Dynamic Building Skins:
Performance Criteria Integration

MARIA KONSTANTOGLOU,
Dept. of Architecture, University of Thessaly Pedion Areos, 38334, Volos,
Greece, mkonsta@arch.uth.gr, mkonstantoglou@lbl.gov

ANTONIOS KONTADAKIS,
kontadakis@bioklimatikos.com
ARIS TSANGRASSOULIS,
atsagras@uth.gr

Contemporary architecture has become increasingly more transparent and requires design approaches that provide thermal regulation while reducing energy consumption and its associated emissions. The term “intelligent” and “adaptive” building skins is used in façade design to describe building envelopes that enhance the relationship between the built and the natural environments by employing design principles inspired by nature. The notion of systems integration and dynamic performance characterizes high performance façades that are designed to meet a set of performance criteria such as to achieve occupants’ visual and thermal comfort and buildings energy efficiency. This paper examines the potential of modular architecture and dynamic façade systems to propose a façade design that regulates a building’s climate by automatically responding to environmental conditions to meet a set of performance requirements such as the need for daylight and occupants’ visual and thermal comfort. Individual components and daylighting systems such as light shelves and venetian blinds supported with motorized components are incorporated into the façade proposal of a typical office space and were examined in terms of their performance and dynamic character. Photovoltaic cells, also part of the façade system are used to allow for energy production. The façade design explores the principles of modularity and dynamic movement in order to convert the building envelope into an “adaptive” building skin. Four window to wall scenarios were set up based on the proposed modular façade concept principles and tested in simulation tool Energy Plus. A series of control strategies that address performance requirements such as the illuminance levels and the visual contact to the exterior have been set and examined in relation to the four façade scenarios for Athens climatic data on an hourly basis for one year.

Keywords: Modular facades; adaptive building skins; daylighting systems

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ABSTRACT: The notion of systems integration and dynamic performance characterizes high performance façades that are designed to meet a set of performance criteria such as to achieve occupants' visual and thermal comfort and buildings energy efficiency. This paper examines the potential of modular architecture and dynamic façade systems to propose a façade design that regulates a building's climate by automatically responding to environmental conditions to meet a set of performance requirements such as the need for daylight and occupants' comfort. Individual components and daylighting systems such as light shelves and venetian blinds supported with motorized components are incorporated into the façade proposal of a typical office space and were examined in terms of their performance and dynamic character. Four window to wall scenarios were set up based on the proposed modular façade concept principles and tested in simulation tool Energy Plus. A series of control strategies that address performance requirements such as the illuminance levels and the visual contact to the exterior have been set and examined in relation to the four façade scenarios for Athens climatic data on an hourly basis for one year.
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INTRODUCTION
The term "intelligent" and "adaptive" building skins is used in façade design to describe building envelopes that enhance the relationship between the built and the natural environment by employing design principles inspired by nature. The development of the facade technology in the 20th century mainly involves the creation of multilayered, lightweight and transparent skins [1], [2]. These characteristics are embodied in the "curtain wall" facade type, which has led to design variations such as the "alternating" facade [3] that combines single-skin and multi-skin facades, and the "integrated" facade equipped with facade systems such as decentralized ventilation units [4].

The latest developments in facade technology focus on the "hybrid" facade a standard facade with some service units integrated, the "intelligent" facade that introduces the idea of dynamic movement and the "component" facade in which all building services components are integrated [5]. This study will explore and focus on the notions of modularity and dynamic movement in facade design together with their effect on a typical office space' energy balance.

FUTURE BUILDING SKINS
Based on their extended research on future building envelopes, Knaack and Klein [6] have addressed the demands that should be considered when designing and constructing building facades. According to their research, the facade should offer increased protection measurements on solar gain by utilizing variable sun shading devices or adjusting the geometry of the external envelope based on the position and progression of the sun. To achieve sufficient solar protection, the facade should feature semi-transparent and translucent materials. It should also offer reduction in cost by optimizing the integration of facade components.

MODULAR ARCHITECTURE
Modularity in facade design promotes a series of quality characteristics that improve the building envelope's design process, manufacturability and performance. As summarized by Kamrani and Salhieh [7] modularity in product design promotes the reduction in product development time, it allows for customization and upgrades and also results to cost efficiencies due to amortization.

Modular architecture in facade design utilizes modular systems, which by definition are closed systems with elements prefabricated by the manufacturers independent of a particular building [8]. The possibility to use modular systems to create unique building forms lies in their ability to be combined in a number of different ways following geometric and constructional rules.

