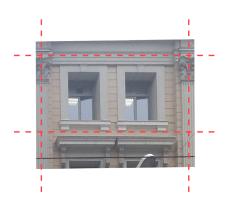


Building 5 National Bank of Greece Central Building, Stadiou



		1
Facade grid	Height	5.8
	Width	-
WWR	0.21	
Structure type	concrete	
Total building height	23m	
Number of floors	4	
Year	1840	
Materials	concrete, stone, marble, glass	



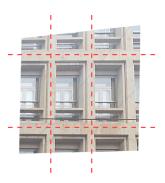




Building 6 Bank of Greece, Stadiou



Facade grid	Height	5.7
	Width	2.5
WWR	0.46	
Total building height	34m	
Number of floors	6	
Year	1933	
Materials	concrete, stone, glass	

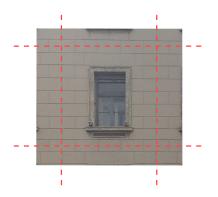




Building 7
Bank of Greece, Panepistimiou



Facade grid	Height	6.2
	Width	-
WWR	0.18	
Structure type	concrete, stone	
Total building height	31m	
Number of floors	5	
Year	1933	
Materials	concrete, stone, glass	

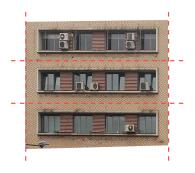




#### Building 8 Parnassou



Facade grid	Height	3.2
	Width	~1.5
WWR	0.26	
Structure type	concrete	
Total building height	32m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

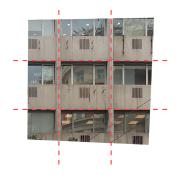




#### Building 9 Stadiou



Facade grid	Height	3.2
	Width	3.6
WWR	0.45	
Facade type	parapet	
Structure type	concrete	
Total building height	32m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

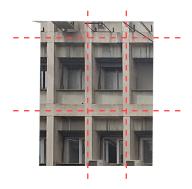




**Building 10 Technical Chamber of Greece Of** Nikis 2

ffices	; <b>,</b>	
	2.9	
	1.2	
		7

Facade grid	Height	2.9
	Width	1.2
WWR	0.26	
Facade type	parapet	
Structure type	concrete	
Total building height	26m	
Number of floors	9	
Year	unknown	
Materials	concrete, glass	



**Building 11** Megaro Vlachou, Paparrigopoulou



Facade grid	Height	3.2
	Width	1.8
WWR	0.53	
Facade type	parapet	
Structure type	concrete	
Total building height	32m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	







Building 12 Lambrakis Press Group, Chr. Lada 3



Facade grid	Height	3.4
	Width	1.2
WWR	0.35	
Facade type	curtan wall	
Structure type	concrete	
Total building height	34m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

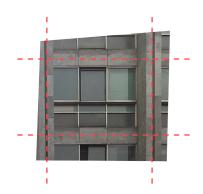


**Building 13** 



Facade grid	Height	3.4
	Width	4.2
WWR	0.68	
Facade type	parapet	
Structure type	concrete	
Total building height	34m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	



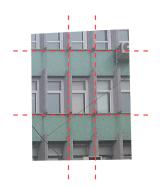




#### Building 14 I. Paparrigopoulou & Parnassou



Facade grid	Height	3.1
	Width	0.9
WWR	0.51	
Facade type	parapet	
Structure type	concrete	
Total building height	31m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

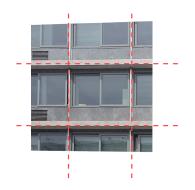




#### Building 15 Ermou



Facade grid	Height	3.3
	Width	3.5
WWR	0.55	
Facade type		
Structure type	concrete	
Total building height	33m	
Number of floors	10	
Year	unknown	
Materials	concrete, glas	S





#### **Building 16**



Facade grid	Height	3.2
	Width	2.7
WWR	0.50	
Facade type	double skin	
Structure type	concrete	
Total building height	32m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

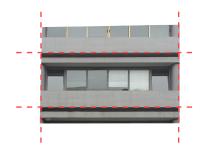




#### Building 17 Korai



Facade grid	Height	3.1
	Width	1.2
WWR	0.51	
Structure type	concrete	
Total building height	31m	
Number of floors	10	
Year	unknown	
Materials	concrete, glass	

