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Potential of using greenery to reduce overheating of buildings in Polish climate conditions

Key words: greenery, low-energy architecture, passive buildings, solar radiation, overheating

Introduction

Reducing the energy consumption in buildings is one of the most important challenges of modern architectural design in the era of climate changes. Designing the energy efficient architecture requires a number of different factors to be taken into account in the energy balance of the building. These include both the reduction of energy used for heating purposes in winter and the reduction of energy used for cooling purposes in summer. The issue of overheating of the buildings in summer is one of the common problems of low-energy architecture, that gives great opportunities for the use of greenery.

The potential impact of greenery on the reduction of energy demand can be considered in several aspects. One of the most important is the influence of greenery on amount of solar radiation reaching the building interior through the glazed parts of façades – this is called passive solar heat gain. Restricting the access of the sunlight to the façades can help to reduce the energy usage for the cooling purposes in summer. It can be achieved using various kinds of greenery, located on the ground in the building plot – like deciduous trees or conifers, or directly on the façade – like vertical gardens or creepers. On the other hand, shading the façade by the greenery may lead to energy losses due to reduced passive solar heat gains in winter. The aim of the research is to assess the potential of using greenery to reduce the energy consumption of the building in Polish climate conditions and to find the most profitable balance between potential solar energy gains and losses caused by greenery.

Main scientific problem

A significant part of the energy consumed in buildings is used for heating and cooling purposes. In order to reduce it, a number of technical solutions are used, like improving thermal insulation of the building envelope, efficient mechanical ventilation systems with heat recovery and efficient heat sources using renewable energy. To assess the energy demand in the building, it is necessary to calculate the energy balance of the building, that consists both losses and gains of energy. The balance of thermal energy used in building include losses of energy from:

– heat transfer through external partitions (floors, walls, roofs) and windows;
– heat transfer through the ventilation air.

Gains of thermal energy come from:

– internal heat gains – heat emitted by people living in the building, electrical devices, lighting etc.;
– passive solar heat gains – from the solar radiation entering the building interior through the glazed parts of façades (windows), which are the main subject of the research described in this article.

The rest of thermal energy – the difference between losses and gains – have to be covered by heat source in the building. It is the energy demand for heating purposes.

The amount of each component of the energy balance may vary during the year, depending on seasons. This applies especially to:

– heat transfer – that decreases in summer and is much larger in winter;
– solar passive gains – that are, inversely, higher in summer than in winter.

Passive solar heat gains are very useful in winter, when they are relatively small and we need to take as much as possible to reduce the energy demand for heating purposes. But on the other hand, the solar radiation is much higher in summer, causing the risk of overheating and, as a consequence, the higher energy demand for cooling (air-conditioning etc.). The reduction of energy used both for heating purposes in winter and for cooling purposes in summer should be the aim of responsible designed energy-efficient architecture. One of the tools to achieve such a favourable energy balance of the building is to ensure the appropriate access to the sunlight in each season.

This issue shows a potential of urban planning in designing an energy-efficient development (Sobczyk & Bracha, 2014) and gives great opportunities for the use of greenery. One of the most important aspects is the influence of greenery on amount of passive solar gains through the glazed parts of façades. It can be achieved using various kinds of greenery, located on the ground in the building plot or directly on the façade.

Amount of passive solar heat gains can be calculated using the following formula (Feist, Munzenberg & Thumulla, 2009):

$$Q_s = r \cdot g \cdot A_g \cdot G \; [\text{kWh}\cdot\text{year}^{-1}] \qquad (1)$$

where:
Q_s – total amount of passive solar gains;
r – reduction coefficient, including the solar incidence angle, shading and dirt;
g – total solar energy transmittance of the glazing (g-factor);
A_g – glazing area;
G – total solar radiation during the heating season.

As we can see, the amount of passive solar heat gains depends on a few factors. Total solar radiation (*G*) is constant, but the designer can influence the rest of them:

– total solar energy transmittance – *g*-factor (*g*) that depends on the type of glazing;
– glazing area (A_g), that depends on the amount and dimensions of windows or glazed curtain walls;
– reduction coefficient (*r*), that depends, i.a., on the urban layout, including location and distribution of the greenery.