DYNAMIC FAÇADE SYSTEMS
The introduction of dynamic movement with the application of advanced systems aims to address performance requirements such as the need for heating, lighting, cooling and energy generation. This study will

focus on dynamic shading systems that provide solar protection, decrease glary conditions and provide view to the outside. Conducted research on dynamic shading systems mostly focuses on venetian blinds. The department of "Energy and Building Design" of the University of Lund [9] has examined motorized blinds and concluded that energy savings for motorized blinds reach up to 50% on a yearly basis. A study by Lee et al. [10] at the Oakland Federal Building concluded that the automated blinds utilization and the implementation of the lighting control system resulted to energy savings ranging from 7% - 15% and 19% - 52% for cooling and lighting respectively.

Limited are the examples of research on dynamic daylighting systems. Konstantoglou et al. [11] examined the performance of a fully dynamic system with daylighting and shading components. Results demonstrated that dynamic light-shelves increase daylighting levels in non-daylight areas and that Daylight Autonomy values (DA) increase up to 50%. Also automated blinds increase energy savings by up to a factor of 1.53 compared to static blinds. Meek and Breshears [12] conducted a study on the facade system for the new Health Science Research Laboratory of the University of California San Diego. Results have shown that the dynamic exterior shading system in the view window provides the highest indoor quality and energy efficiency with the minimum building ventilation rates.

PROPOSED MODULAR FAÇADE CONCEPT

The latest developments in facade design and the growing need for performance criteria integration has been the incentive for a concept idea that combines the principles of modularity and dynamic movement. The facade system is a post beam system that consists of frame-based modules integrated inside posts that run over the whole height of the façade as shown in Figure 1. Inside the posts there is media that provides the modules and more specifically the shading systems with input. The modules dimensions and façade grid are specific to the building type.

The set of functions potentially integrated into the facade includes performance criteria such as daylighting, solar protection, ventilation and energy production. The modules display a variety of features that depend on design preferences, building type and use. Such features are light-shelves for light redirection, overhangs for shading and blinds for solar protection and glare reduction. These systems are potentially automatically controlled by control strategies that block direct solar radiation, minimize glare, and provide sufficient lighting levels on the work-plane surface. The façade also features building integrated photovoltaics (BIPVs) for energy generation.

Figure 1: Modular Façade Concept

EVALUATION STUDY

To examine various layouts of the modular facade system and the impact of their transparency and automatic movement in the facade's overall performance, a series of simulations were performed in EnergyPlus. The façade alterations and the implemented shading systems were selected in order to examine their impact on the buildings energy performance and more specifically on the primary energy consumption for heating, cooling and lighting. The energy model located in Athens, Greece represents a south facing office space 5.4m long and 3.4m wide resulting in a floor area of 18.36 m^2. The south facing wall opening area is defined by four scenarios: a 10% Window to Floor Ratio, and three Window to Wall Ratio scenarios (WWR: 40%, 60% and 80%) as shown in Figure 2. Room layout and shading devices geometric characteristics are shown in Figure 3.Applied model properties are shown in Table 1.

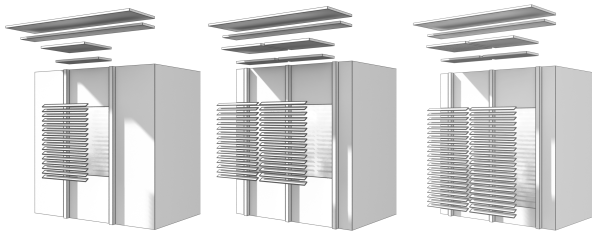

Figure 2: Modular Façade scenarios in Energy Plus. From left to right: 10%WFR, 40%WWR, 60%WWR

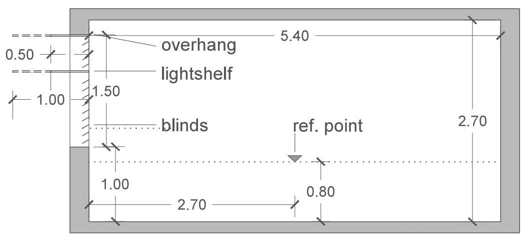

Figure 3: Office model section diagram

Table 1: Model Properties

Office space properties	Floor Reflectance	0.2
	Walls Reflectance	0.5
	Ceiling Reflectance	0.8
Window properties	Area	3.9 m^2, 5.5 m^2, 7.3 m^2
	U-Factor	2.314 W/m^2K
	Visible Transmittance	0.74
	SHGC	0.615
Light-shelf properties	Width	0.5 m, 1.0 m
Overhang properties	Width	0.5 m, 1.0 m
Blinds properties	Width	0.1 m
	Reflectance	0.5
	Material	Aluminum