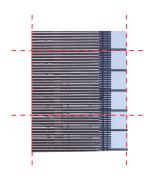




**Building 18** Michalakopoulou



Facade grid	Height	3.6
	Width	-
WWR	1.00	
Facade type	curtain wall	
Structure type	concrete, steel	
Total building height	25m	
Number of floors	7	
Year	unknown	
Materials	concrete, glass	





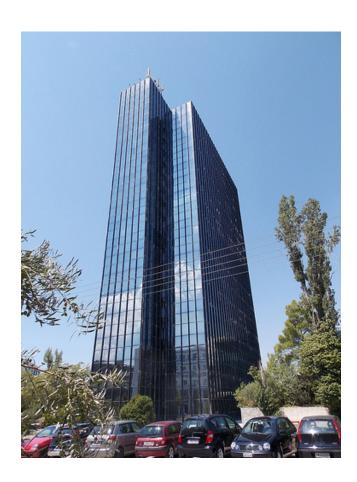
**Building 19** Piraeus Bank, Panepistimiou



Facade grid	Height	3.4
	Width	-
WWR	0.84	
Facade type	curtain wall	
Structure type	concrete	
Total building height	31m	
Number of floors	9	
Year	unknown	
Materials	concrete, glas	S



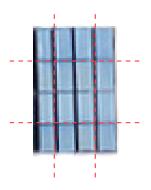




Building 20 Atrina Center Tower, Kifisias Ave 32 Marousi

1
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Facade grid	Height	4		
	Width	2		
WWR	1.00			
Facade type	curtain wall			
Structure type	concrete, steel			
Total building height	80m			
Number of floors	20			
Year	1980			
Materials	concrete, steel, glass			

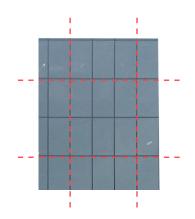


Building 21 Korai



Facade grid	Height	3.4		
	Width	1.6		
WWR	1.00			
Facade type	curtain wall			
Structure type	concrete, steel			
Total building height	34m			
Number of floors	10			
Year	unknown			
Materials	concrete, steel, glass			



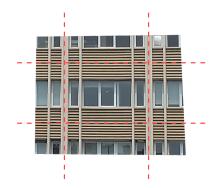


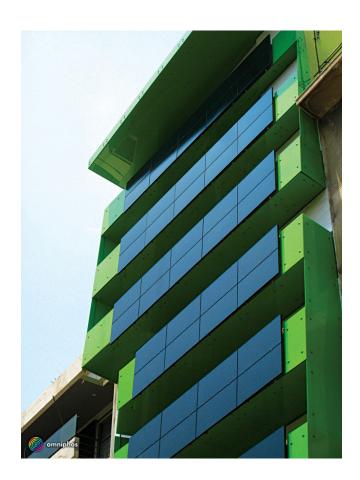


#### Building 22 Dragatsaniou



Facade grid	Height	3.6	
	Width	4	
WWR	0.44		
Facade type	curtain wall		
Structure type	concrete		
Total building height	32m		
Number of floors	9		
Year	unknown		
Materials	concrete, steel, glass		





#### Building 23 Sustainable Office building, Alexandras Ave 93

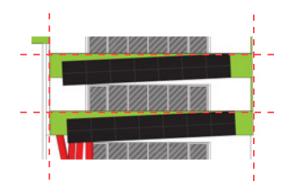


	ı			
Facade grid	Height	3.3		
	Width	-		
WWR	0.44			
Total building height	30m			
Number of floors	9			
Year	2008			
Materials	concrete, steel, glass			
Architect	K. Antonopoulos			
Description				

One of the few "green" buildings in the centre of Athens. The building company pursued to meet the contemporary demands of office buildings and the sustainable technology. The main characteristics of the sustainable approach are: the use of PV panels on the facade and roof, the internal recycling system, heating and cooling with the use of natural gas, central cleaning system which caters for less waste and substantial noise control.