The third of these factors mentioned above is the focus of the research described in this article. The reduction factor is strongly connected with shading the façades of the building, that depends on various features of the surroundings, like:

– orientation of façades towards the directions of the world;
– distances to the other buildings in the neighbourhood;
– heights of buildings in the neighbourhood;
– building materials used on building façades in surroundings;
– location and distribution of greenery around buildings.

Majority of the factors mentioned above is connected with geometry of the urban layout, so they are foreseeable at the stage of urban design. Appropriate design of the spatial layout of buildings can therefore give some energy savings without the need for other technical solutions that would increase construction costs.

State of the art

Worldwide studies carried out so far show the great importance of the proper building layout: according to Strømann-Andersen and Sattrup (2011), in the climate conditions in Denmark, it is possible to achieve energy savings of up to 30% for offices and 19% for housing, including energy for heating and cooling and electricity for lighting purposes. Comprehensive study on the impact of the environment on the building's energy demand, conducted in Singapore by Wong et al. (2011) points to the role of the different features of surrounding of the building, like building height and density, green plot ratio and their combination. The issues of energy efficiency in urban design, with an emphasis on the solar radiation, have been discussed also by the other authors (Chwieduk, 2006; Amado & Poggi, 2012; van Esch, Looman & de Bruin-Hordijk, 2012; Stangel, 2013; Amado & Poggi, 2014; Sarralde, Quinn, Wiesmann & Steemers, 2015; Grzymała, 2016; Morganti, Salvati, Coch & Cecere, 2017; Zhou, Zhuang, Yang, Yu & Xie, 2017; Tong et al., 2018). This shows a great potential, that is still not sufficiently taken into account in the realities of the Polish spatial planning system.

As far as the greenery impact on an energy balance is concerned, there are known various scientific researches in various locations and climatic conditions. The studies on the role of green walls in thermal performance of buildings have been carried out by Cheng, Cheung and Chu (2010), Kontoleon and

Eumorfopoulou (2010), Pérez, Rincón, Vila, González and Cabeza (2010), Jim and He (2011). There are also studies of double-skin façades conducted (Stec, van Passen & Maziarz, 2005). A particularly interesting research on the use of a vertical deciduous climbing plant as a shading element has been carried out by Ip, Lam and Miller (2010). The last mentioned publication draws attention to the seasonal variability of shading coefficient, which is advantageous in case of deciduous creepers.

This article is focused on somewhat other approach to the topic of the use the greenery not located directly on the building façade, but the plants (trees) located in the direct surrounding of the building, in front of the façades, taking into consideration location, distribution and size of the greenery. The matter of the research is to find the most advantageous distribution of greenery in building surroundings, that ensures to maximize reduction of solar radiation in summer and minimize losses of passive solar heat gains in winter.

The research should include the aspects, like:

- insolation time, area and direction;
- climate data (Ministry of Investment and Development, 2019);
- variability of greenery over the time (including seasonal variation during the year and growth rate of plants).

Material and methods

The article discusses the preliminary research on the possibilities of achieving energy savings in buildings at the stage of greenery design in Polish legal and climate conditions. The research is to show how distribution of greenery in building surroundings influence the amount of solar energy reaching the façades.

The following software has been used for the research:

- Sketchup – to create a simplified 3d model of the building quarters with surrounding development and greenery;
- DL-Light extension – for the calculation of solar energy reaching the selected building façades. The results of calculations have been presented as diagrams of the average solar radiation distribution (measured in $Wh \cdot m^{-2} \cdot day^{-1}$) on the façades in and, alternatively, diagrams of the radiation reduction factor expressed as a percentage.

The analysis has been carried out on selected theoretical examples in order to better observe general regularities, without an interrupting influence of specific local conditions. The research has been carried out using climatic data of Cracow, that are easily available in DL-Light extension for Poland.

