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Algae Window for reducing energy consumption of building structures in the Mediterranean city of Tel-Aviv, Israel

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ABSTRACT

The present study focused on analyzing the potential impact of incorporating living microalgae to the built facades, Algae Window, on the energy consumption reduction of a building. Two microalgae species of *Chlamydomonas reinhardtii* and of *Chlorella vulgaris* were cultivated and the impacts cells density were studied on the light penetration and heat transfer. The experimentally measured impacts of the two studied microalgae species were used to calculate the U-factor (Thermal conductance), VT (Visible Transmittance) and SHGC (Solar Heat Gain Coefficient) of the Algae Window. Based on the empirical results, the impact of the algae window on the energy consumption was estimated by extensive simulation study within an office space in the LEED accredited Porter building in Tel-Aviv University, Israel. The results show that incorporation of the microalgae into the windows has the potential to improve the energy efficiency in the studied building under the conditions of the Mediterranean climate. The impact of the algae window on the energy consumption was estimated in comparison to single glazing and to double glazing, and was found to differ significantly according to the facade orientation in both microalgae species; at maximum concentrations in the algae window as compared to single glazing window, the energy saving reached up to 20 KWh m^{-2} $year^{-1}$ in South, 8 KWh m^{-2} $year^{-1}$ in East, 14 KWh m^{-2} $year^{-1}$ in West, and energy increase up to 18 KWh m^{-2} $year^{-1}$ in North. Three factors were found to explain the variance in the energy saving performance of the Algae Window, namely, the algae concentration, the window size and the combination factor of the algae concentration with the window size that yielded the largest effect on decreasing the energy consumption. This study suggests that incorporating microalgae cultivation in building windows can provide energy saving to the building and addresses the main design factors that can effect on the savings as well as on other energetic aspects involved in the system such as energy production from algal biomass that has multiple applications in the urban environment.

Contents

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Nomenclature

A	Absorptance of layer in window
h	convection coefficient from the glass surface (W $m^{-2}K^{-1}$)
I	solar irradiance (W m^{-2})
K	thermal conductivity of glass layer (W $m^{-1}K^{-1}$)
N	inward-flowing fraction
t	thickness of layer in window (mm)
TA	Average nominal air temperature (°C)
T	Transmittance of glazing system
U	Overall heat transfer coefficient of the window system (W m^{-2} K^{-1})
Greek symbols	
α	volumetric absorption coefficient (1/cm)
λ	wavelength (nm)
$\rho 1$	reflectance at a glass to air interface
$\rho 2$	reflectance at a glass to water interface
$\tau 1$	transmittance of the glass and air window
$\tau 2$	transmittance of the glass and water window
θ	radiation incidence angle on window
Subscript	
ex	external
f	front glass surface
g	glass
int	internal
k	Layer k in the window system
L	Number of glazing layers in the window
s	direct solar
w	water
Abbreviations	
SHGC	Solar Heat Gain Coefficient
VT	Visible Transmittance

1. Introduction

Worldwide, the building sector is responsible for more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions [38]. Many available technologies can significantly reduce the energy use in buildings such as extensive glass facades that exacerbate high heat loss and unwanted internal heat gains [20]. Most of these technologies have undergone thorough testing and use in existing buildings; however, many of them are not in use due to a myriad of barriers. Consequently, energy use in buildings continues to be higher than necessary [24].

The next generation of buildings already incorporate multiple elements such as solar panels and small wind turbines to generate local clean energy and constructed wetlands to clean locally the building gray water to ensure the sustainable environment [9]. However, solar panels and wind turbines are not able to provide 100% of the energy demands of the building 24/7 and additional renewable technologies to backup and supplement these systems are required. Microalgae photobioreactors (PBR) are emerging functional building blocks, which could also provide for energy savings in the buildings ([20,30]).

Algae cells are complex systems that interact with the environment, grow and replicate. The algae cell is separated from its environment by a biological membrane [27]. The major inputs to the algae cell are light [37], inorganic carbon [26], nitrate [36], phosphate [25], biological signals from other organisms (for example epiphyte bacteria; [32]). As a living system, the major output from the cell to its environment is oxygen (if photosynthesis takes place; [15]), biomass [11], proteins [2], starch [4], cell wall [10], detritus and light that passes to the lower levels [5]. Research using algae within PBR's has been well documented as related to aspects of biomass productivity, including bioremediation of wastewaters, CO_2 sequestration, light harvesting as well as producing energy (e.g. [8,18,21,23,28,29,35,42]).

Recently, there has been an increasingly interest to exploit the algae benefits in the urban environment, and some living algae bioreactors have been integrated into building facades where one of the first famous built example is the BIQ building in Germany [41]. This interest has been expanded to research on algae in PBR in buildings facades from several aspects of growing conditions and biomass production, thermal regulation and solar optimization ([20,30]). From the energetic aspect, using façade of buildings as an area for growing microalgae allows to create an insulating layer for energy savings and act as a biomass reservoir that can be converted into active bio-energy for the building use. Intelligent utilization of energy and improvement of its efficiency is a necessary step in a world where energy consumption increases constantly and the urban warming is aggravated. Currently, there are few attempts at incorporating algae reactors within building façades to provide passive cooling and heating during the summer and winter months, respectively [31]. Recent studies have examined the microalgae bioreactor in a building from the energetic aspects: Umdu et al. [39] studied the microalgae panel bioreactor thermal transmission showing a significant interaction between the U-factor of the studied system and its design factors (reservoir, air layer, and reservoir wall thicknesses). Kerner at al. [19] studied the impact of insulating additional outer two glass plates to the inner medium of the microalgae bioreactor, for creating efficient heat management to cover the demand for heat in a building with algae production, showing that 80% of the heat extracted from the microalgae façade were used as a heat source for the building's supply system.

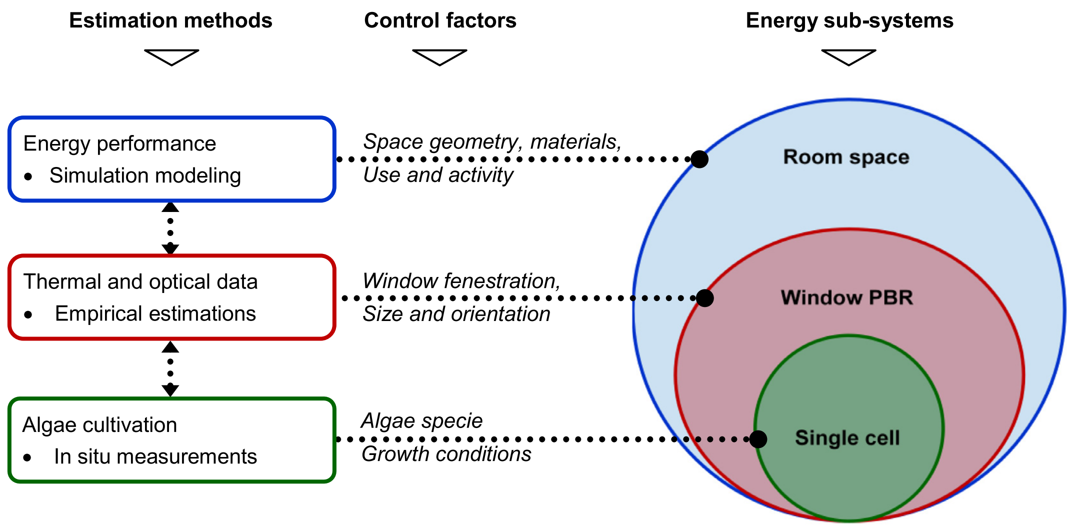

Fig. 1. Modeling procedure of the algae window system.

In this work we studied the potential impact of microalgae bioreactor incorporated into windows, Algae Window, on the building energy balance. Using experimental data on light and heat transfer modifications in the window by the incorporated algal culture combined together with energy simulating modeling, we estimated the impact of algae type, concentration, reactor size and location on the energy balance of a room space in a building in Tel Aviv, Israel. The estimation of these design parameters provides the essential information on the feasibility of using algal wall to improve the overall energy efficiency of the building. The presented study focused on the potential impact of the algae window as a passive element on the energy consumption in the studied building. Other aspects that can affect the energy balance were not considered in the study, namely energy production from the microalgae biomass, and thermal energy that can be extracted from the water within the bioreactor.

2. Materials and methods

The methodology in this study is focused on estimating the energetic impact of the algae window system through three subsystems - single cell of a microalgae, window with embedded PBR with multiple single cells and the room space within a building structure. The estimation of the energy consumption is based on an integrative approach between measured parameters of thermal and optical properties of studied cultivated microalgae species and a modeling tool for simulating the impact of the studied algae species on the energy consumption within various window configurations in a studied space room. Fig. 1 shows the modeling procedure through the three sub-systems and the control factors taken into account in the study.

2.1. Single cell of microalgae

2.1.1. The algae cultivation

The studied algae species are *Chlamydomonas reinhardtii* (*C. reinhardtii*) wild type (WT) UTEX 90, and *Chlorella vulgaris* (*C. vulgaris*) UTEX 395 obtained with in lab stockpile (according to UTEX Culture Collection of Algae organization, [40]). The two species have different diameter sizes where *C. reinhardtii* is about 10 µm [16] and *C. vulgaris* is about 2 to 10 µm [12]. The algae were grown in TRIS acetate phosphate (TAP) medium according to Gorman and Levine [13], a microalgae growth liquid medium.

The cultivation of microalgae done using 500 mL TAP medium in 1 L flask with magnetic stirrer in low speed in 24 °C under natural light conditions for 4 weeks. During the tests the maximum concentration of the cultivated microalgae was 2100 cells/mL in both algae species

2.1.2. Cell counting

An estimation of the concentration of microalgae was performed using a counting cell - Counting chamber, BLAUBRAND®, Neubauer improved, and Nikon ECLIPSE TE2000-S microscope. Parallel to a calibration curve compared to the measurement of OD 600nm using spectrophotometer infinite M200PRO- TECAN.

2.2. Window with PBR of microalgae multiple cells

To understand the impact of the microalgae on the thermal and optical properties within a window system, measurements were performed with a range of concentrations of microalgae from 0% up to 100% in the two studied species: The % microalgae concentration was calculated as the ratio between each concentration level and the maximum concentration (2100 cells/mL), where the maximum concentration was set as 100%, and the base case of pure water with no algae was set as 0%.

2.2.1. U-factor (thermal conductance)

The U-factor determines the rate of heat transfer through a fenestration system due to a difference between the indoor and outdoor temperature values and, its units of measurement are W m^{-2} K^{-1}. The U-factor for the studied algae window was evaluated in two steps. First, the conductance of the window itself (two glass panels and the intervening space with water) was characterized using "hot plate" method [17]. A special device was built consisting of a copper plate (length and width of 5.5 cm, 1 cm thickness) with an embedded electrical heater, 17 Watts were transferred to the system, which heated the heater to about 50 °C. In the system, two sample windows were located on both sides of the heater (glass thickness of 6 mm, length and width of 8 cm), and next to them two additional copper plates. Each copper plate was monitored with a K-type thermocouple connected to NEWTRON TM-5005 thermometer to determine heat transfer through the system. The entire system was isolated from the external environment by wrapping a thermally insulated material of polyacrylamide. The sides of the window were also built of insulating material to allow the heat to pass through the liquid itself, not through the sides of the window. The ratio of the heating power to the temperature difference between the central (heated) plate and the side plate is proportional to the U-factor of the window placed between these two plates.