Images' and info source: https://goo.gl/tp7cvK









Building 24 Headquartes of OTE, Kifisias Ave 99 Marousi

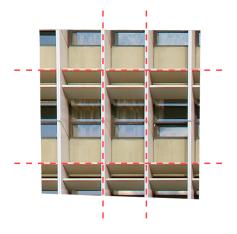


Facade grid	Height	3.2		
racaac gria	Tieigite	3.2		
	Width	0.9		
WWR	0.53			
Total building height	68m			
Number of floors	21			
Year	1975			
Materials	concrete, glass			
Architect	P. Marsellos, G. Mavromattis,			
	D. Nakos			

#### Description

The building belongs and hosts the central administration of the Hellenic Telecommunications Organization. With app. 62m height at the time of its construction it was the 2nd highest building in Athens. Nowadays it is the 8th in sequence. The character of the building facade lies on the use of consecutive horizontal and vertical shading screens. In 2008-2009, 25 years after its construction the exterior has been refurbished and treated with durable and weather resistant materials and techniques.

Images' source: https://goo.gl/FKAIBw





#### Building 25 Sanitas Offices, Kifisias Ave 115 Ambelokipi



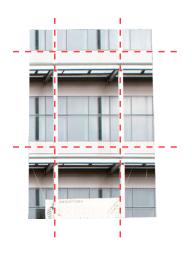
Facade grid	Height	4.3	
	Width	1.2	
WWR	0.50		
Facade type	curtain wall		
Total building height	30m		
Number of floors	7		
Year	2006		
Materials	steel, glass		
Description			

The building facade has been designed with attention to the orientation of the building as well as the fact that it is located next to a busy avenue.

There are external horizontal shading grills. The windows have steel profile frames.

Images' source: https://goo.gl/j95kuB





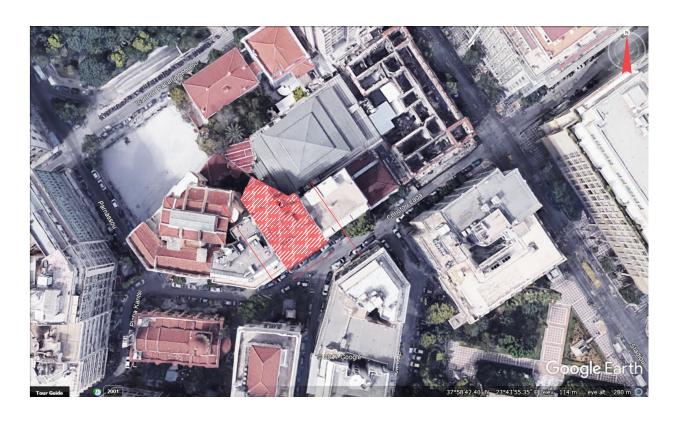
### APPENDIX II - BUILDING 12 - DRAWINGS

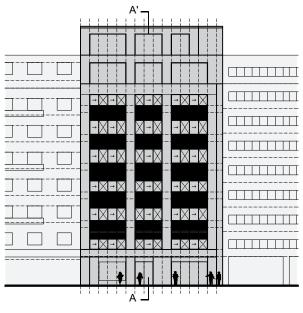


Building 12 Lambrakis Press Group, Chr. Lada 3

Facade grid	Height	3.80		
	Width	1.20		
WWR	0.35			
Facade type	curtain wall			
Structure type	concrete			
Total building height	34m			
Number of floors	9			
Year	~1970			
Materials	concrete, natural stone, glass			