Preliminary analysis

An initial analysis of the amount of the solar energy reaching building façades has been carried out on the 3d model of a typical urban building quarter. The dimensions of the quarter has been defined as 40 × 55 m, the height of the building has been set at 15 m, which corresponds to five residential or four office storeys. The distance between quarters is 25 m. The adopted dimensions of the quarter result from the sunshine requirements for flats in the Polish construction law (at least 3 h in the days of equinox), assuming a building width of 15 m.

As a result, there has been created diagrams of distribution of the solar energy reaching west and south façades of the building quarter. The diagrams present the data for multiple situations:

– in summer, without any greenery around the building quarter;
– in summer, with rows of trees along the west and south façades;
– in winter, without any greenery around the building quarter;
– in winter, with rows of trees along the west and south façades – trees with leaves (analogical to the summer as a more comparable version);
– in winter, with rows of trees along the west and south façades – trees without leaves (as a realistic version, because majority of trees in Poland are deciduous).

In all mentioned variants, the trees have been ~10 m high, the distance between trees ~10 m and distance to the building wall ~7 m.

Results has been presented as diagrams of distribution of the solar energy reaching façades – the west and the south one (Figs. 1–5). For comparison, the same results have been presented as

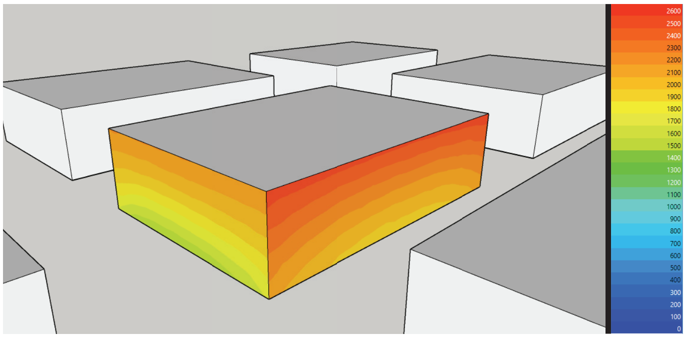

FIGURE 1. Distribution of the solar radiation on building façades – summer, without greenery (author: Wojciech Skórzewski)

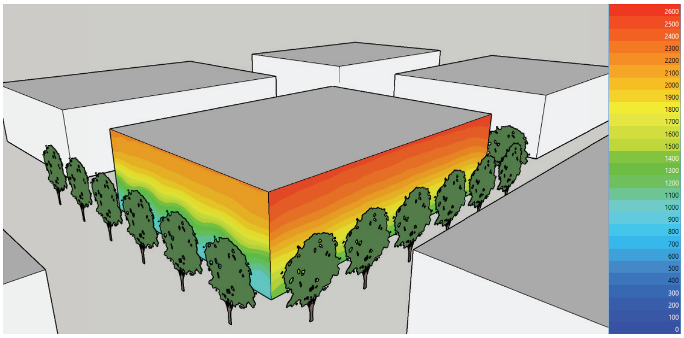

FIGURE 2. Distribution of the solar radiation on building façades – summer, with trees (author: Wojciech Skórzewski)

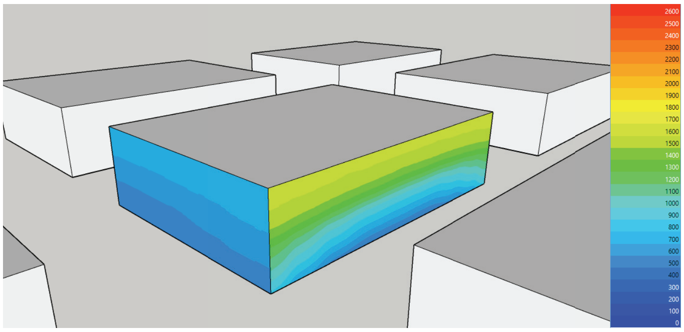

FIGURE 3. Distribution of the solar radiation on building façades – winter, without greenery (author: Wojciech Skórzewski)