In the second step, the overall U-factor of the studied window system was derived including estimates for the heat convection on both sides of the window. The window profile determined in the study consists of the microalgae in a medium of 20 mm thickness encased between two layers of 6 mm clear glass. The U-factor was calculated according to Eq. (1), based on ASHRAE [1].

$$U = \frac{1}{\frac{1}{h_{ex}} + \frac{1}{h_{int}} + \frac{t_{g1}}{1000 \cdot K_{g1}} + \frac{t_w}{1000 \cdot K_w} + \frac{t_{g2}}{1000 \cdot K_{g2}}} \quad (1)$$

where:

h = outdoor (h_{ex}) and indoor (h_{int}), respectively, convection coefficient from the glass surface, W m^{-2} K^{-1}
t = width, mm
K = thermal conductivity, W m^{-1} K^{-1}
g_1, g_2, w = glass layer 1, glass layer 2 and water layer, respectively.

The convection coefficients from the glass to the environmental conditions according to ISO 15099 (2003):

Outdoors: h_{ex} = 24 W m^{-2} K^{-1}; TA_{ex} = 0°C, I_s = 300 W m^{-2}, Indoors: h_{int} = 8 W m^{-2} K^{-1}; TA_{int} = 20°C

The thermal conductivity of the glass layers was taken as 1 W m^{-1} K^{-1} representing flat clear glass (made by Phoenicia, Israel). Based on the preliminary experiment, which found that the effective conductivity of water with algae was the same as pure water (up to the measurement resolution), the thermal conductivity of pure water was used. The value was selected as 0.64 W m^{-1} K^{-1} about 10% higher than that of water at 25 °C, to represent some added effective conduction due to natural convection in the water layer.

A sensitivity test was performed to study the effect of different thermal conductivity values of water with natural convection in the window system (K_w) on the energy consumption in the studied space. The different values were estimated as the percentage of the thermal convection of still water layer at 25 °C, starting from 10% to 100%. The calculated overall U-factor of the window system with the different values was estimated as follows:

U-factor 4.9 when K_w = 0.64 (10%); U-factor 5.0 when K_w = 0.73 (25%); U-factor 5.1 when K_w = 0.87 (50%); U-factor 5.3 when K_w = 1.16 (100%)

The results are presented in Table A.1 in the Appendix. The table shows the annual energy differences at the case of maximum algae concentration (100%) with *C. reinhardtii* and with *C. Vulgaris*, compared to the base case of water only (0% algae), using the water conductivities (Kw = 0.64, 0.73, 0.87, 1.16 W m^{-1} K^{-1}) . The cases of maximum and minimum algae concentrations were studied at large window size (90% size of facade), at four orientations - South, East, West and North. In all the four orientations, the results show small differences of the energy consumption with the various K_w up to 0.4 kWh m^{-2} $year^{-1}$.

2.2.2. Solar heat gain and visible transmittance

The ability to control solar heat gain through fenestration is estimated by the two properties VT (Visible transmittance) and SHGC (Solar heat gain coefficient).

For estimating VT and SHGC, measurement of the radiation transmittance through small scale of glass model (length and width of 2.5 cm, 1 cm depth) with the algae species, at different concentrations, was performed using spectrophotometer CARY 500 Scan of VARIAN. The measurements were performed in two sets in the visible light of 350–750 nm and in infrared light of 700–1000 nm.

Visible transmittance (VT) represents the optical property of the amount of visible light transmitted through the glazing in the system. For determining the transmitted solar radiation, the integral of the measured transmittance results over wavelength 350–750 nm were normalized with the solar spectral irradiance according to Standard ASTMG173. The same procedure was performed on the measured transmittance over wavelength 700–1000 nm for using this data later on for calculating the SHGC.

The Solar Heat Gain Coefficient (SHGC) represents the solar heat gain through the fenestration system as related to the incident solar radiation. The SHGC is composed of two components; the first one is the directly transmitted solar radiation, the second one is the inward-flowing portion of the absorbed solar radiation, radiation that is absorbed in the glazing and fenestration and is subsequently conducted, convected, and radiated to the interior of the building. The SHGC was calculated using Eq. (2) according to ASHRAE [1].

$$SHGC(\theta) = T^f{}_{1,L}(\theta) + \sum_{k=1}^{L} N_k \, A^f{}_{k:(1,L)}(\theta) \quad (2)$$

where:

$T^f{}_{1,L}(\theta)$ = Front transmittance of the glazing system (calculation at normal incidence: $\theta = 0$)
L = number of glazing layers (L = 2 glass layers)
$A^f{}_{k:(1,L)}$ = Front absorptance of layer k (k = 3 layers of glass, water and glass)
N_K = inward-flowing fraction for layer k

The calculation used the environmental conditions according to ISO 15099 (2003):

Outdoors: h_{ex} = 14 W m^{-2} K^{-1}; TA_{ex} = 30 °C, I_s = 500 W m^{-2}, Indoors: h_{int} = 8 W m^{-2} K^{-1}; TA_{int} = 25 °C

For calculating Eq. (2), the transmittance of glazing (T) was estimated from the integral data of the overall wavelength (visible and infrared light) as measured at the different concentrations. The inward flowing fractions (N) were calculated from the relation of the U-factor of the glazing to the effective heat transfer coefficient between the exterior environment and the *kth* glazing layer (U / $h_{ex,k}$) according to ASHRAE [1].

The absorptance (A) was calculated according to Eq. 5 using the absorptance estimates of the two glass layers (α_g) and of the water layer (α_w) using Eqs. (3) and (4) for calculating the absorptance of the three k layers (A_1, A_2, A_3). These expressions for transmittance and absorptance account only for one single pass of radiation. Changes due to multiple reflections are neglected, since reflectance values are relatively small at zero incidence angle.

$$\tau_1(0,\lambda) = (1 - \rho_1(0,\lambda))^4 \cdot e^{-2\ \alpha_g\ t_g} \quad (3)$$

$$\tau_2(0,\lambda) = (1 - \rho_1(0,\lambda))^2 \cdot e^{-2\ \alpha_g\ t_g} \cdot (1 - \rho_2(0,\lambda))^2 \cdot e^{-\alpha_w\ t_w} \quad (4)$$

$$A_1 = (1 - \rho_1) \cdot \left(1 - e^{-\alpha_g t_g}\right)$$
$$A_2 = (1 - \rho_1) \cdot e^{-\alpha_g\ t_g} \cdot (1 - \rho_2) \cdot \left(1 - e^{-\alpha_w\ t_w}\right)$$
$$A_3 = (1 - \rho_1) \cdot e^{-\alpha_g\ t_g} \cdot (1 - \rho_2)^2 \cdot e^{-\alpha_w\ t_w} \cdot \left(1 - e^{-\alpha_g\ t_g}\right) \quad (5)$$

where:

τ_1 = transmittance of glass and air window
τ_2 = transmittance of glass and water window
ρ_1 = reflectance between glass to air, when $\rho_1 = \rho_4$

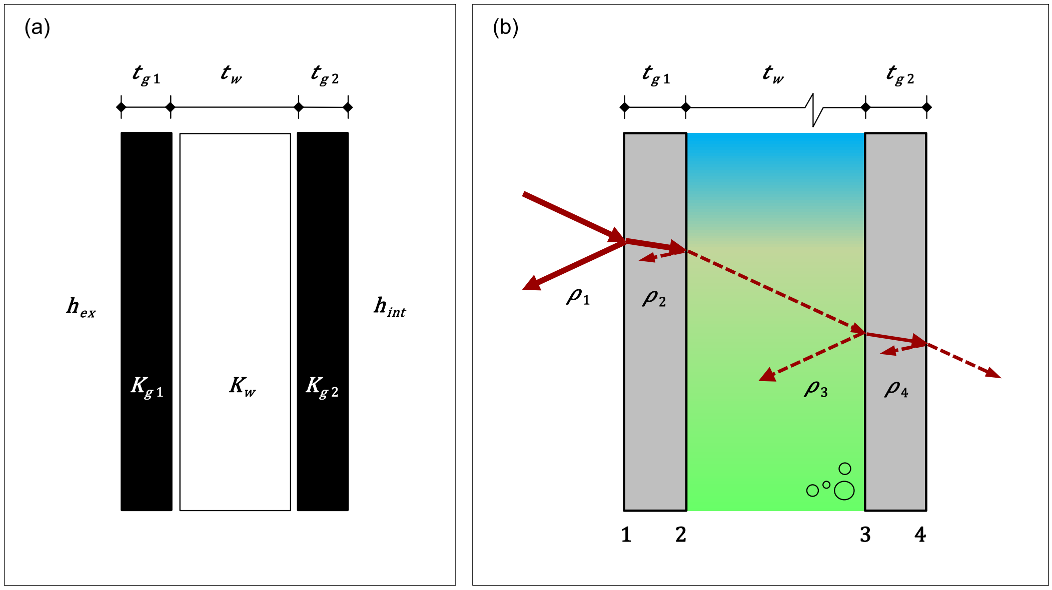

Fig. 2. Schematic setup for calculating thermal and optical properties in the studied window profile. (a) Parameters for overall U-factor calculation, (b) One single pass incident radiation.

ρ_2 = reflectance between glass to water, when $\rho_2 = \rho_3$
α = volumetric absorption coefficient of glass (α_g) and of water (α_w), 1/cm
t = thickness of glass (t_g) and of water (t_w)

Fig. 2 illustrates the schematic setup for calculating the thermal and optical properties in the studied window, where (a) is the setup for calculating the overall U-factor based on Eq. (1) and (b) illustrates the one single path of incident radiation for calculating SHGC based on Eqs. (2) to (5).

2.3. Room space within a building structure

The impact of the algae window on the energy consumption within a room space in a building structure was estimated by an extensive modeling and simulation study.

2.3.1. EnergyPlus Model

The energy performance of the algae window was studied using the US DOE's EnergyPlus software; a widely used simulation engine for modeling the energy required for heating and cooling a building using a variety of mechanical systems and energy sources [7]. Ladybug and Honeybee were used for geometrical modeling and as a graphical interface for EnergyPlus. They are two open source plugins for Grasshopper and Rhinoceros, a 3D modeling software, that help explore and evaluate environmental performance. Ladybug imports standard EnergyPlus weather files (EPW) into Grasshopper, while Honeybee connects the visual programming environment of Grasshopper to the EnergyPlus validated simulation engine which evaluates building energy consumption ([14,22,33,34]). These plugins enable a dynamic coupling between the flexible, component-based, visual programming interface of Grasshopper and a validated environmental data sets and simulation engines.

2.3.2. Simulated windows

The simulation study was applied in an office space in the Porter School of Environmental Studies (PSES) building at the Tel-Aviv University, Israel. The PSES building has received the highest accreditation of two certified Green Buildings standards; LEED Platinum and Israel Green Building Standard Diamond rating (IS 5281). Fig. 3 shows the studied space in the building, which act as an office room characterized by concrete walls with thermal insulation and with inner white plaster coating, where the studied window is located in the center of the North façade which constitutes 15% of the façade area. The parameters used in the simulation study were set according to the characteristics of the studied space and window. A climate weather data for Tel Aviv was used for the evaluation of all cases: Tel Aviv is situated on a plain along the east coast of the Mediterranean Sea (32°06′N 34°47′E) and characterized by hot and humid climatic conditions: The daily maximum temperature is 29.0–30.0 °C on average with minimum relative humidity of 60%, the daily minimum temperature is around 22.2 °C with average relative humidity around 83% [3].

The model was adjusted according to the use and activity in the studied office space including the number of people using the space, hours of activity and the existing lighting system in the PSES building. Two main research directions were studied in the simulation study:

1. Simulations conducted on an existing window in the studied space (Fig. 4), applying the two studied microalgae species (*C. reinhardtii* and *C. vulgaris*) within the window in various concentrations from A-10% to A-100%. The total number of simulations were 23 yielding results per year, per month and per day (21th day of 4 seasons) for all the study cases (Table 1a).
2. Parametric simulations (Fig. 4) according to window orientation (4 main façade directions; South, East, West, North), and according to window dimensions (6 cases determined as the percentage of the window area from the façade area; 15%, to 90% every 15%). The total number of simulations were 552 yielding results per year for all the study cases (Table 1b).

