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Atria, roof-space solar collectors and windows for low-energy new and renovated office buildings: a review

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Abstract

As part of achieving near zero energy office buildings, solar gains can be optimised by built form, internal layout and the position, type and area of windows. Those solar gains can then displace heating and lighting energy in most non-domestic buildings without overt engineered solar energy harnessing features. Such approaches have been adopted to successfully realise many low-energy buildings. This review discusses key parameters and the particular challenges in the design of atria, windows and roof-space solar air heaters to reduce energy and carbon emissions associated with heating and lighting in newly-built and renovated non-domestic buildings.

Keywords

Atria, roof-space collectors, solar energy, building renovation.

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1. Introduction

Passive solar gains can assist in displacing heating and lighting energy in most buildings without overt engineered solar features. As part of achieving near zero energy office buildings, solar heat, daylight and solar induced ventilation can be optimised by built form, internal layout and the position, type and area of glazed features. Windows provide solar heat gains and daylight directly to a space. For atria and roof-space collectors, solar heat collection can be readily de-coupled from adjacent spaces by simply conveying solar heated air when required by using fans actuated by appropriate sensors and controls.

Bringing daylight into office buildings can also usually, even with overcast skies, provide sufficient illumination for the majority of activities during most of many days. However, appropriate daylighting strategies depend on climate, the latitudinal sunpath, and the building's function, form and site. It has thus been a critical part of building design. However, with the advent of electric lighting, air-conditioning, lifts and escalators, office buildings became larger and taller but also often floor plans became deeper allowing limited penetration of daylight. In office buildings, providing adequate daylight has many important health, comfort, amenity and economic benefits (Knoop et al, 2019). The only proviso is that conditions leading to glare or excessive solar gain are avoided. Properly supporting the stimulus that maintains daylight-driven circadian rhythms requires a complex combination of light intensity, duration and timing of exposure to daylight, the amount of particular wavelengths in the received daylight spectrum, and that daylight's spatial distribution (Münch et al, 2020).

To be successful, energy efficient design has to be reconciled harmoniously with a building's specific physical constraints and functional requirements. Energy-efficient design itself has to address three functional requirements, namely:

- reduce the energy required for heating, ventilating and/or lighting and thus the greenhouse gas emissions and running costs of the building;
- incur low embodied energy and greenhouse gas emissions in the materials and processes of construction or renovation;
- provide a comfortable, pleasant and aesthetically-pleasing internal environment, possibly with supplemental usable space.

In doing so, energy efficient design can also introduce additional constraints on orientation, pattern of fenestration, built form and internal layout, for example where an atria forms a glazed courtyard

2. Atria

An atrium may reduce the energy consumption of a building (Moosavi et al, 2014) by:

- conduction of heat through walls from the warm atrium to adjacent spaces;
- the natural or forced recirculation of heated air between the atrium and the heated building;
- pre-heating a net flow of ventilation air from the outside ambient environment into the heated building via the atrium;
- the warmer-than-ambient environment of an atrium increases the thermally-optimum area for a window facing into it in comparison with one facing externally. Daylighting of the adjacent spaces may thus be increased (To and Chan, 2006);
- when in inclement weather an atrium is sufficiently warmer than the ambient environment, it constitutes useable space (Danielski et al, 2016)

In addition, during periods when the temperature of the atrium is similar to ambient, ventilative air flows from the heated building into the atrium, and then outside reduces heating loads indirectly. The temperature in the atrium will be elevated both directly and due to the ingress of warm air from the heated building. This can also lead to periods of overheating of an atrium (Lu et al, 2019).

Atria may be categorised as those:

- separated from the main body of the building via a glazed lightweight partition allowing air flow. These cannot be thermally de-coupled readily from adjacent spaces. Heat gain to the building is either by natural ventilation, ventilation pre-heating, direct radiative gain, conduction and by a reduction of heat lost via adjacent facades.
- where the glazed area of the separating partition is small and the contribution of direct radiative gain is reduced compared with an integral direct system. The fabric of the partition is less leaky to air flow and solar ventilation pre-heating air-flow is often conveyed mechanically. The feature is more isolatable from the main body of the building.
- forming glazed streets where the glazed area is small. When forming linking areas between existing and new buildings, the separating partition is of external wall construction and remains insulated as such.