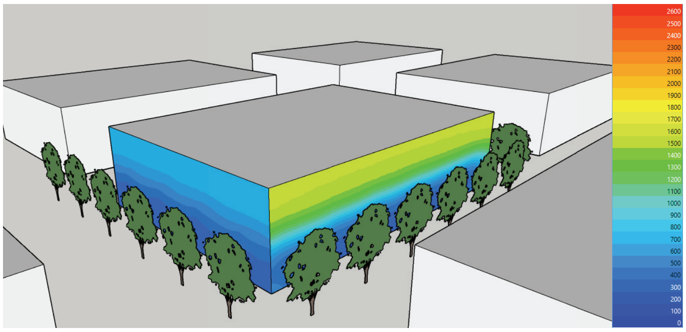

FIGURE 4. Distribution of the solar radiation on building façades – winter, with trees (with leaves) (author: Wojciech Skórzewski)

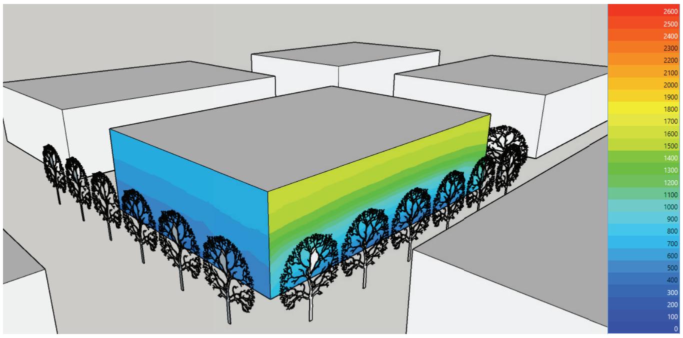

FIGURE 5. Distribution of the solar radiation on building façades – winter, with deciduous trees (without leaves) (author: Wojciech Skórzewski)

diagrams of radiation reduction factor expressed as a percentage. In the first two pictures presented below we can see the situation in summer – building quarter without any greenery in the streets and then the same building quarter with some trees in the streets added, so that we can check how the amount of solar energy changes. As we can see, the decrease of the radiation is more significant on the west façade (similarly it is on the east one), which is caused by sun rays angle. Let's compare it with the same situation in winter. After adding trees, losses of solar energy are less significant at the east and west façades than on the south one. The decrease of solar gains in winter on the south façade, while the reduction of overheating is not so effective in summer, tends us not to locate trees in front of this façade. But if we grow deciduous trees instead of evergreen, the balance is more advantageous.

Detailed research

To confirm these observations, there has been more detailed analysis carried out. The research has been conducted using the same software as the preliminary analysis (Sketchup with DL Light extension). The analysis has used simplified model of building quarter with the same size 40 × 55 m and height of 15 m, without any surroundings. The amount of the solar energy entering the building interior has been calculated for the typical window with dimensions 1.23 × 1.45 m, located on the different heights on the façade: on the groundfloor, first and second floor. The same calculation has been carried out for the windows located on the south façade and on the west façade. It has been assumed that the results for the eastern façade would be similar to those for the western façade. The calculations for the northern façade were, which is not directly affected by solar radiation anyway, were abandoned.

Greenery has been represented as simplified models of trees with a cylindrical trunk and a crown in the shape of a rotating ellipsoid. The crown and trunk of the tree were given materials with different solar radiation transmittance (Balcomb, 1992; Chwieduk, 2014): trunk – no transmittance, tree crown with leaves ~6%, tree crown without leaves ~60% (for deciduous trees in winter) (Chwieduk, 2014).

For each façade there have been multiple variants of location and height of trees taken into consideration:

– three variants of distance between façade and trees: 5, 10 and 15 m;
– three variants of height of trees: 5, 10 and 15 m – which correspond to the successive growth stages of the tree in time.

Such assumptions give nine combinations of greenery distribution for each window on each façade (total 54 variants of calculation). For each variant, the calculation has been proceeded for two periods of the year: summer – from June 21st to September 22nd and winter – from December 22nd to March 20th.