#### SECTION A-A'

#### SOUTH-EAST ELEVATION - CHR. LADA STR.

Facade Length = 18.80m

Facade Height = 26.60m

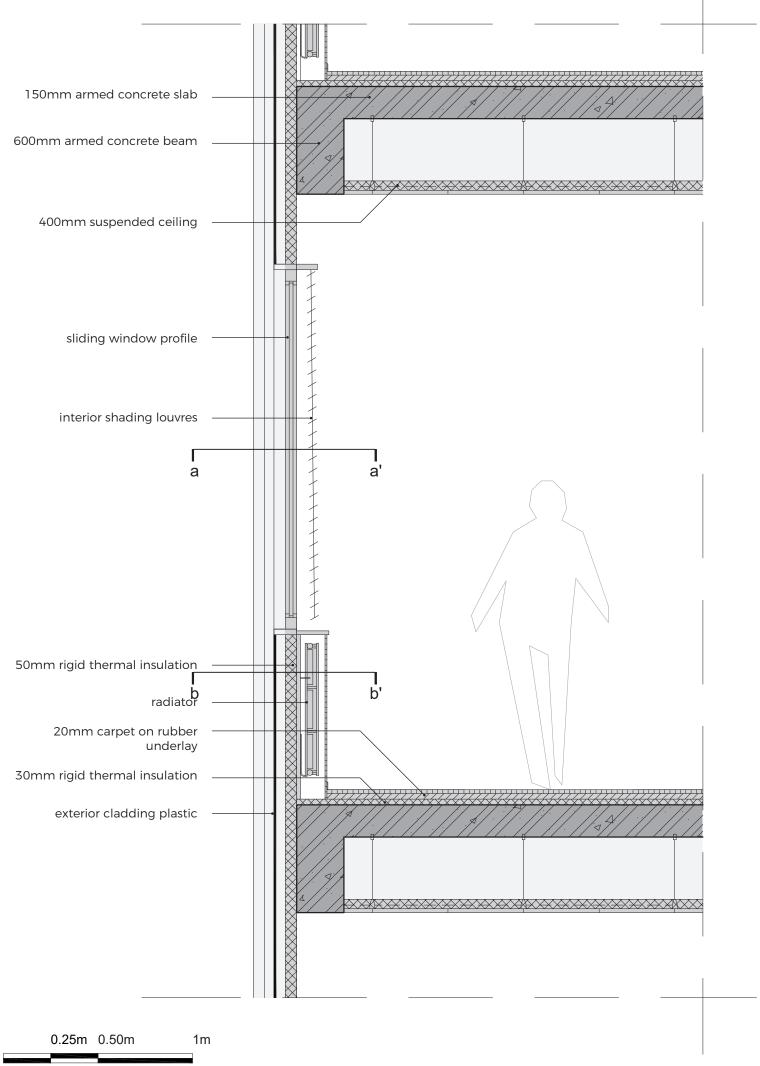
Total Building Height = 34.20m

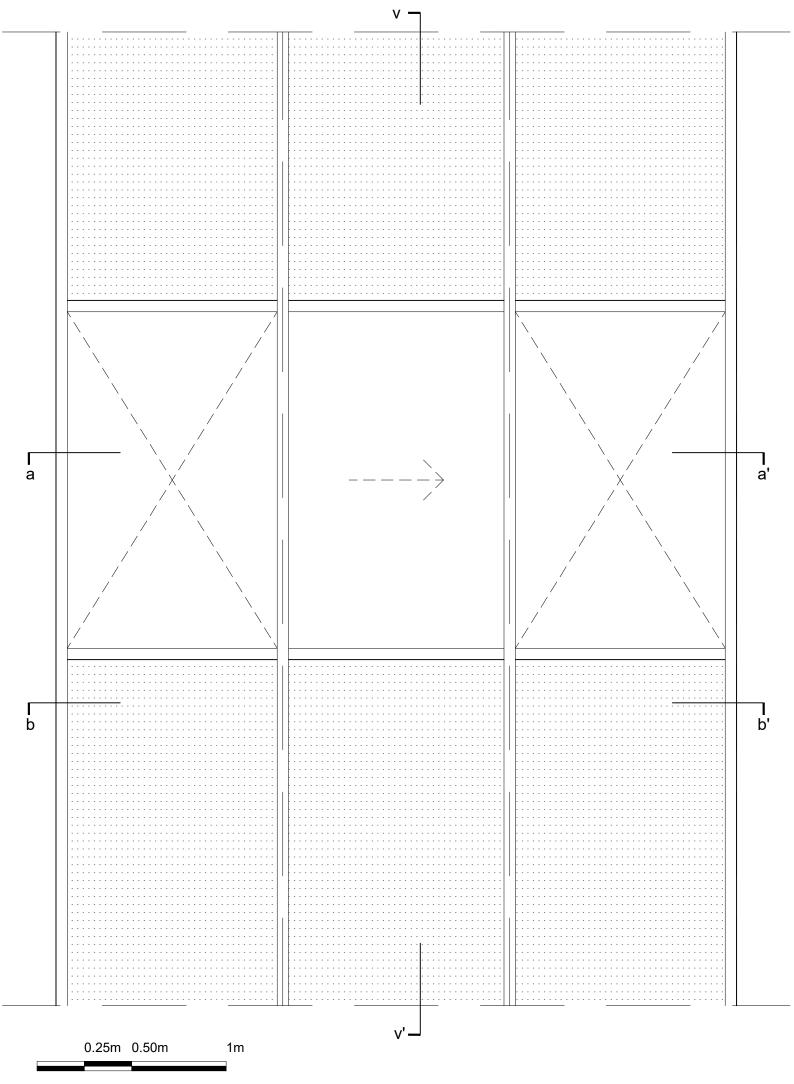
Facade Grid: Height = 3.80m

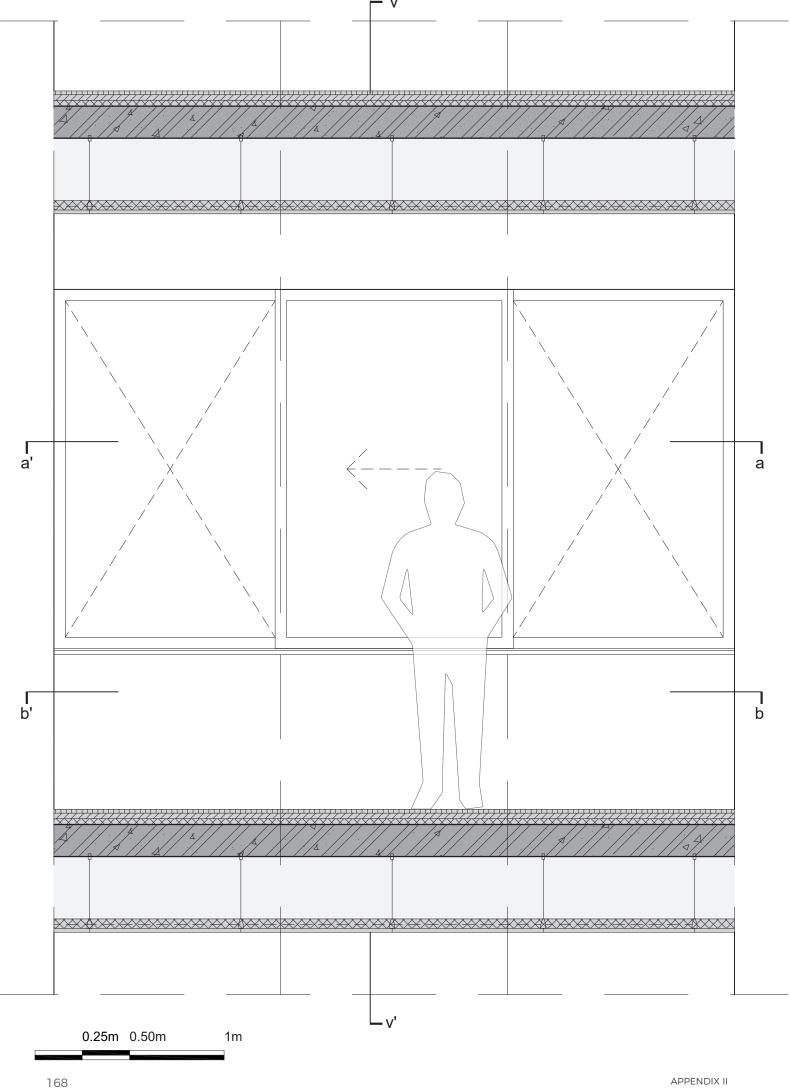
Width = 1.20m

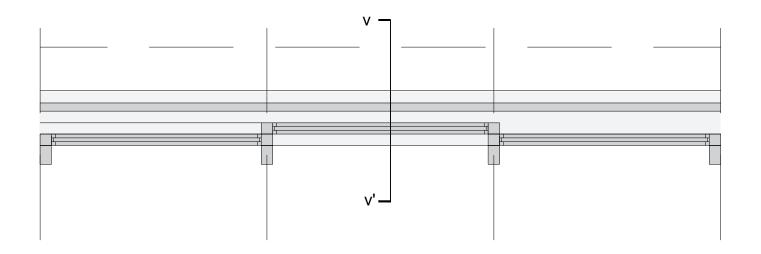
1m 3m 7m 15m

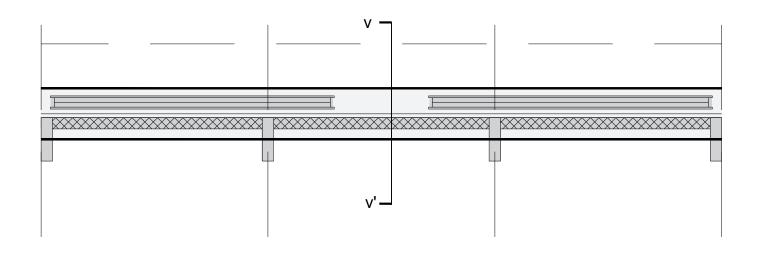
BUILDING 12 - DRAWINGS 165

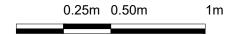




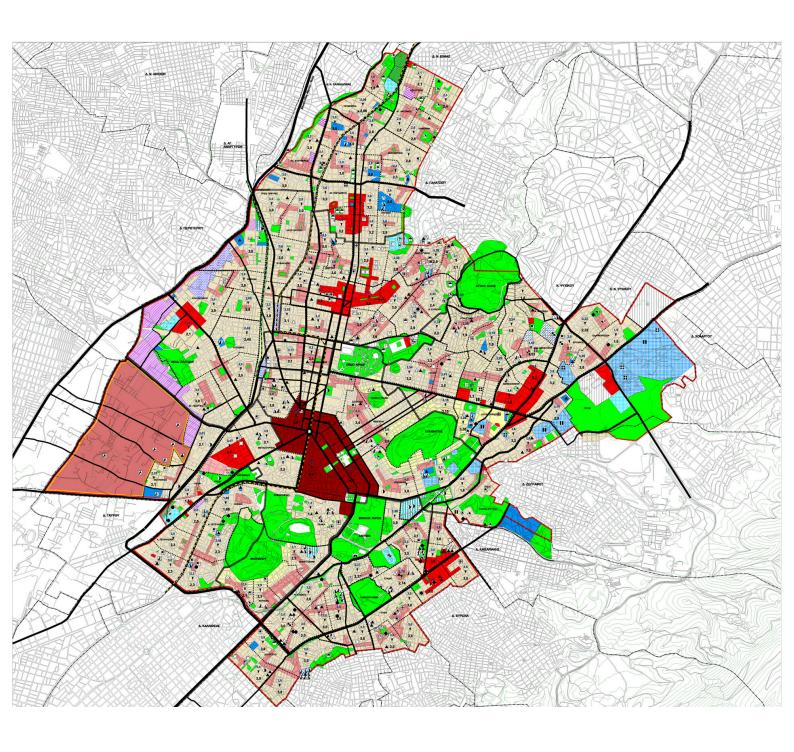








## APPENDIX III - GENERAL URBAN PLAN OF ATHENS (WITH LEGEND)



	Όρια Δήμων & Κοινοτήτων	Border of Municipalities/commun.				
		·			Εκπαίδευση	Education
	Όρια Γενικού Πολεοδομικού Σχεδίου Όρια Επέκτασης	Border of General Urban Plan  Border of Expansion	Δ		Νηπιαγωγείο	Kindergarden
	Όρια Εγκεκριμένου Γενικού	Border of Expansion  Border of Approved GUP	•	▲	Δημοτικό	Elementary School
	Πολεοδομικού Σχεδίου	Border of Approved GOP	$oldsymbol{\Lambda}$	$lack \Lambda$	Γυμνάσιο	Lower Secondary Grade School (Gymnasium)