The parametric simulations were performed for each window orientation and size in the studied space, for the reference profiles and the algae window containing the two microalgae species in different concentrations.

In all simulations, the window profile was determined as 20 mm width between two layers of 6 mm clear glass. The assumption is that the used glass will have a safety factor such as laminated safety glass used in the actual algae window profiles in the BIQ building in Germany [6,41]. The dimension of the window in the studied office in PSES building is a square of 0.85 m without

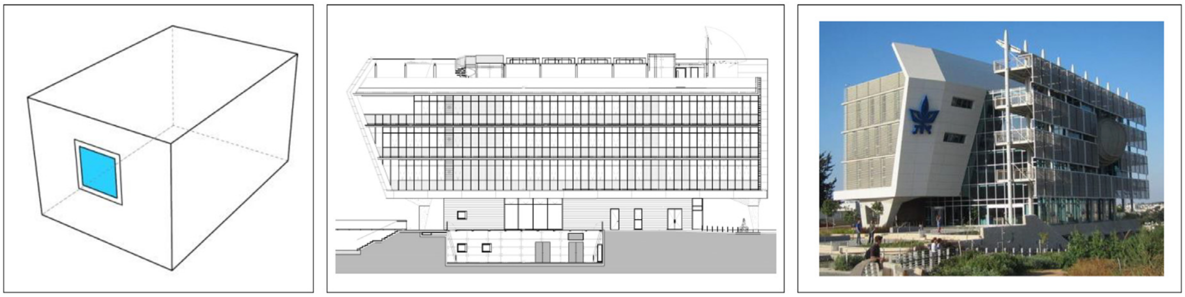

Fig. 3. Studied space room in PSES building at Tel-Aviv University Israel (Studied window - North window, size 15% of façade).

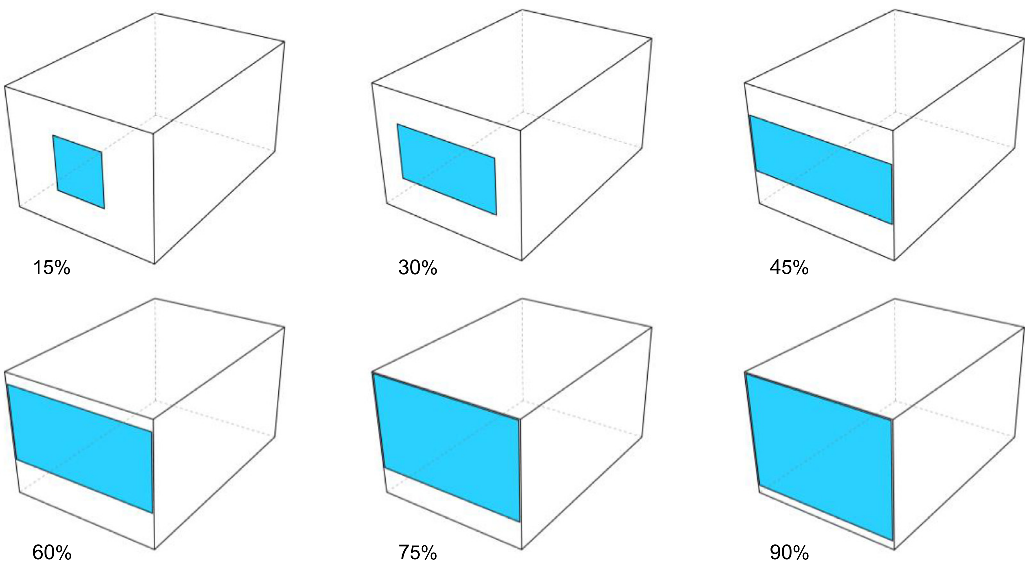

Fig. 4. Simulated window configurations based on six window sizes, each configuration studied at four main orientations (N, E, S, W).

Table 1a
The simulated study cases and parameters of the studied window system in the studied space room in PSES building (Façade orientation: North, Window size: W-15%).

Study cases in the window system	Microalgae		No. of results		
	Specie	Concentration	Year	Month *(12)*	Day – 24 hrs *(21th – 4 seasons)*
WIN-SG (single glazing)		–	1	12	96
WIN-DG (Double glazing)		–	1	12	96
WIN-Water (base case)		–	1	12	96
Algae window	2	10	20	240	1920
Total No. of Simulations			23		

Table 1b
The simulated considered study cases and parameters of the studied window system according to the window orientation and dimensions.

Study cases in the window system	Microalgae		Parametric change		No. of results *(4 orientations * 6 window size)*
	Specie	Concentration	Window facade	Window size	
WIN-SG (single glazing)		–	• South	• 15%	24
WIN-DG (Double glazing)		–	• East	• 30%	24
WIN-Water (base case)		–	• West	• 45%	24
Algae window	2	10	• North	• 60%	480
				• 75%	
				• 90%	
Total No. of Simulations					552

Table 2
Comparison of heat transfer in TAP containing the studied microalgae species.

	C. reihardtii	*C. vulgaris*
ΔT [°C] = TAP with H_2O VS TAP with H_2O and algae specie	0.01	0.20

the frame, and the window size relative to the façade area of the studied space is 15%.

3. Results and discussion

3.1. Thermal and optical properties

The algae window energy performance was determined through the thermal and optical properties of the U-factor, VT and SHGC. Table 2 shows the results of the measured temperature difference between the microalgae species and the tap, indicating no significant temperature difference between the system containing microalgae and the one that contains water without microalgae. Hence, based on the experiment results, for calculating the U-factor of the algae window, the thermal conductivity of water can be used to represent the mixture of microalgae and water.

In the heat transfer experiment, large temperature differences were found in the system between the heater of the system (50 °C) and the copper plates on the sides of the sample windows (about 27 °C). The large temperature difference may create natural convection flow within the water layer, depending on the depth of the water layer and the vertical dimension of the window profile. Umdu et al. [39] in their study on thermal transmission within microalgae panel bioreactor, showed the existence of heat convection in the bioreactor with the increased water layer in the reservoir due to air water circulation at thickness above 17.5 cm (observed U-factor raised from 4.07 to 5.29 when the reservoir thickness increased from 17.5 to 30 cm). At the much smaller reservoir thickness of around 2 cm, as was studied in this research, natural convection flow is not expected to occur. If some convection does exist in the experiment, its effect will be similar in both cases with and without the algae, and therefore the conclusion on the values of the U-factor should remain valid. Nevertheless, the window system in this study (microalgae medium between two layers of 6 mm clear glass) needs to be tested also in real scale to validate this conclusion.

The calculation of the overall U-factor of the studied window system was according to Eq. (1) taking into account the thermal conductivity of the glass layers and of the water which represents the mixture of water and microalgae as was found in the experiment. The estimated U-factor for the studied algae window was found to be as 4.9 (W m^{-2} K^{-1}) at center of glass and of 20 mm width. In the study of Umdu et al. [39], the experiment method was different than the presented study including 3 glass layers of water reservoir, air layer and heat exchange plate. The measured U-factor values ranged from 3.84 to 53.19 (W m^{-2} K^{-1}) depending on the change in the design parameters of water resorvier, air layer and reservoir wall thickness.

As described in Section 2.3.2 the parametric simulations included change of the window dimension from 15% up to 90%. Enlarging the window size as one single unit will require a thicker glass due to the water pressure; accordingly at maximum window size of 90%, the required glass width can reach up to 30mm, which can be impractical due to high weight and cost. However, a large window can be segmented into several small sections connected by dividers. Each section contains a single glass sheet that can be reasonably thin and light due to the smaller size. The vertical glass units along the façade of BIQ building in Germany are an example of such construction. In the simulation analysis we assumed that the actual window construction will include multiple smaller glass segments of 6 mm thickness connected with dividers. Since there is a variety of divisions and of frame types, we avoided the explicit modeling addition of the frames and focused on the glass impact only.

In all the simulations, the calculated U-factor of 4.9 W m^{-2} K^{-1} was used for the whole year. U-factor changes during the year mainly due to the external changes in air temperature (TA_{ex} of 0 °C in winter and 25 °C in summer), and in heat transfer mainly due to convection (h_{ex} of 24 W m^{-2} K^{-1} in winter and 14 W m^{-2} K^{-1} in summer). Nevertheless, the difference in the U-factor is small; 4.9 W m^{-2} K^{-1} in winter and 4.3 W m^{-2} K^{-1} in summer. Accordingly, the error in the estimated yearly energy consumption will be small. Moreover, by using the same U-factor for the whole year, the error in all simulations is in the same direction, hence the effect on the differences among the studied cases is also small. It is to be mentioned that the paper deals with the comparison of the differences in the energy saving among the studied cases and not in the absolute values of the energy consumption.

Fig. 5 shows the measured transmittance of visible light 350–750 nm and infrared light 700–1000 nm, in the glass model consisting of the algae species, at different algae concentrations. The results in the figure indicate a significant impact of the algae concentrations on the transmittance within the window system, at the studied VIS and NIR wavelengths.

Fig. 6 illustrates the volumetric absorption coefficient α_w of the water layer with and without the algae species, for microalgae concentrations of maximum (A-100%) and minimum (A-20%), and for the base case (water only). The volumetric absorption coefficients were calculated according to Eq. (4), based on the measured overall transmittance of the window system, and subtracting the effect of absorption and reflections at the glass layers. The volumetric absorption coefficients as shown in the figure were used to calculate the average over the wavelengths of VIS and of NIR and as average over all wavelengths (weighted average of 0.512 for VIS and 0.488 for NIR according to ASHRAE [1]):

- Water (base case) - 0.150 (VIS), 0.173 (NIR), 0.161 (Av.)
- *C. reinhardtii* - Max. 0.630 (VIS), 0.431 (NIR), 0.533 (Av.). Min. 0.300 (VIS), 0.231 (NIR), 0.266 (Av.)
- *C.vulgaris* - Max. 0.755 (VIS), 0.562 (NIR), 0.661 (Av.). Min. 0.237 (VIS), 0.294 (NIR), 0.265 (Av.)

The averaged volumetric absorption coefficients indicate that the absorption by water was up to 30% of the algae absorption at maximum concentrations.

The results indicate a larger impact of the *C. vulgaris* on the absorption and on the transmittance than of the *C. reinhardtii* as the concentration increases to maximum.

Based on the measured data and using eq's 2 to 5, the VT and SHGC were estimated for the studied window with the microalgae species at different concentrations. Table 3 shows the calculated VT and SHGC for the different algae concentrations.

As shown in Table 3, the results indicate the impact of the algae concentrations on the visible transmittance (VT) and on the solar heat gain coefficient (SHGC) through the algae window system. The VT results range from 0.50 minimum (10%) to 0.08 maximum (100%) for the window with *C. reinhardtii* and 0.45 (20%) to 0.04 maximum (100%) for the widow with *C. vulgaris*. Due to the algae concentration impact on VT, the SHGC decreases as the algae concentration increases, reaching up at maximum concentration (100%) to 0.13 for *C. reinhardtii* and 0.07 for *C. vulgaris*.