Results

For each variant of calculation there has been prepared a set of results, consisting of:

– an average daily amount of solar energy (measured in Wh·m^{-2}) on the façade surface in summer period, without any greenery in front of the building;
– an average daily amount of solar energy (measured in Wh·m^{-2}) on the façade surface in summer period, with rows of trees in front of the façade;
– a difference between this two values mentioned above, which represents

the profit or loss of the solar energy due to the use of greenery;

– similarly the same results for winter period and additionally the version with deciduous trees without leaves;
– the balance of the gains and losses of the solar energy between winter and summer period in two variants (for evergreen and for deciduous trees), which shows the positive or negative influence of greenery on the balance of solar energy reaching the building.

On Figures 6–8 we can see a few sample results for selected variants of calculation. The calculations of other variants have been made by analogy.

After calculating balances of solar energy for each variant, summaries for the south façade (Figs. 9 and 10) and for the west façade (Figs. 11 and 12) have been prepared, both in two variants of greenery: evergreen and deciduous trees.

We can observe, that influence of the location of greenery is quite different for the south façade and for the west façade (similarly for the east one). According to the research results locating greenery in front of the west or east façade is much more beneficial than in front of the south one.

The trees situated on the west or east side of the building almost always have a positive effect on the overall solar energy balance of the building. For western and eastern façades, we are dealing with a significant reduction in solar radiation in the summer. This is due to the low angle of sunlight from east and west directions, which vertical elements such as trees easily shade. On the other hand, in winter the amount of solar radiation delivered from these directions to the façade is still small, so shading of the sun rays by the trees has a little importance here. As we can see in the charts, the positive impact of trees on the energy balance increases with their height. This means that the greatest benefits of greenery come after a period of time.

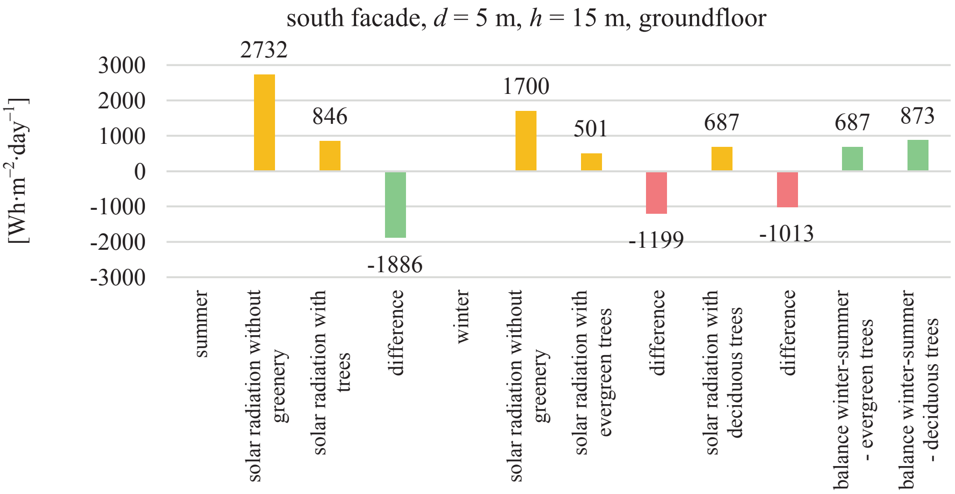

FIGURE 6. Results of detailed analysis, example 1: south façade, window on the groundfloor level, trees distance from the façade 5 m, trees height 15 m (author: Wojciech Skórzewski)