	Όρια Γειτονιάς	Border of Neighborhood	Δ	1	Λύκειο	Higher Secondary Grade School (Lyceum)
•••••	Όρια Συνοικίας	Border of District	Δ	A	Μεταλυκειακά Κέντρα	After-lyceum center
	Όρια Διαμερίσματος	Border of Geographical Area	Δ		Μέση Επαγγελματική Σχολή	
	Υπερτοπικό Κέντρο Δήμου	Hyperlocal Municipality Center	Δ	$\Delta$	Ανώτερα Κ.Α.Τ.Ε.Ε	Higher Technical School
	Κέντρο Δήμου	Local Municipality Center	Δ	▲	Πανεπιστήμιο	University
	Τοπικό Κέντρο Γειτονιάς	Local Neighborhood Center			Περίθαλψη	Healthcare
	Κατοικία	Residence	Œ	$\blacksquare$	Κέντρο Υγείας	Healthcare Center
	Γενική Κατοικία	General Residence	::		Γενικό Νοσοκομείο (Νομαρχιακό)	General Hospital
***************************************	Εγκαταστάσεις Μεταφορών	Transportation Facilities	ш	П	Ειδικό Νοσοκομείο	Specialized Hospital
*******	Γεωργική Γη	Argicultural Land	KKK	444	Referen	Malfarra
	Αστικό Πράσινο - Ελεύθεροι Χώροι	Urban Green - Free spaces	2222	2222 <b>1</b>	Πρόνοια Παιδικός Σταθμός	Welfare Nursery School