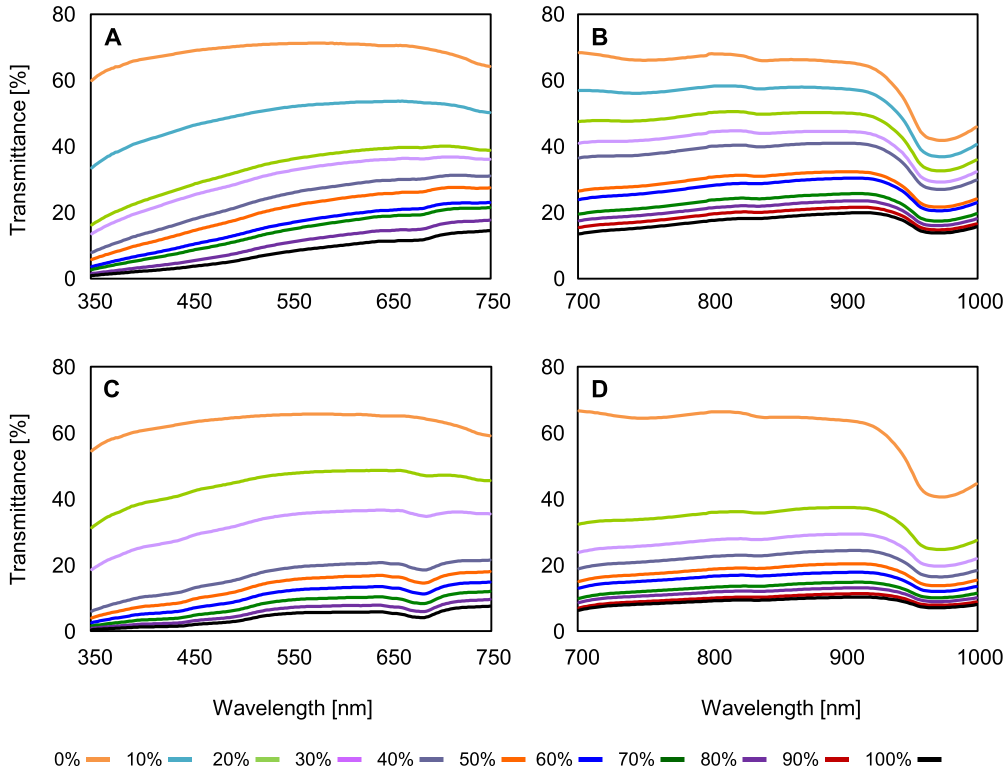

Fig. 5. Radiation transmittance through the window system between different algae concentrations and base case of 0% (water only). A: *C. reinhardtii* transmittance at 350–750 nm B: *C. reinhardtii* transmittance at 700–1000 nm C: *C. vulgaris* transmittance at 350–750 nm D: *C. vulgaris* tansmittance at 700–1000 nm.

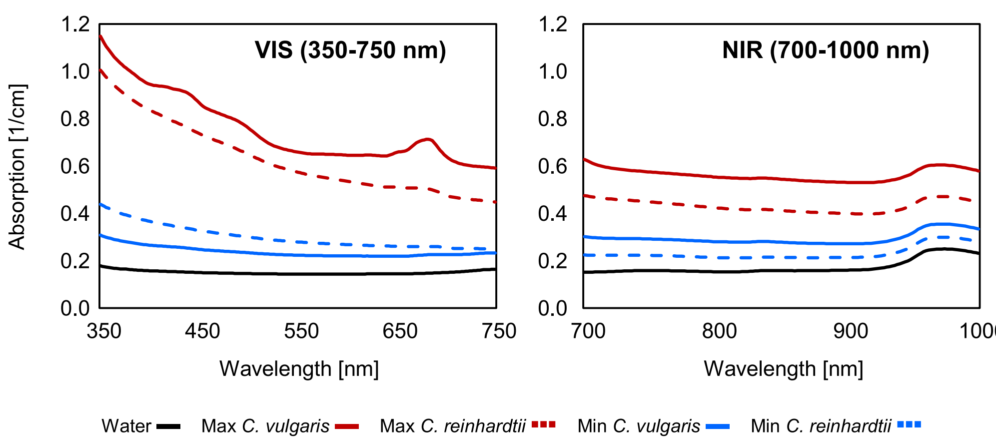

Fig. 6. Volumetric absorption coefficient of water and of algae species (*C. reinhardtii* and *C. vulgaris*) in the window system at the studied wavelength of VIS and NIR. Max. (A-100%) and Min. (A-20%).

Table 3
VT and SHGC estimations through the algae window system at different concentrations.

Algae specie and properties		Empty	Microalgae concentrations [%]									
			10	20	25	30	40	50	60	70	85	100
C. reinhardtii	VT	0.84	0.50	–	0.34	0.31	0.24	0.21	0.16	0.14	0.11	0.08
	SHGC	0.82	0.53	–	0.41	0.37	0.31	0.27	0.23	0.21	0.16	0.13
C. vulgaris	VT	0.84	–	0.45	–	0.33	0.17	0.14	0.11	0.08	0.06	0.04
	SHGC	0.82	–	0.40	–	0.30	0.20	0.16	0.13	0.11	0.09	0.07

VT = Visible Transmittance, SHGC = Solar Heat Gain Coefficient

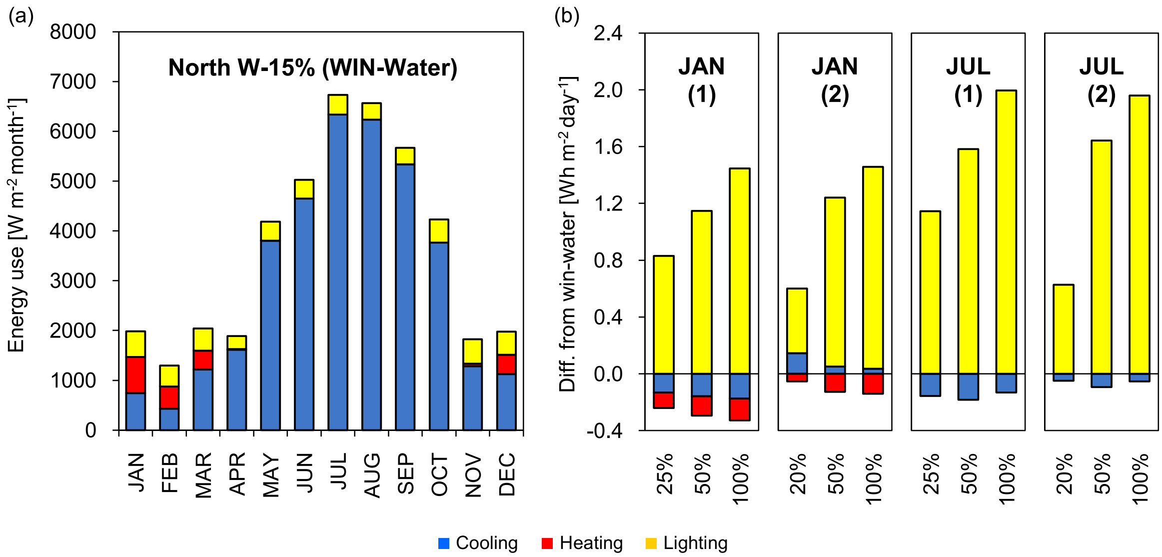

Fig. 7. Simulated energy consumption for cooling, heating and lighting at the studied space (with Northern window and size of W-15%). (a): Monthly energy use at base case (WIN-Water, 0% algae), (b): Daily energy use differences of algae window (20%, 25%, 50%, 100% concentrations) and WIN-Water, in January and July at 12:00. where: 1) *C. Reinhardtii* and (2) *C. Vulgaris.*

3.2. Simulated energy performance

3.2.1. Energy use results in the studied space

The energy performance of the studied algae window was simulated with the two algae species in different concentration. Fig. 7 shows the simulated results in the studied space with window oriented to North and size of 15% of the façade area: The monthly energy consumption in base case (WIN-water with 0% Algae), for cooling, heating and lighting (left), and the daily energy consumption difference between 3 main algae concentrations and the base case at noontime 12:00 in winter and in summer (right). As shown in the figure, the monthly energy consumption in WIN-Water is mainly for cooling of 5742 Wh m^{-2} $month^{-1}$ average of summer months, small consumption for heating of 483 Wh m^{-2} $month^{-1}$ average of winter months and 405 Wh m^2 $month^{-1}$ for lighting average of the whole year. The small amount of energy consumption is due to the well-insulated external surfaces of the space and the small window size within the space. As compared to the base case (WIN-water), the daily maximum savings at midday (12:00) was up to 0.2 Wh m^{-2} day^{-1} for heating in winter and for cooling in summer, with slight advantage for the algae window with *C. reinhardtii* than with *C. vulgaris*. The minor savings for heating and cooling are due to the uniform U-factor value to all studied algae concentrations and species, and also due to the small size of the window. The main effect of the algae window was for lighting which increased as the algae concentration increases, up to 1.4 Wh m^{-2} day^{-1} in winter and 2.0 Wh m^{-2} day^{-1} in summer, in both algae species.

3.2.2. Energy use results in the parametric simulations

3.2.2.1. The impact of the reference window profiles. The simulations were also applied on reference window profiles in the studied space as to understand the algae impacts within the studied windows types. The reference window profiles were the studied window system (20 mm width between two layers of 6 mm clear glass) with water only defined as the base case (WIN-Water), and standard window profiles of Single Glazing (WIN-SG) and of Double Glazing (WIN-DG). The properties of the window profiles used in the simulations:

- Base case (WIN-Water): U-factor 4.90, VT 0.79, SHGC 0.69
- Standard single glazing (WIN-SG): U-factor 5.80, VT 0.86, SHGC 0.90
- Standard double glazing (WIN-DG): U-factor 3.12, VT 0.76, SHGC 0.81

Fig. 8 shows the differences in the energy use between the base case (WIN-Water, 0% algae) and the two standard window profiles of Single Glazing (WIN-SG) and of Double Glazing (WIN-DG). It is shown that the energetic performance of the base case is less than the WIN-DG and better than the WIN-SG. The differences change among the four orientations (S-south, E-east, W-west, N-north) and the window size (ranging from 15% to 90% of façade area). The large difference occurs in the energy for cooling which increases as the window size increases, with maximum differences in the South orientation and minimum in the North. The small difference occurs in the energy for heating due to the well-insulated external surfaces of the studied space which characteristics are the basis for all simulations. The energy differences for lighting is also small, but has a changing trend along the window size correlated with the energy for cooling, indicating that in the small window sizes (15%–30%) the demand for lighting is larger and the demand for cooling is smaller, and as the window size increases up to 90% the demand for lighting decreases while the demand for cooling increases.

Table 4 shows the yearly energy consumption in the three reference window profiles without microalgae concentrations, at minimum and maximum window sizes. The results in the table show that at maximum window size - the double glazing (WIN-DG) has the best thermal performance, and the WIN-Water is similar to the single glazing (WIN-SG) with slight advantage for the window with water. At minimum window size, the trends seem to be opposite.

3.2.2.2. The impact of the Algae window. Based on the studied space characteristics and climatic conditions, parametric simulations were conducted of changing the window dimensions and its orientation in the studied space. Table 5 shows main simulated results in the studied space with the two algae species in minimum and maximum window sizes.