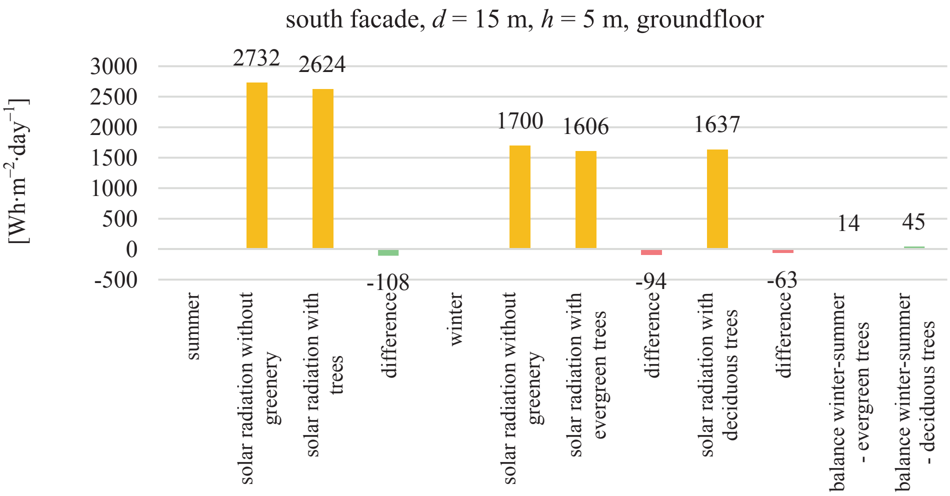

FIGURE 7. Results of detailed analysis, example 2: south façade, window on the groundfloor level, trees distance from the façade 15 m, trees height 5 m (author: Wojciech Skórzewski)

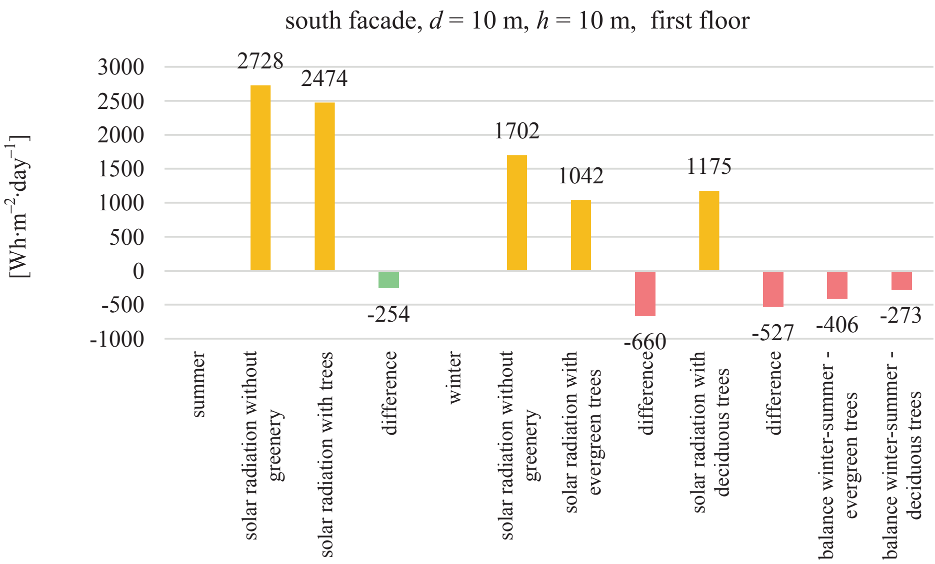

FIGURE 8. Results of detailed analysis, example 3: south façade, window on the first floor level, trees distance from the façade 10 m, trees height 10 m (author: Wojciech Skórzewski)

The situation is quite different for the southern façade. The angle of incidence of summer sunshine is high, so only trees located very close to the façade are able to limit its access. In turn, trees significantly reduce radiation from the south in winter, when the angle of incidence of sunlight is low. As we can see in the presented charts, greenery in front of the south façade has a positive impact on