The shading and daylighting systems that were examined are external non-rectractable blinds, an overhang with two widths (0.5m and 1m) and length of 3.4m, and a horizontal lightshelf with two widths (0.5m and 1m) and lengths that adjusts to the different WWR scenarios as shown in Figure 2. To examine the role of automated movement in relation to the modular facade system, a set of control strategies was tested to control the blinds movement. The control strategies that were applied are shown in *Table 2*. The room occupancy and hours of operation were defined as 0.1 person/m2 from 08:00 to 19:00 during weekdays. The installed power for lighting was set as 16 W/m^2 and the electric power as 15 W/m^2.

Table 2: Blinds Control Strategies

S1	No Shading (Base Case)
S2	Static Blinds (0°, 10°, 20°, 30°, 40°,50°, 60°, 70°, 80°, 90°)
S3	Sunblocking Control Strategy (blocks direct solar radiation)
S4	Glare Control Strategy (minimizes glare)
S5	View Out Control Strategy (ensures visual contact)
S6	Dynamic Control Strategy based on Illuminance levels (500 lux)
S7	Combined Control Strategy (combines S5 and S6)

SIMULATIONS FRAMEWORK

A set of simulations was used to calculate interior daylighting levels, glare and heating, cooling, lighting primary energy consumption in EnergyPlus for the whole year. As presented in Table 2 all dynamic strategies but S3 were developed using results from hourly simulations for fixed slat angles from 0° to 90°, with a 10° step. Based on the performance requirements as defined in the control strategies (illuminance level 500 lux, DGI<22 with the observer located at the center of the room looking directly at the window, visual contact class >=3), hourly schedules of slat angles were set up using linear interpolation between adjacent values. The applied methodology has already been used in conducted research [13] and is schematically presented in Figure 4.

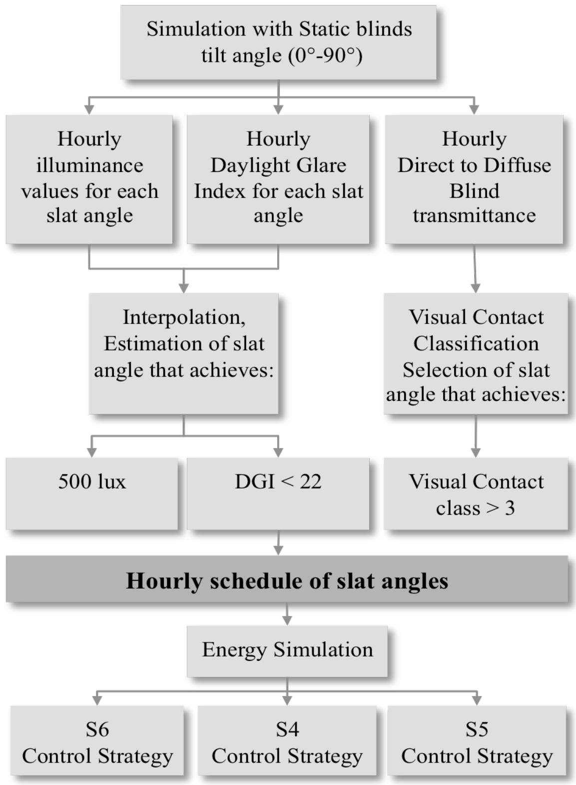

Figure 4: Schematic representation of the S4 S5 S6 control strategies calculation method