It is shown in the Table 5 a clear difference between the northern window and the south, east and west orientations, where the main change in the energy consumption between small (20%) to

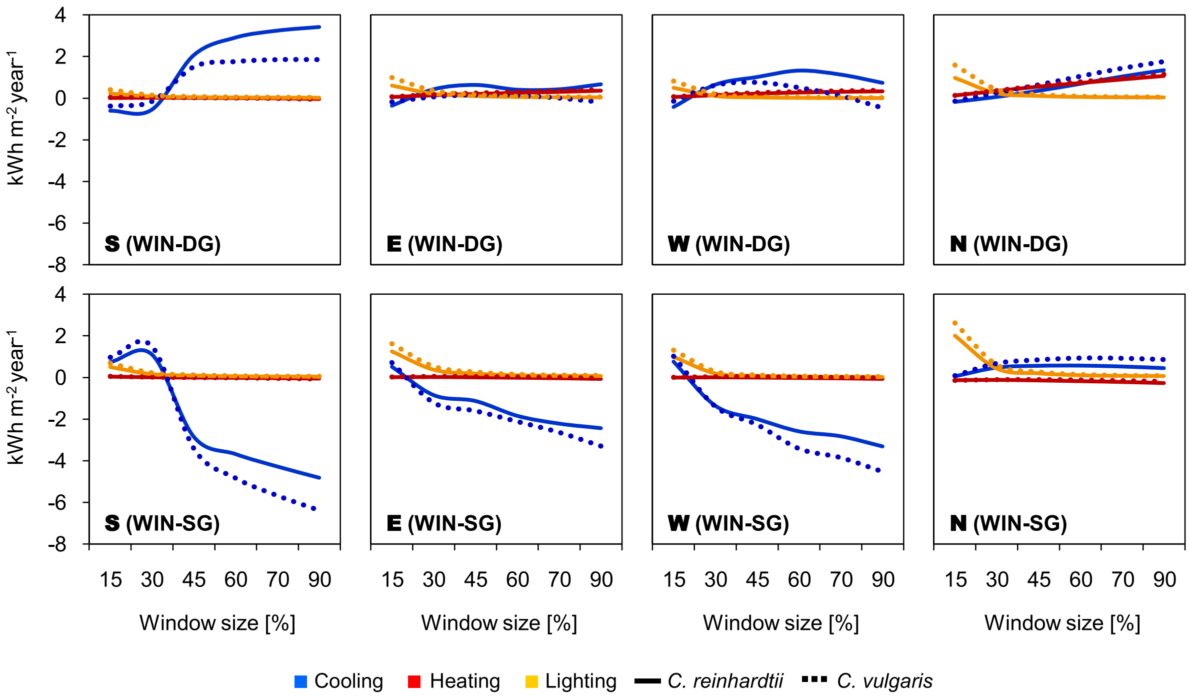

Fig. 8. Differences of energy consumption (kWh m^{-2} year^{-1}) for cooling, heating and lighting, between the base case (WIN-Water, 0% algae) and the reference standard windows of WIN-DG and of WIN-SG, in four orientations (S-south, E-east, W-west, N-north).

large (100%) algae concentration is for lighting in the northern window and for cooling in the other orientations. These changes enhance as the window size increase from minimum to maximum. The energy consumption for heating is the smallest where it increases from south to north, among the changes from minimum to maximum window size and enlarge algae concentration, the changes in the heating are the smallest as compared to cooling and lighting.

Figs. 9 and 10 illustrate the change in energy consumption in the studied space, simulated against four variables: the microalgae species, the concentration of the microalgae in the window medium, the size of the window, and four main directions of the window façade. In the Figures, the potential energy saving was defined as the difference among the energy use between the algae window and the reference windows of WIN-SG (Single glazing) and of WIN-DG (Double Glazing), where; the symbol ● (−) represents the savings and symbol ● (+) represents non-savings.

It is shown in the figures, that the algae concentration in the south, east and west orientations, changes in the different window sizes and at the two algae species. The simulated results indicate that the north façade differs from the other orientations; a greater thermal effect by the U-factor occurs on the northern façade than the radiation effect of VT and SHGC due to no direct radiation penetrating to the north. Consequently, as the algae concentration increases in the window the more energy consumption is needed in the room. In the south, east and west orientations, the effect of radiation transmittance and shading is stronger than the thermal effect, and consequently as the algae concentration increases in the window, less energy consumption is needed in the room and energy saving is possible. When the window size is smaller than W-30%, there is no energy saving of the algae window in all the four orientations and the energy consumption is mainly for lighting.

As for the maximum energy use differences, in the northern oriented window there is no saving which increases as the window size and algae concentration increases, up to 18 KWh m^{-2}

Table 4
Simulated yearly energy consumption at the studied space with reference window profiles, at minimum and maximum window sizes, PSES building in Tel-Aviv, Israel.

Energy use * (kWh m^{-2} year^{-1})		Minimum Window size (W-15%)			Maximum Window size (W-90%)		
		WIN-water	WIN-SG	WIN-DG	WIN-water	WIN-SG	WIN-DG
SOUTH	C	30.9	30.1	31.5	42.2	47.2	39.0
	H	0.4	0.3	0.4	0.3	0.4	0.3
	L	7.6	7.1	7.4	6.3	6.2	6.3
EAST	C	29.8	29.3	30.2	55.8	58.3	55.2
	H	1.3	1.3	1.2	0.8	0.9	0.5
	L	9.6	8.4	9.0	6.4	6.3	6.4
WEST	C	26.4	25.7	26.9	65.3	68.7	64.6
	H	1.2	1.2	1.2	0.9	0.9	0.6
	L	8.3	7.4	7.8	6.2	6.2	6.2
NORTH	C	35.8	35.7	35.9	27.9	27.5	26.6
	H	2.2	2.4	2.1	3.6	3.9	2.5
	L	10.8	8.8	9.8	6.4	6.3	6.4

W-15%: Min. of 15% window size from façade area, W-90%: Max. of 90% window size from façade area.
Reference windows: WIN-Water = water, WIN-SG = Single glazing, WIN-DG = Double glazing.
* Annual energy use (kWh m^{-2} year^{-1}) for C (cooling), H (heating), L (lighting).

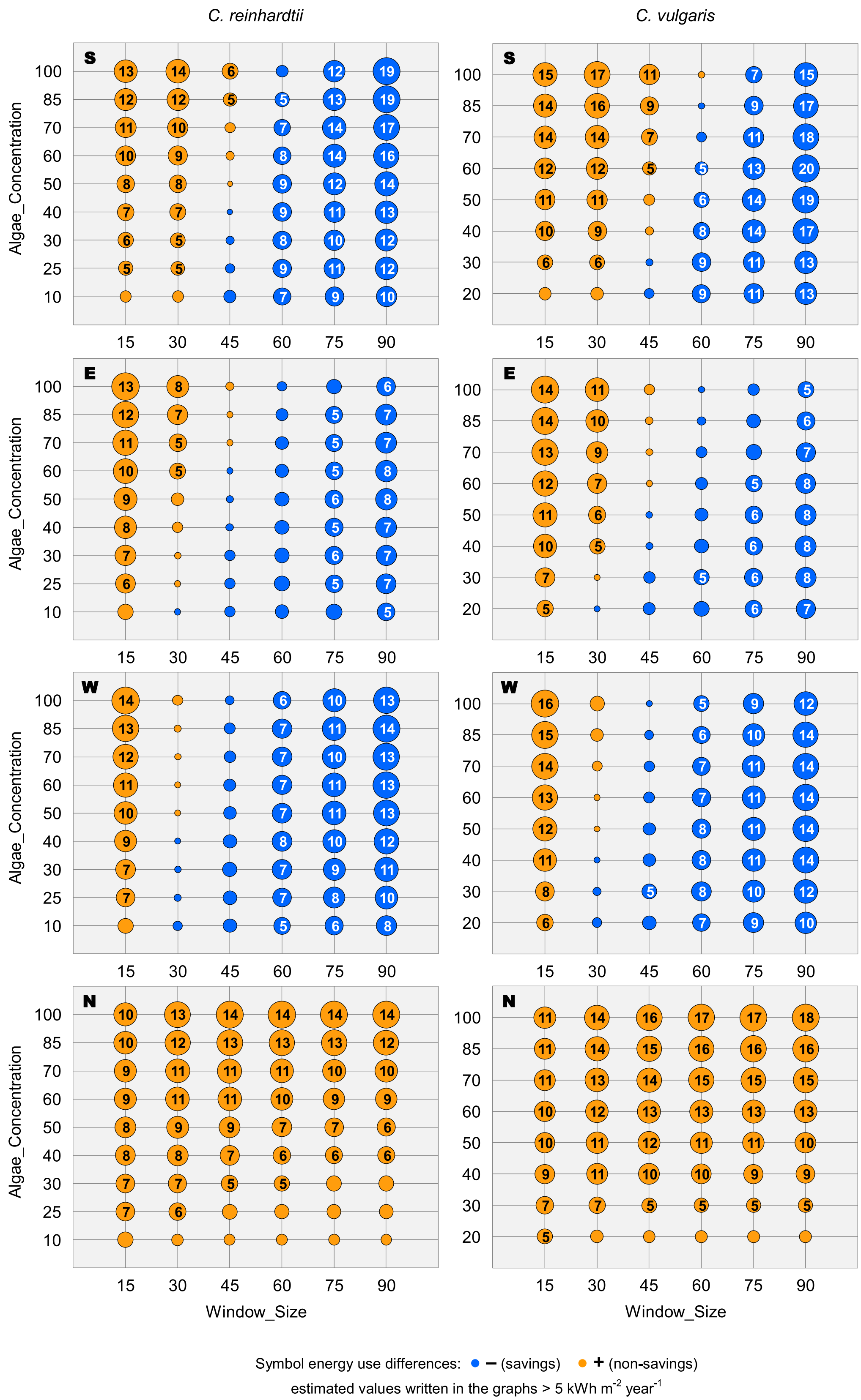

Fig. 9. Energy use differences (kWh $m^{-2}year^{-1}$) from reference WIN-SG (Single Glazing), according to the algae type, algae concentrations and window size at four orientations (S-south, E-east, W-west, N-north).

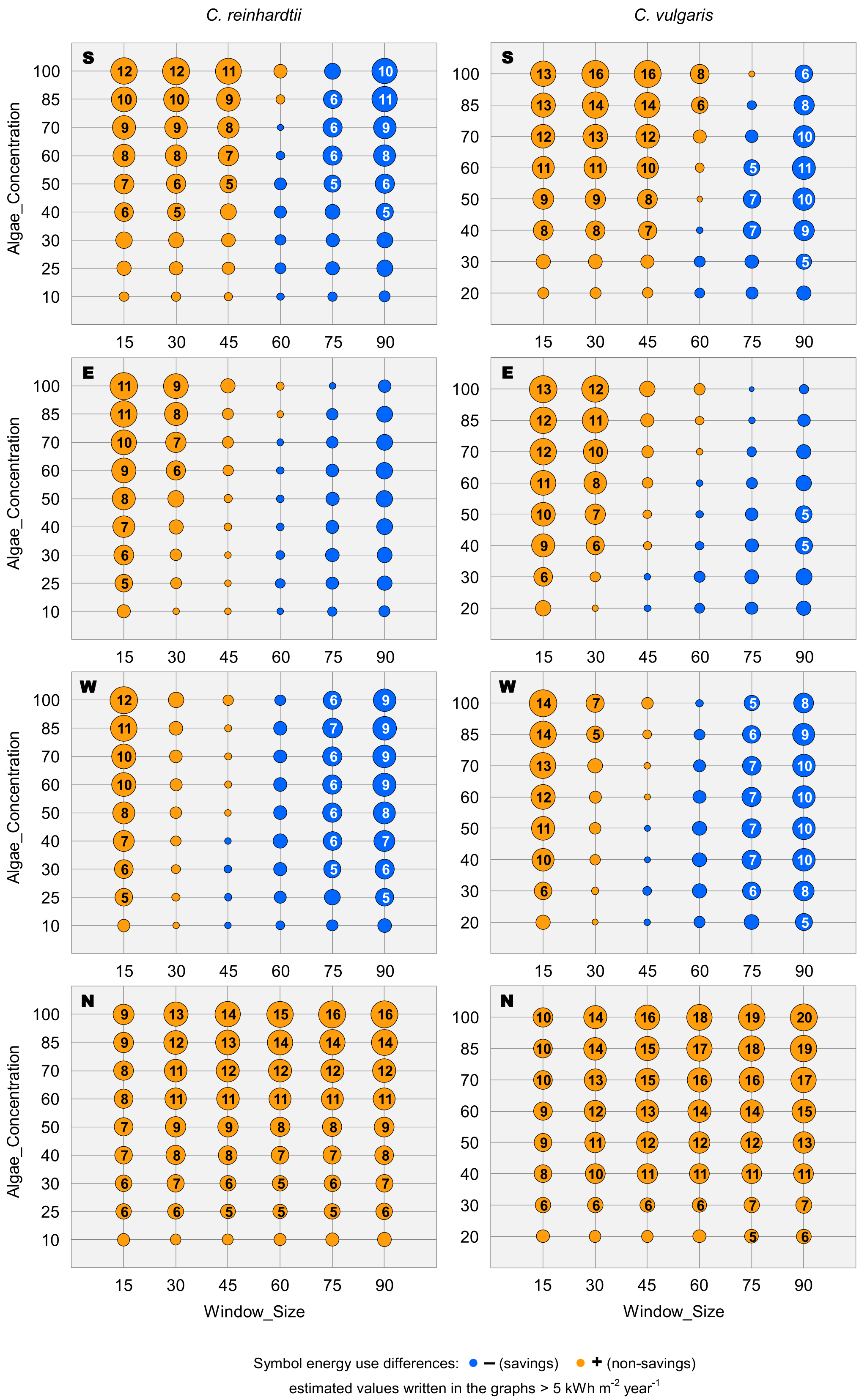

Fig. 10. Energy use differences (kWh m^{-2}year^{-1}) from reference WIN-DG (Double Glazing), according to the algae type, algae concentrations and window size at four orientations (S-south, E-east, W-west, N-north).