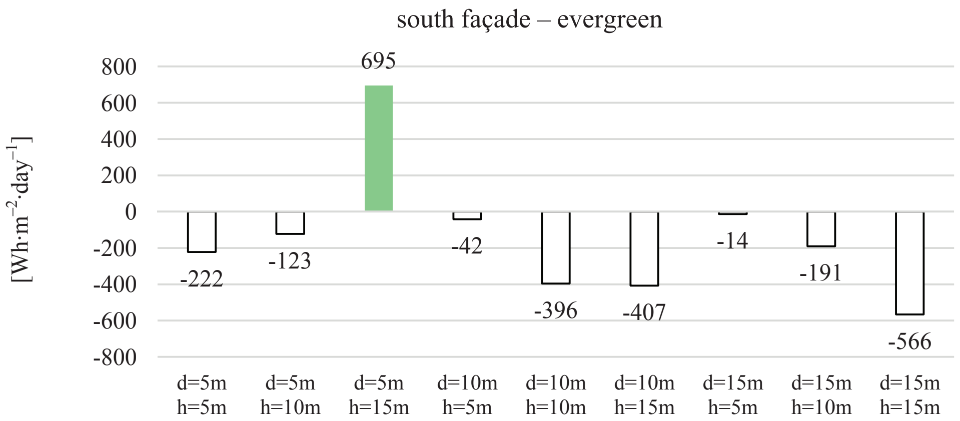

FIGURE 9. Results of detailed analysis – balance of the influence of the greenery on the amount of solar energy reaching façade surface between winter and summer: south façade, evergreen trees (author: Wojciech Skórzewski)

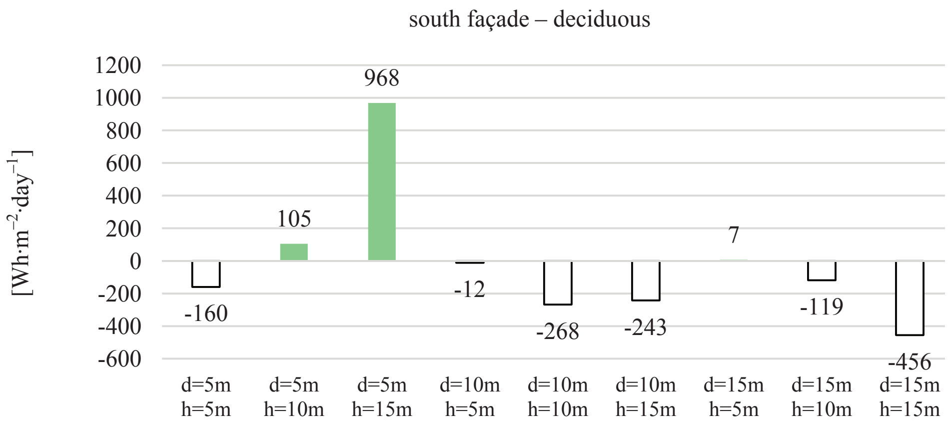

FIGURE 10. Results of detailed analysis – balance of the influence of the greenery on the amount of solar energy reaching façade surface between winter and summer: south façade, deciduous trees (author: Wojciech Skórzewski)

the solar energy balance only in a specific combinations of location and size of plants. The best benefits are in case of the shortest distance (5 m) and the maximum height (15 m). That show, that for the south façade greenery should be very close to the building to prevent building against overheating.

Conclusions

The results of the presented research show, that the greenery has a great potential for reducing overheating in buildings in summer. However, the potential of greenery to improve energy balance of buildings depends on its location rela-