Control strategy S1 is the base case scenario and strategy S2 refers to static blinds with slat angles from 0 to 90. In dynamic control strategies S3 to S7, the blinds tilt angle changes to ensure the performance requirements without retracting the blinds. Control strategy S3 is the EnergyPlus sun blocking control strategy, where the slate angle tilts to block beam solar radiation. S4 is a glare control strategy that is based on the Daylight Glare Index and adjusts the slat angle to avoid glare. If for all slat angles DGI < 22, then the blinds are set to horizontal position (90°). In strategy S5 the blinds schedule assures visual connection to the exterior, which is estimated and classified, based on the Standard EN 14501:2005 “Blinds And Shutters - Thermal And Visual Comfort - Performance Characteristics And Classification” (Table 3). For this study, hourly tilt angle values are set so that visual contact class is at least 3. In strategy S6 the blinds tilt angle is adjusted in order to meet a set point of 500 lux on the sensor located in the centre of the room. The blinds slat angle schedule is defined using linear interpolation between adjacent values to meet the set point of 500 lux. In case this condition is not met by daylight, the electrical lighting control system tops up. Strategy S7 is a combination of strategies S5 and S6 which addresses both the need for visual contact and illuminance levels and in every time step it implements the strategy with higher tilt angles. For all control strategies, blinds tilt angle is set to horizontal position (90°) during non - occupancy hours.

Table 3: Visual Contact Classification based on the Standard EN 14501:2005

$t_{v,n-n}$	$t_{v,n-dif}$		
	$0 < t_{v,n-dif} \leq 0.04$	$0.04 < t_{v,n-dif} \leq 0.15$	$t_{v,n-dif} > 0.15$
$t_{v,n-n} > 0.15$	4	3	2
$0.05 < t_{v,n-n} \leq 0.10$	3	2	1
$t_{v,n-n} \leq 0.05$	2	1	0
$t_{v,n-n} = 0.00$	0	0	0

RESULTS ANALYSIS

Energy consumption results for all systems including static blinds, automated blinds, overhang and light-shelf are shown in Figure 5. Primary energy consumption is estimated with the use of the following conversion factors 2.9 for electricity and 1.05 for heating according to Greek Regulation for Energy Performance of Buildings (KENAK) [14]. Base case scenario (WFR10%) is the basic one and represents the minimum requirements for window size according to the Building Code regulation.

Shading on Energy Performance

The presence of shading affects primary energy consumption compared to the base case scenario. Shading is more beneficial for higher window to wall ratio scenarios (WWR60% and WWR80%) when the glazing surface increases. Overhangs and light-shelves perform better for the smaller window to wall ratio scenarios. Automated blinds are more beneficial for higher window to wall ratio scenarios.

Light-shelf and overhang

The case scenario with the overhang (1m width) shows the lowest primary energy consumption for WWR40% and WWR60% compared to all others cases and control strategies (including base case, static and automated blinds). For scenario WFR10%, the light-shelf (0.5m width) represents the best scenario with the lowest primary energy consumption.

Static Blinds

The presence of static shading and more specifically blinds in horizontal position (strategy S2, 90°) reduces