Table 5
Simulated yearly impact of the algae within the window system on the energy consumption at the studied space, at minimum and maximum window sizes, PSES building in Tel-Aviv, Israel.

Energy use * (kWh m^{-2} $year^{-1}$)		Minimum Window size (W-15%)				Maximum Window size (W-90%)			
		C. reinhardtii		*C. vulgaris*		*C. reinhardtii*		*C. vulgaris*	
		A-25%	A-100%	A-20%	A-100%	A-25%	A-100%	A-20%	A-100%
SOUTH	C	31.9	33.0	32.2	33.4	34.6	25.5	34.6	26.2
	H	0.5	0.6	0.5	0.7	0.2	0.3	0.2	0.3
	L	10.3	17.1	9.0	18.5	6.5	9.3	6.4	12.6
EAST	C	31.0	32.1	31.2	32.5	50.7	45.5	50.7	43.6
	H	1.3	1.4	1.4	1.4	1.2	1.8	1.2	2.0
	L	13.0	18.1	11.7	19.0	6.8	12.2	6.6	15.1
WEST	C	28.2	29.9	28.3	30.4	58.3	50.4	58.3	48.5
	H	1.3	1.4	1.4	1.5	1.3	1.8	1.3	2.0
	L	11.4	17.0	10.2	18.3	6.4	10.6	6.3	13.3
NORTH	C	35.9	36.2	36.1	36.4	30.5	33.0	30.5	33.7
	H	2.2	2.2	2.2	2.2	4.1	4.3	4.1	4.5
	L	15.4	18.9	14.0	19.4	6.8	14.5	6.6	17.2

W-15%: Min. of 15% window size from façade area, W-90%: Max. of 90% window size from façade area.
A-20%, A-25%: Minimum algae concentrations, A-100%: Maximum algae concentration.
* Annual energy use (kWh m^2 $year^{-1}$) for C (cooling), H (heating), L (lighting).

Table 6
Factional impact of the maximum energy differences of the studied algae species at the four orientations. symbol **(−)** represents the savings and symbol (+) represents non-savings.

		Energy use (Wh m^{-2} $year^{-1}$)	Max. energy use differences from WIN-SG			Max. energy use differences from WIN-DG		
			Size*	Energy use difference	Fractional impact	Size*	Energy use difference	Fractional impact
C. reinhardtii	SOUTH	35.1	W-90% A-100%	−19	54.1%	W-90% A-85%	−11	31.3%
	EAST	57.8	W-90% A-60%	−8	13.8%	W-90% A-60%	−5	8.6%
	WEST	62.0	W-90% A-85%	−14	22.5%	W-90% A-100%	−9	14.5%
	NORTH	51.9	W-90% A-100%	+14	26.9%	W-90% A-100%	+16	30.8%
C. vulgaris	SOUTH	37.1	W-90% A-60%	−20	53.9%	W-90% A-60%	−11	29.6%
	EAST	58.0	W-90% A-60%	−8	13.8%	W-90% A-50%	−5	8.6%
	WEST	62.2	W-90% A-85%	−14	22.5%	W-90% A-70%	−10	16.1%
	NORTH	55.4	W-90% A-100%	+18	32.5%	W-90% A-100%	+20	36.1%

* Size: W = Window size, A = Algae concentration.

$year^{-1}$In the South, east and west orientations the saving occurs as the window size increases, where the largest saving occurs in the south 20 KWh m^{-2} $year^{-1}$, followed by the west 14 KWh m^{-2} year and the east 8 KWh m^{-2} $year^{-1}$. The significance of these maximum magnitudes, relative to the total energy consumption in the studied room, change according to the window orientation as shown in Table 6.

These impacts were studied for Mediterranean climate of Tel-Aviv, Israel (32°06′N 34°47′E). Different climate region and geographic location should yield similar trends but different quantitative impacts.

3.2.3. Statistical analysis

The multiple linear regression was applied in estimating the total energy saving of the algae window for each orientation. The explanatory variables considered are the algae concentration and the window size, for each of the studied algae specie (*C. reinhardtii* and *C. vulgaris*). The simulated results were studied by regression analysis using Eq. (6). The energy saving was estimated as the energy consumption in the algae window compared to the energy consumption of three reference cases: 1) Base case of window with water; WIN-water, 2) Reference standard window of Single glazing; WIN-SG, 3) Reference standard window of Double glazing; WIN-DG. The estimated data used for the regression are given in Tables B.1–B.3 in the Appendix.

$$ES_{Total} = a + b_1X_1 + b_2X_2 + b_3X_1X_2 \quad (6)$$

where:

ES_{Total} = Energy saving of the algae window (estimated as the energy consumption of the algae window compared to three comparison cases:1. WIN-water, 2. WIN-SG, 3. WIN-DG)
X_1 = Algae concentration in the window system (ranging from A-10% to A-100%)
X_2 = Window size (relative size to the façade wall ranging from W-15% to W-90%)

Table 7 shows the regression results according to Eq. (6) of as compared to the three comparison cases:

1. WIN-water, 2. WIN-SG, 3. WIN-DG. All correlations are statistically highly significant.

The main results are as follows, according to reference case 1. The effects are similar in cases 2 and 3 but with different magnitudes:

- Algae concentration was found to enlarge the energy consumption as the algae concentration increases (Positive b_1). The effect is small for all orientations. For 10% increase of the algae

Table 7
Regression results of the algae window system studied at the various simulations.

Energy saving		Regression results									
Window facade	Reference case	*C.reinhardtii*					*C.vulgaris*				
		a	b_1	b_2	b_3	R	a	b_1	b_2	b_3	R
SOUTH	WIN-water	2.28	0.204	−0.097	−30.805	0.97	3.62	0.227	−0.151	−23.257	0.94
	WIN-SG	4.92		−0.188		0.97	7.25		−0.273		0.97
	WIN-DG	1.03		−0.038		0.95	3.36		−0.123		0.93
EAST	WIN-water	2.12	0.122	−0.074	−15.203	0.97	2.53	0.141	−0.099	−12.902	0.96
	WIN-SG	3.82		−0.125		0.97	4.73		−0.164		0.97
	WIN-DG	2.53		−0.067		0.97	3.44		−0.106		0.96
WEST	WIN-water	2.74	0.120	−0.100	−20.670	0.97	2.63	0.140	−0.122	−18.592	0.96
	WIN-SG	4.18		−0.159		0.96	4.92		−0.205		0.96
	WIN-DG	3.15		−0.087		0.97	3.89		−0.133		0.97
NORTH	WIN-water	3.28	0.074	−0.042	8.942	0.97	3.61	0.068	−0.046	15.156	0.93
	WIN-SG	4.96		−0.061		0.98	5.84		−0.066		0.94
	WIN-DG	3.50		−0.020		0.97	4.34		−0.024		0.95

X1 = Algae concentration, X2 = Window size, X1X2 = Combination factor.

concentration, the maximum energy consumption increases up to 0.204 KWh m^2 $year^{-1}$ and 0.227 KWh m^{-2} $year^{-1}$ in the South windows with *C. Reinhardtii* and *C. vulgaris*, respectively.

- Window size was found to reduce the energy consumption as the window size enlarges for all orientations (Negative b_2). At each reference case, the effect is the largest in the South orientation;. For 15% increase of the window size, the maximum energy saving reaches up to 0.188 KWh $m^{-2}year^{-1}$ and 0.273 KWh m^{-2} $year^{-1}$ in the South windows (case 2) with *C. Reinhardtii* and *C. vulgaris*, respectively.
- Combination impact represents the explanatory variable of the window size with the algae concentration, and indicates that changing the algae concentration and window size together has the strongest effect. The combining factor was found to reduce the energy consumption as the algae concentration increase along with the window size enlargement in the South, East and West (Negative b_3), and increase the energy consumption in the North (Positive b). For every increase in the algae concentration with **t**he window size level, the energy saving reaches up to 30.805 kWh m^{-2} $year^{-1}$ in the Southern windoew with *C. reinhardtii* and 23.257 kWh m^{-2} $year^{-1}$ with *C. vulgaris*, and the energy consumption increases of 8.942 KWh m^{-2} $year^{-1}$ in the Northern window with *C. reinhardtii* and 15.156 kWh m^{-2} $year^{-1}$ with *C. vulgaris*.