	Περιαστικό Πράσινο	Suburban Green			Γηροκομείο	Elderly Center
	Κοινωνικές εξυπηρετήσεις	Social Amenities	_	_		
7////	Βιοτεχνικό Πάρκο - Βιοτεχνικές Εγκαταστάσεις μη Ιδιαιτέρως Οχλούσες				Ορφανοτροφείο Βρεφοκομείο	Orphanage Nursery
1111111	Πολεοδομικό κέντρο με περιορισμό σε χρήσεις	Urban Center under restrictions			Αθλητισμός	Sports
	Πολεοδομικό κέντρο με περιορισμό σε χρήσεις (2)	Urban Center under restrictions (2)	$\oplus$	<b>(1)</b>	Γήπεδο	Court
	Βιοτεχνικό Πάρκο προς εξυγίανα η		•	$\odot$	Στάδιο	Stadium
· · · · · · · · · · · · · · · · · · ·	Βιομηχανικό Πάρκο - Βιοτεχνικές/Βιομηχανικές		•	<b>(1)</b>	Κολυμβητήριο	Swimming pool
Millilli	Εγκαταστάσεις μη Ιδιαιτέρως Οχλούσες		$\oplus$	$\oplus$	Γυμναστήριο	Gym
*****	Ζώνη Βιομηχανίας - Βιοτεχνικές/Βιομηχανικές Εγκαταστάσεις Οχλούσες		•	•	Ναυτιλιακή Εγκατάσταση	Sailing facility
ШШ	Βιομηχανικές Εγκαταστάσεις που Παραμένουν			-	Πολιτιστικές Λειτουργίες	Cultural Functions
	Χονδρεμπόριο	Wholesale Trading	_	1000	Πολιτιστικές	0.15