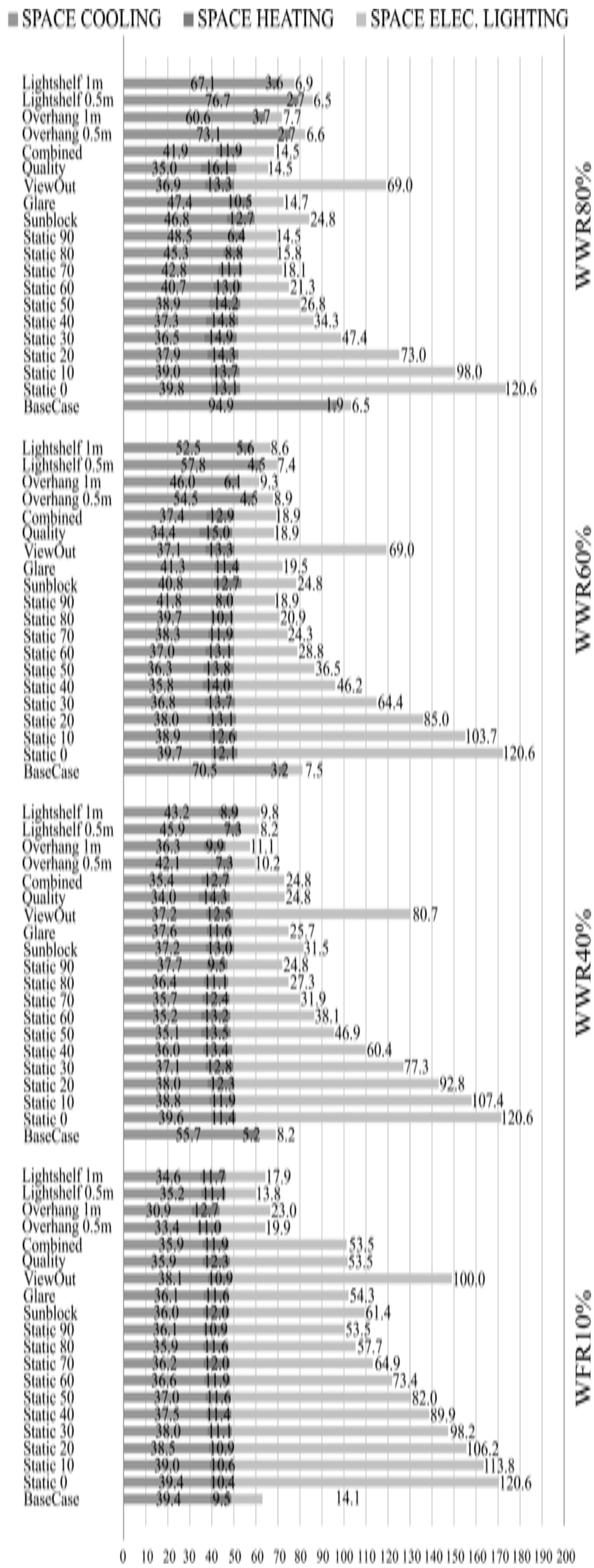

Figure 5: Primary Energy Consumption for all systems (blinds, overhang, light-shelf): Static blinds (S2, 0°-90°), Automated blinds (S3-S7), Overhang (S8), Light-shelf (S9)

primary energy consumption by 15.4% and 32.8% for scenarios WWR60% and WWR80% respectively compared to the base case scenario (S1-no shading). However for scenarios WWR10% and WWR40% horizontal static blinds increase primary energy consumption by 59.4% and 4.2 % respectively.

Automated Blinds

Tilt angle values for automated blinds vary depending on the simulated control strategies. A representative example is shown in Figure 6 with tilt angle values for five control strategies for winter solstice (December 21st) and geographical location Athens, Greece. As shown in the charts, the requirements for the View Out strategy (S5) are lower than the tilt angle values of all other control strategies and therefore conditions for visual contact class 3 are met by all control strategies. For the Glare control strategy (S4) slat angle values are high enough so that conditions are met by the rest of the strategies for the early morning and late evening hours of the day for all window to wall ratio scenarios. The only control strategy that presents higher values than the Glare control is the Sunblocking (S3) for scenarios WWR40%, WWR60% and WWR80% from 11:00 am to 2:00 pm. The Combined control strategy is defined by the Dynamic strategy and meets the requirements for Glare control for scenarios WWR40%, WWR60% and WWR80%. For WFR10% Glare control strategy requires lower tilt angle values than the Combined. Differences in values highly affect the primary energy consumption for all Window to Wall Ratio scenarios. Results on primary energy consumption highlight an interaction of the shading systems and the implemented control strategies with the overall energy consumption and occupants visual comfort.

Dynamic control strategy (S6) shows the best energy performance for WWR80% compared to all case scenarios and strategies. Control strategies S3 to S7 represent the lowest primary energy consumption compared to static blinds with tilt 40° and higher for all scenarios. The Dynamic control strategy (S6) is the best in terms of lowest energy consumption for scenarios WWR40%, WWR60% and WWR80% compared to the rest of control strategies. In the case of WWR10% the Glare control strategy (S4) represents the lowest energy consumption.

Overall the implementation of the automated blinds significantly affects the cooling loads. Strategies S3 to S7 for all WWR scenarios significantly reduce primary energy consumption for cooling compared to the base case scenario (S1). For WFR10% automated blinds reduce Energy consumption for cooling by up to 8.9% (S6, S7) compared to S1. Dynamic control strategy (S6) presents the lowest energy consumption for cooling and decreases energy loads by 39%, 51.2% and 63.2% for scenarios WWR40%, WWR60% and WWR80% respectively compared to the base case scenario (S1).