The regression results indicate that for each orientation, the simulation results provide *a good match* to the mono*tonic lin*ear trends assumed by the Eq. (6) according to window *size and algae* concentration as shown in Fig. 11. The trend indicate that the maximum available energy saving can be reached as the window size and algae concentration increase, in the case of S, E and W orientations. In the case of the N orientation, the minimum energy use can be reached as the window size and algae concentration decreases. As to microalgae specie, the energy saving increases in both studied species with the increase in the window size. The difference between the two species occurred in the algae concentration: at maximum concentration, microalgae specie with large cells (*C. reinhardtii*) have more impact on energy saving than the specie

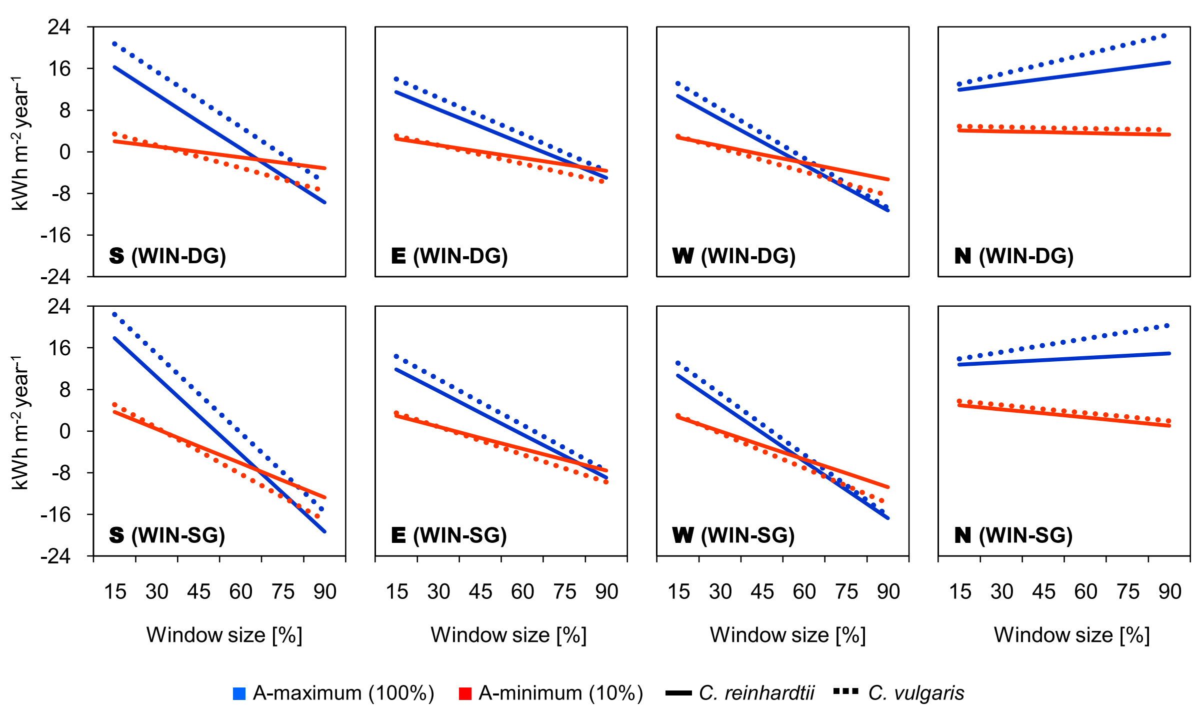

Fig. 11. Energy use differences (kWh m^{-2} $year^{-1}$) from reference windows of WIN-DG (Double Glazing) and of WIN-SG (Single Glazing) according to the algae concentrations and window size, for each algae specie at four orientations (S-south, E-east, W-west, N-north), using the regression results.

with smaller cells (*C. vulgaris*), and at minimum concentration the trend is reverse where *C. vulgaris* has more impact on the energy saving than *C. reinhardtii*. The differences between the two species reached up to 5 KWh m^{-2} $year^{-1}$ in the south orientation.

4. Conclusions

The study focused on estimating the impact of studied cultivated microalgae species within a window system, Algae Window, on improving energy savings in a building. The results of the study show that the algae window has the potential to act as a passive element to improve the energy efficiency in the studied building under the conditions of the Mediterranean climate. The following findings were found to be statistically significant, and are of special interest for the design of algae windows within a building:

(a) The energetic performance of the algae window is affected by the facade orientation. The main difference was found between the North façade and the South, East and West facades. In the design of an algae window in a building, the preferable location is in the south and west orientations where the largest energy saving occurs due to larger penetrated solar radiation during the day, especially in cities in hot climates as Tel-Aviv, Israel.

(b) From the regression analysis for each façade orientation, three explanatory factors were found to affect differently on the energy consumption for each algae specie: Algae concentration, window size and the combination factor of the algae concentration with the window size that yielded the largest effect on decreasing the energy consumption.

(c) The studied ability of the algae window to create energy saving along with the potential to produce bio-energy as a PBR, can greatly improve the energy efficiency in the building.

Declaration of competing interest

The authors have no conflict of interest to disclose.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.109460.

Appendix

Table A.1
Annual energy consumption differences between maximum algae concentration (A-100%) and base case (0% algae), with different water thermal conductivity at the algae window, PSES building in Tel-Aviv, Israel.

Energy use differences [kWh $m^{-2}year^{-1}$]		South			East			West			North		
		C	H	L	C	H	L	C	H	L	C	H	L
C. reinhardtii	Kw = 0.64	−16.9	−0.02	3.1	−10.7	0.95	5.8	−14.9	0.93	4.3	5.1	0.74	8.1
	Kw = 0.73	−16.6	−0.01	3.1	−10.6	0.95	5.8	−14.7	0.93	4.3	5.0	0.73	8.1
	Kw = 0.87	−16.4	−0.01	3.1	−10.5	0.96	5.8	−14.5	0.94	4.3	4.9	0.73	8.1
	Kw = 1.16	−16.1	0.01	3.1	−10.3	0.96	5.8	−14.2	0.95	4.3	4.8	0.72	8.1
C. vulgaris	Kw = 0.64	−14.6	0.04	6.3	−11.4	1.10	8.6	−15.7	1.08	7.0	5.4	0.78	10.8
	Kw = 0.73	−14.8	0.05	6.3	−11.3	1.10	8.6	−15.9	1.08	7.0	5.3	0.77	10.8
	Kw = 0.87	−14.9	0.05	6.3	−11.2	1.10	8.6	−15.7	1.08	7.0	5.2	0.78	10.8
	Kw = 1.16	−15.3	0.07	6.3	−11.0	1.11	8.6	−15.3	1.10	7.0	5.1	0.76	10.8

C = Cooling, H = Heating, L = Lighting.
Kw = Natural water thermal conductivity [W m^{-1} K^{-1}].

Table B.1
Annual energy consumption differences vs WIN-Water, PSES building in Tel-Aviv, Israel.

Algae type	Orientation	Window size	Energy use differences in kWh m^{-2} $year^{-1}$ according microalgae concentration										
			100	85	70	60	50	40	30	25	20	10	0
C. reinhardtii	SOUTH	15	11.9	10.8	9.4	8.6	6.9	6.0	4.6	3.9	–	1.8	0.0
		30	12.6	10.9	9.0	8.2	6.4	5.5	4.1	3.5	–	1.9	0.0
		45	9.1	7.3	5.4	4.6	2.9	2.0	0.9	0.4	–	−1.0	0.0
		60	0.1	−1.6	−3.4	−4.1	−5.4	−5.3	−4.8	−5.0	–	−3.8	0.0
		75	−7.4	−8.9	−9.6	−9.4	−8.1	−7.0	−6.1	−6.3	–	−4.7	0.0
		90	−13.9	−13.9	−11.9	−11.3	−9.5	−8.2	−7.5	−7.7	–	−5.4	0.0
	EAST	15	10.9	10.2	9.2	8.7	7.4	6.7	5.4	4.6	–	2.4	0.0
		30	8.7	7.4	5.7	5.0	3.3	2.3	1.2	1.1	–	−0.1	0.0
		45	2.1	0.9	0.9	0.7	0.0	−0.1	−0.9	−0.9	–	−1.0	0.0
		60	0.3	−0.7	−1.0	−1.3	−1.7	−1.7	−2.0	−2.1	–	−1.4	0.0
		75	−1.4	−2.8	−2.8	−3.1	−3.4	−3.3	−3.5	−3.1	–	−2.1	0.0
		90	−3.6	−5.0	−5.0	−5.2	−5.2	−4.9	−4.5	−4.3	–	−2.9	0.0
	WEST	15	12.3	11.4	10.1	9.4	7.9	7.1	5.7	4.9	–	2.5	0.0
		30	3.1	2.2	1.8	1.6	1.3	0.9	0.5	0.2	–	−0.6	0.0
		45	0.5	−0.4	−0.6	−0.8	−1.1	−1.5	−1.9	−1.7	–	−1.5	0.0
		60	−3.5	−4.8	−4.5	−4.7	−4.8	−4.9	−4.6	−4.0	–	−2.8	0.0
		75	−7.1	−8.0	−7.6	−7.7	−7.8	−7.2	−6.5	−5.6	–	−3.6	0.0
		90	−9.7	−10.5	−9.9	−10.0	−9.2	−8.5	−7.5	−6.5	–	−4.2	0.0
	NORTH	15	8.4	8.0	7.5	7.2	6.5	6.0	5.1	4.6	–	2.5	0.0
		30	12.2	11.5	10.4	9.9	8.5	7.6	5.9	4.9	–	1.9	0.0
		45	13.3	12.2	10.7	9.9	7.9	6.7	4.6	3.7	–	1.7	0.0
		60	13.7	12.2	10.2	9.2	6.8	5.6	4.0	3.3	–	1.8	0.0
		75	13.9	12.1	9.9	8.7	6.3	5.3	4.1	3.4	–	1.9	0.0
		90	14.0	12.0	9.5	8.4	6.2	5.3	4.2	3.5	–	2.0	0.0

(*continued on next page*)

Table B.1 (*continued*)

Algae type	Orientation	Window size	Energy use differences in kWh m^{-2} $year^{-1}$ according microalgae concentration										
			100	85	70	60	50	40	30	25	20	10	0
C. vulgaris	SOUTH	15	13.3	12.6	11.8	10.5	9.2	8.1	4.3	–	2.5	–	0.0
		30	15.7	14.3	12.8	10.7	9.0	7.7	4.1	–	2.6	–	0.0
		45	14.1	12.1	10.4	8.2	6.6	5.2	2.0	–	0.7	–	0.0
		60	5.9	3.8	2.0	0.0	−1.6	−2.8	−4.5	–	−4.0	–	0.0
		75	−1.6	−3.7	−5.3	−7.2	−8.5	−8.6	−5.8	–	−5.0	–	0.0
		90	−8.3	−10.3	−11.8	−13.3	−12.2	−10.7	−6.8	–	−6.2	–	0.0
	EAST	15	11.7	11.2	10.6	9.8	8.9	8.1	4.9	–	3.0	–	0.0
		30	11.4	10.4	9.4	7.8	6.4	5.2	1.1	–	0.1	–	0.0
		45	3.5	2.4	1.8	1.3	0.7	0.5	−1.1	–	−1.4	–	0.0
		60	1.7	0.6	−0.4	−0.9	−1.2	−1.7	−2.6	–	−2.3	–	0.0
		75	0.0	−1.2	−2.0	−2.5	−3.2	−3.4	−3.7	–	−3.1	–	0.0
		90	−1.7	−2.9	−3.7	−4.3	−5.0	−5.1	−4.7	–	−3.7	–	0.0
	WEST	15	13.5	12.8	12.1	10.9	9.8	8.8	5.4	–	3.3	–	0.0
		30	5.5	4.3	3.1	1.9	1.5	1.0	−0.4	–	−0.9	–	0.0
		45	1.4	0.4	−0.2	−0.6	−1.2	−1.2	−2.5	–	−2.0	–	0.0
		60	−1.9	−3.0	−3.6	−4.0	−4.6	−4.6	−4.8	–	−3.4	–	0.0
		75	−5.0	−6.6	−7.2	−7.5	−7.6	−7.5	−6.6	–	−4.8	–	0.0
		90	−7.6	−9.1	−9.7	−9.9	−9.9	−9.5	−7.6	–	−5.4	–	0.0
	NORTH	15	8.5	8.3	8.0	7.5	7.0	6.6	4.5	–	2.8	–	0.0
		30	13.2	12.7	12.1	11.2	10.3	9.4	5.4	–	2.7	–	0.0
		45	14.8	14.1	13.3	12.0	10.7	9.4	4.3	–	2.4	–	0.0
		60	15.8	14.8	13.7	12.0	10.3	8.6	3.9	–	2.5	–	0.0
		75	16.5	15.3	14.0	11.9	9.9	8.1	4.1	–	2.7	–	0.0
		90	17.0	15.6	14.1	11.8	9.6	7.8	4.2	–	2.8	–	0.0

Table B.2
Annual energy consumption differences vs WIN-DG, PSES building in Tel-Aviv, Israel.