	Τουρισμός - Αναψυχή	Tourism - Recreation	0		Λεπουργίες	Cultural Functions
	Ιδιαίτερες Χρήσεις	Special Uses	•		Μουσείο	Museum
Στ	Στρατός	Military	•	•	Βιβλιοθήκη	Library
**	Νεκροταφεία	Cemeteries	********		Όρια Προστασίας	Protection Border
	Αρχαιολογικοί Χώροι	Archaeological Sites		~	Όρια Ζώνης Οικιστικού Ελέγχου (Ζ.Ο.Ε)	Border of Urban Control Zone
_	Ελεύθερη - Ταχεία Λεωφόρος	Free - Fast Avenue	_	_	Όρια Ανάπλασης Αρθρου 13	Border of Article 13
	Πρωτεύουσα Αρτηρία				Ζώνη Ειδικών	Zono of special metivation
_	Δευτερεύουσα Αρτηρία				Κινήτρων	Zone of special motivation
	Συλλεκτήρια			· V	Διάταγμα Ελαιώνα	Decree of Eleonas
	Αστικές Σιδηροδρομικές Γραμμές	Urban Rails	16	-	Όριο περιοχής Διατάγματος Ελαιώνα	Area border of Eleonas Decree
	Προαστιακή Σιδηροδρομική Γραμμή	Suburban Rails	(3,	0	Συντελεστής Δόμησης Νομοθετημένος	Building Factor statutory
	Υπεραστική Σιδηροδρομική Γραμμή		(2,	0	Συντελεστής Δόμησης	Building Factor suggested
Р	Χώρος Στάθμευσης	Parking Space			Προτεινόμενος	3 33