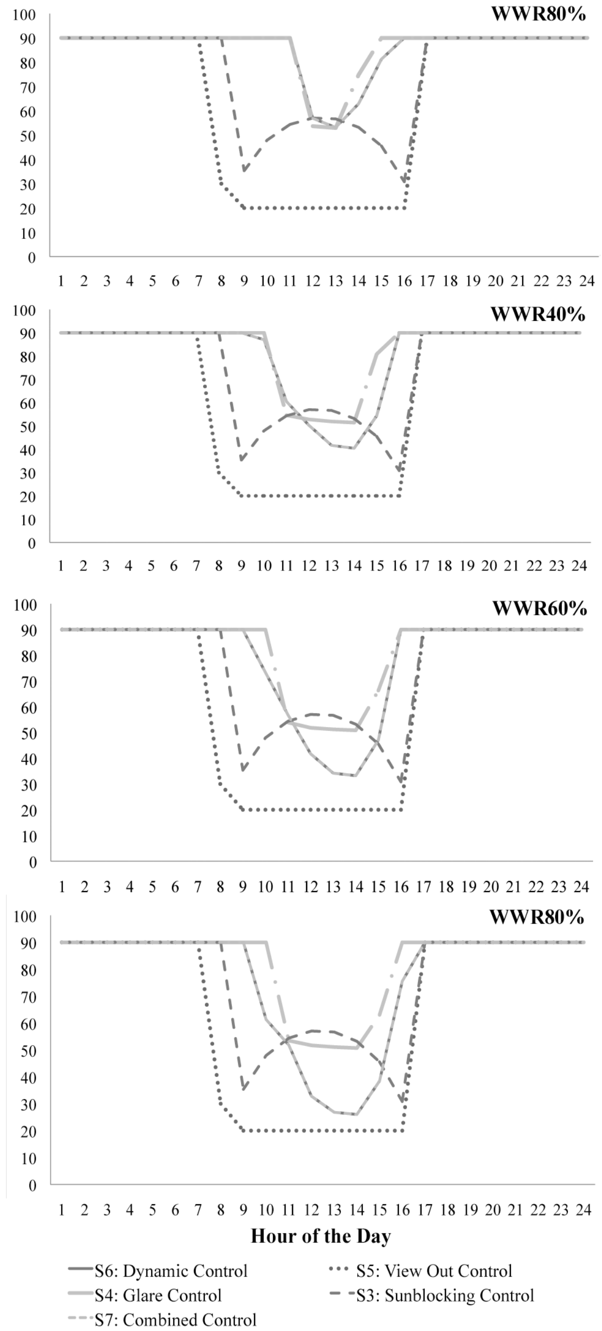

Figure 6: Hourly tilt angle values in degrees for Control Strategies S3-S7 for December 21st

Primary energy consumption for heating is also affected by automated shading. Strategies S3 to S7 increase energy consumption for heating by a percentage that ranges from 29.5% to 742% for WFR10% and

WWR80% respectively compared to the base case scenario S1. In relation to horizontal static blinds (S2-90°) the increase in energy consumption for heating for the automated blinds lowers to 12.9% and 150% for scenarios WFR10% and WWR80% respectively.

The usage of automated blinds also affects lighting consumption. Compared to static blinds in 50° tilt angle there is a decrease in primary energy consumption for lighting for control strategies S6 and S7. Lighting consumption is reduced by a percentage of 35% and 42% for WFR10% and WWR80% respectively.

PV Energy Generation

To estimate the energy generation from the integrated PV panels, for all window to wall ratio scenarios, the simulation tool PVwatts was used. The PV array area for each scenario was first calculated assuming that it covers the spandrel area and part of the area next to the window opening. The PV array area for all scenarios 10%WFR, 40%WWR, 60%WWR and 80%WWR and the equivalent AC Energy are shown in *Table 4*. To calculate primary energy consumption AC energy values were multiplied by a factor of 2.9.

Table 4: PVs, Energy generation

Façade Scenarios	PV array Area (m^2)	DC Rating (kW)	AC Energy (kWh)	Primary Energy (kWh/m^2)
10%WFR	6.4 m^2	0.73	944	149.1
40%WWR	4.45 m^2	0.51	659	104.1
60%WWR	2,8 m^2	0.32	414	65.4
80%WWR	1.35 m^2	0.15	194	30.6

Results have shown that for scenarios WFR10% and WWR40%, energy generated by PVs is sufficient to cover energy requirements for the automated blinds (S3-S7) as well as the cases of the overhang and light-shelf. For scenarios WWR60% and WWR80%, lighting loads get reduced because of the increased glazing area, however the energy generated by PVs is rather low related to the overall energy balance.

CONCLUSIONS

This study has explored the potential development of a modular system with integrated dynamic shading systems. Results have shown that automated blinds are more beneficial in the case of larger glazing area. Whereas overhangs and static light-shelves along with PVs perform better in the case of smaller window to wall ratio scenarios.

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