Algae type	Orientation	Window size	Energy use differences in kWh m^{-2} $year^{-1}$ according microalgae concentration										
			100	85	70	60	50	40	30	25	20	10	0
C. reinhardtii	SOUTH	15	11.5	10.4	9.0	8.2	6.6	5.7	4.2	3.5	–	1.5	−0.4
		30	12.2	10.4	8.5	7.7	6.0	5.0	3.7	3.1	–	1.4	−0.4
		45	11.2	9.5	7.5	6.7	5.0	4.1	3.1	2.6	–	1.1	2.1
		60	3.0	1.4	−0.5	−1.2	−2.5	−2.3	−1.8	−2.0	–	−0.9	3.0
		75	−4.2	−5.7	−6.3	−6.1	−4.8	−3.7	−2.8	−3.0	–	−1.4	3.3
		90	−10.5	−10.5	−8.5	−7.9	−6.1	−4.8	−4.1	−4.2	–	−1.9	3.4
	EAST	15	11.2	10.5	9.5	9.0	7.7	7.0	5.7	4.9	–	2.7	0.3
		30	9.5	8.2	6.5	5.8	4.0	3.1	2.0	1.8	–	0.7	0.8
		45	3.0	1.9	1.9	1.6	1.0	0.9	0.0	0.0	–	0.0	0.9
		60	1.0	0.1	−0.3	−0.6	−0.9	−1.0	−1.2	−1.3	–	−0.7	0.7
		75	−0.7	−2.0	−2.0	−2.4	−2.6	−2.5	−2.7	−2.3	–	−1.3	0.8
		90	−2.5	−3.9	−3.9	−4.2	−4.2	−3.9	−3.5	−3.2	–	−1.8	1.1
	WEST	15	12.4	11.5	10.2	9.6	8.1	7.2	5.8	5.0	–	2.6	0.1
		30	4.0	3.1	2.7	2.5	2.2	1.8	1.4	1.1	–	0.3	0.9
		45	1.7	0.9	0.6	0.4	0.2	−0.3	−0.6	−0.4	–	−0.2	1.3
		60	−1.8	−3.1	−2.9	−3.1	−3.2	−3.3	−3.0	−2.4	–	−1.2	1.6
		75	−5.7	−6.5	−6.1	−6.3	−6.3	−5.8	−5.0	−4.2	–	−2.1	1.5
		90	−8.6	−9.4	−8.8	−8.9	−8.2	−7.4	−6.4	−5.4	–	−3.2	1.1
	NORTH	15	9.4	9.0	8.4	8.2	7.4	7.0	6.1	5.5	–	3.5	0.9
		30	12.9	12.1	11.1	10.5	9.1	8.3	6.5	5.5	–	2.5	0.6
		45	14.3	13.2	11.7	11.0	9.0	7.8	5.6	4.7	–	2.7	1.0
		60	15.1	13.7	11.7	10.7	8.2	7.0	5.5	4.8	–	3.2	1.5
		75	15.9	14.1	11.9	10.7	8.3	7.3	6.0	5.4	–	3.9	2.0
		90	16.4	14.4	12.0	10.8	8.6	7.7	6.6	6.0	–	4.4	2.4
C. vulgaris	SOUTH	15	13.4	12.7	11.9	10.6	9.3	8.1	4.4	–	2.5	–	0.1
		30	15.7	14.3	12.8	10.7	9.1	7.7	4.1	–	2.6	–	0.0
		45	15.7	13.7	12.0	9.8	8.2	6.8	3.6	–	2.3	–	1.6
		60	7.7	5.6	3.9	1.8	0.2	−1.0	−2.6	–	−2.2	–	1.8
		75	0.3	−1.8	−3.4	−5.3	−6.7	−6.7	−4.0	–	−3.1	–	1.9
		90	−6.5	−8.5	−10.0	−11.5	−10.4	−8.8	−5.0	–	−4.3	–	1.8
	EAST	15	12.5	12.1	11.5	10.7	9.8	9.0	5.8	–	3.9	–	0.9
		30	12.0	11.0	10.0	8.4	7.0	5.8	1.8	–	0.7	–	0.6
		45	4.0	3.0	2.4	1.8	1.3	1.1	−0.5	–	−0.8	–	0.6
		60	2.2	1.2	0.1	−0.4	−0.6	−1.2	−2.1	–	−1.8	–	0.5
		75	0.4	−0.8	−1.5	−2.1	−2.8	−3.0	−3.3	–	−2.6	–	0.4
		90	−1.4	−2.7	−3.4	−4.0	−4.7	−4.8	−4.5	–	−3.5	–	0.3
	WEST	15	14.2	13.5	12.8	11.7	10.6	9.5	6.1	–	4.0	–	0.7
		30	6.5	5.3	4.1	2.8	2.5	2.0	0.6	–	0.1	–	1.0
		45	2.4	1.5	0.9	0.5	−0.1	−0.1	−1.4	–	−0.9	–	1.1
		60	−1.0	−2.1	−2.8	−3.2	−3.7	−3.7	−3.9	–	−2.6	–	0.9
		75	−4.6	−6.1	−6.8	−7.0	−7.1	−7.0	−6.2	–	−4.3	–	0.5
		90	−7.6	−9.2	−9.8	−10.0	−9.9	−9.6	−7.7	–	−5.5	–	−0.1
	NORTH	15	10.1	9.8	9.5	9.1	8.6	8.1	6.0	–	4.4	–	1.6
		30	14.2	13.7	13.2	12.3	11.4	10.5	6.5	–	3.7	–	1.0
		45	16.2	15.5	14.7	13.4	12.1	10.8	5.7	–	3.8	–	1.4
		60	17.8	16.8	15.7	13.9	12.2	10.5	5.9	–	4.4	–	1.9
		75	19.0	17.8	16.5	14.4	12.4	10.5	6.5	–	5.2	–	2.5
		90	19.9	18.6	17.1	14.8	12.6	10.7	7.2	–	5.8	–	3.0

Table B.3
Annual energy consumption differences vs WIN-SG, PSES building in Tel-Aviv, Israel.

Algae type	Orientation	Window size	Energy use differences in kWh m^{-2} year^{-1} according microalgae concentration										
			100	85	70	60	50	40	30	25	20	10	0
C. reinhardtii	SOUTH	15	13.1	12.0	10.6	9.9	8.2	7.3	5.9	5.2	–	3.1	1.3
		30	13.9	12.1	10.2	9.4	7.7	6.7	5.4	4.8	–	3.1	1.3
		45	6.3	4.6	2.6	1.8	0.1	−0.8	−1.8	−2.3	–	−3.8	−2.8
		60	−3.6	−5.2	−7.1	−7.7	−9.1	−8.9	−8.4	−8.6	–	−7.5	−3.6
		75	−11.7	−13.2	−13.8	−13.7	−12.4	−11.2	−10.4	−10.5	–	−8.9	−4.3
		90	−18.7	−18.7	−16.8	−16.1	−14.4	−13.0	−12.4	−12.5	–	−10.2	−4.8
	EAST	15	12.7	12.0	11.0	10.5	9.2	8.5	7.1	6.4	–	4.1	1.8
		30	8.2	6.9	5.3	4.5	2.8	1.8	0.8	0.6	–	−0.6	−0.5
		45	1.2	0.0	0.0	−0.2	−0.9	−1.0	−1.9	−1.9	–	−1.9	−0.9
		60	−1.5	−2.4	−2.8	−3.0	−3.4	−3.5	−3.7	−3.8	–	−3.2	−1.8
		75	−3.6	−5.0	−5.0	−5.3	−5.6	−5.5	−5.7	−5.3	–	−4.2	−2.2
		90	−6.0	−7.4	−7.4	−7.7	−7.7	−7.4	−7.0	−6.7	–	−5.3	−2.4
	WEST	15	14.0	13.1	11.8	11.2	9.7	8.9	7.4	6.6	–	4.2	1.7
		30	1.9	1.0	0.6	0.4	0.1	−0.3	−0.7	−1.0	–	−1.7	−1.2
		45	−1.5	−2.3	−2.5	−2.8	−3.0	−3.4	−3.8	−3.6	–	−3.4	−1.9
		60	−6.0	−7.3	−7.1	−7.3	−7.3	−7.5	−7.2	−6.5	–	−5.4	−2.6
		75	−10.0	−10.8	−10.4	−10.6	−10.6	−10.1	−9.3	−8.4	–	−6.4	−2.8
		90	−13.0	−13.8	−13.3	−13.3	−12.6	−11.8	−10.8	−9.8	–	−7.6	−3.3
	NORTH	15	10.4	10.0	9.4	9.1	8.4	8.0	7.1	6.5	–	4.4	1.9
		30	13.0	12.2	11.2	10.7	9.3	8.4	6.6	5.7	–	2.7	0.8
		45	13.9	12.8	11.3	10.5	8.5	7.4	5.2	4.3	–	2.3	0.6
		60	14.2	12.7	10.7	9.7	7.3	6.0	4.5	3.8	–	2.3	0.5
		75	14.3	12.5	10.3	9.1	6.7	5.7	4.4	3.8	–	2.3	0.4
		90	14.2	12.2	9.8	8.6	6.4	5.5	4.4	3.8	–	2.2	0.2
C. vulgaris	SOUTH	15	15.0	14.3	13.5	12.2	11.0	9.8	6.0	–	4.2	–	1.7
		30	17.4	16.0	14.5	12.4	10.8	9.4	5.8	–	4.3	–	1.7
		45	10.8	8.8	7.1	4.9	3.3	1.9	−1.3	–	−2.6	–	−3.3
		60	1.1	−1.0	−2.7	−4.8	−6.4	−7.6	−9.2	–	−8.8	–	−4.8
		75	−7.3	−9.3	−10.9	−12.8	−14.2	−14.2	−11.5	–	−10.6	–	−5.7
		90	−14.7	−16.7	−18.2	−19.7	−18.6	−17.1	−13.2	–	−12.6	–	−6.4
	EAST	15	14.0	13.5	13.0	12.1	11.3	10.4	7.3	–	5.3	–	2.4
		30	10.7	9.8	8.8	7.2	5.8	4.5	0.5	–	−0.6	–	−0.6
		45	2.2	1.1	0.5	0.0	−0.6	−0.8	−2.4	–	−2.7	–	−1.3
		60	−0.3	−1.3	−2.4	−2.8	−3.1	−3.7	−4.5	–	−4.3	–	−2.0
		75	−2.5	−3.7	−4.5	−5.1	−5.8	−6.0	−6.2	–	−5.6	–	−2.5
		90	−4.9	−6.2	−7.0	−7.5	−8.2	−8.3	−8.0	–	−7.0	–	−3.2
	WEST	15	15.8	15.1	14.4	13.3	12.2	11.1	7.7	–	5.6	–	2.3
		30	4.5	3.3	2.0	0.8	0.4	−0.1	−1.5	–	−2.0	–	−1.1
		45	−0.8	−1.7	−2.3	−2.7	−3.3	−3.3	−4.6	–	−4.1	–	−2.1
		60	−5.2	−6.3	−7.0	−7.3	−7.9	−7.9	−8.1	–	−6.7	–	−3.3
		75	−8.8	−10.4	−11.0	−11.3	−11.4	−11.3	−10.4	–	−8.6	–	−3.8
		90	−12.1	−13.6	−14.2	−14.4	−14.4	−14.1	−12.1	–	−9.9	–	−4.5
	NORTH	15	11.1	10.8	10.5	10.1	9.6	9.1	7.0	–	5.4	–	2.6
		30	14.4	13.9	13.3	12.4	11.5	10.6	6.6	–	3.9	–	1.2
		45	15.8	15.1	14.3	13.0	11.7	10.4	5.3	–	3.4	–	1.0
		60	16.8	15.8	14.7	12.9	11.2	9.5	4.9	–	3.4	–	0.9
		75	17.4	16.2	14.9	12.8	10.8	8.9	4.9	–	3.6	–	0.9
		90	17.7	16.4	14.9	12.6	10.4	8.5	5.0	–	3.6	–	0.8

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