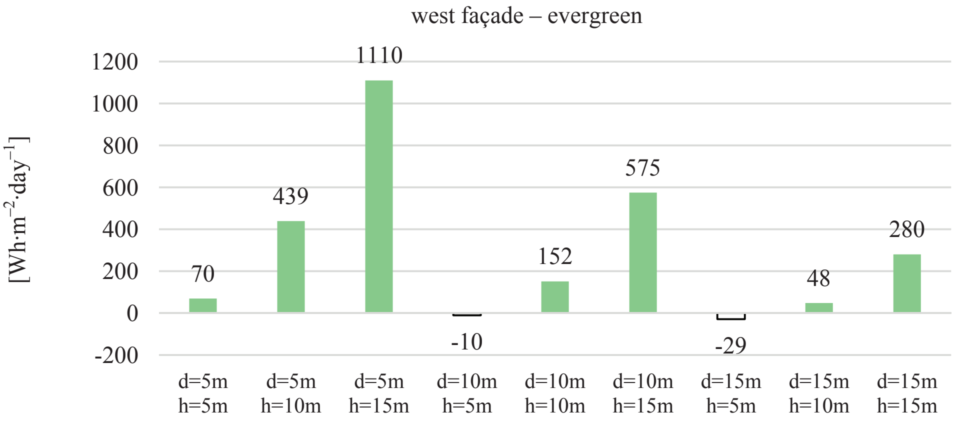

FIGURE 11. Results of detailed analysis – balance of the influence of the greenery on the amount of solar energy reaching façade surface between winter and summer: west façade, evergreen trees (author: Wojciech Skórzewski)

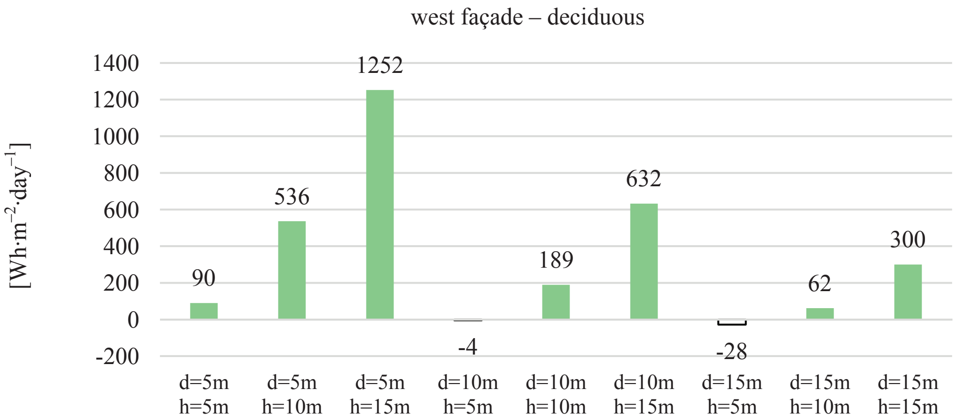

FIGURE 12. Results of detailed analysis – balance of the influence of the greenery on the amount of solar energy reaching façade surface between winter and summer: west façade, deciduous trees (author: Wojciech Skórzewski)

tive to building façades. The key factors determining the effect of greenery on the amount of passive solar heat gains are:

– orientation of the façade towards the directions of the world;
– distance of plants (trees) from the façade;
– height of plants (trees);
– solar radiation transmittance of the tree crown.

It is worth noting, that the façade orientation has a great importance: for the west and east oriented façades location of the greenery in front of them gives greater efficiency in reducing overheating than for the south oriented. It corresponds with the results of studies by Kontoleon and Eumorfopoulou (2010) on the plant-covered walls, which also showed that the reduction of peak daily temperatures thanks to greenery is more significant on the east and west oriented walls. Because the greenery in front of the south façade should be very close to the building to prevent building against overheating efficiently, it seems that south façades are good place for greenery planted directly on the buildings, like green walls or creepers. The study on the bio-shading coefficient of the climbing plants by Ip, Lam and Miller (2010) confirm the usefulness of deciduous creepers for proper shading of the façade, taking the seasonal variability into consideration.

In general, the location and distribution of the greenery in the direct surrounding of buildings is an important aspect of energy-efficient architecture and should be reflected in urban layouts of designed energy-efficient developments.

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Summary

Potential of using greenery to reduce overheating of buildings in Polish climate conditions. The issue of overheating the buildings gives great opportunities for the use of greenery, that can affect the amount of passive solar gains through the glazed parts of façades. Restricting the access of the sunlight to the façades helps to reduce the energy usage for the cooling purposes, but, on the other hand, may cause reduction of solar gains in winter. The aim of the research is to determine the potential of using greenery to reduce energy demand of buildings by achieving the optimal balance between solar energy gains and losses in polish climate conditions.

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