Examples of atria are shown in Figures 1 to 3. Figure 1 illustrates the use of structural slats to provide shading from direct solar gains in an atrium gallery space. Figure 2 illustrates the use of partially transparent photo- voltaic glazing in an atrium (James et al, 2009) to diminish solar gain, while converting some of the incepted solar energy into electricity. Figure 3 shows an atrium space illuminating a green wall in an emblematic building that forms part of an environmentally-sustainable university campus (Walker and Mendler, 2017).

Figure 1: Atrium in the Corning Gass Museum, Corning, NewYork, USA.

Figure 2: Atrium with a semi-transparent photovoltaic glazed roof at the Fraunhofer Institute for Solat Energy Systems, Freiburg, Germany.

Figure 3: Atrium providing daylight to a green wall at Chatham University, Eden Hall Campus, Richland Township, Pennsylvania, USA.

The thermal effectiveness of thermal storage located in atria is reduced due to the high conductance to ambient (Hussain and Oosthuizen, 2012). However, where sparsely-furnished and uncarpeted finishes are acceptable, "thermal mass" can be provided readily. Such interior design also emphasises the periodically-habitable transition between the ambient and internal environments. However, if this remains an unheated area, care is required as to the activities that can be undertaken therein, particularly in relation to comfort conditions, daylighting and noise.

Natural circulation of air between an atrium and adjacent spaces occurs when airflow is induced by the temperature difference between the warm conservatory and the cooler adjacent space. In northern European climates, low airflow rates ensue for the small temperature differences typically encountered in spring and autumn; energy transport is consequentially often minimal. In summer, such action needs to be prevented in order to avoid overheating.

When air entering the building via an atrium forms the major constituent of the air required for ventilation, then solar gains provide some reduction of a ventilation heat load (Moosavi at al, 2014). In addition, as buildings generally become better insulated, so the proportion of energy that is used to heat the essential requirements for ventilation air increase. In a shallow-plan building, infiltration may distribute solar heat from atria effectively. However, to efficiently distribute pre-heated ventilation air from an atrium in most buildings requires fans and purpose-built ducts.

Well-designed atria can reduce building energy usage in both cold and warm climates by supplying daylight and natural ventilation to interiors. However, improper design of atria may lead to increasing energy consumption or occurring visual and thermal discomfort (Hossein et al, 2020). Squat-form buildings with atria that have square or round floor plans can provide daylight to more of the spaces adjacent to the atrium (Li et al, 2019).

3. Windows

Direct solar gain presents particular challenges of glare (Hamedani et al, 2020); overheating (Camacho-Montano et al, 2020); occupant discomfort due to internal radiant temperature assymetry (La Ferla et al, 2020); and damage to fabrics and finishes from exposure to the ultra-violet band of the solar spectrum (Mohelníková et al, 2018). These challenges require that care be given to the pattern of fenestration (Barea et al, 2017), as well as the specification and control of window systems (Inouea and Ichinoseb, 2016), to give adequate daylighting with varying insolation being within the remit of the overall initial building design. Many low heat loss window options are now available using coatings and multiple panes, some with an intervening vacuum (Ghosh and Norton, 2018) or incorporating a ventilated air gap (Michaux et al, 2019). Window systems can also include blinds (Katsifaraki et al, 2017) and prismatic glazing (Tian et al, 2019) systems that deflect daylight deeper into an adjacent interior space,thereby displacing electric lighting.

Close to the window

Distant from the window

Figure 4: Interior projection of daylight by a prismatic glazing at TU Darmstadt, Darmstadt, Germany.

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All these interventions may, at particular times, provide uneven penetrations of daylight. For example, as can be seen in Figure 4, a prismatic glazing system can provide good-quality lighting in the main body of a space but close to the window projects exterior reflected colours (in this case particularly the red of an outside parked vehicle).

For efficient overall operation a heating system must respond readily, both to provide heating when solar gains to particular zones cease, and also to stop doing so when solar gains resume. Thermal mass is essential to ameliorate the immediate effects of direct solar gain through windows to provide stable internal temperatures. The level of thermal mass required can usually be met by either conventional masonry or timber-framed construction (Reilly and Kinnane, 2017).

Moveable window insulation may also be incorporated to reduce heat losses from glazing. An example is sliding translucent shutters that may be used to alter the level of daylight entering the building and the amount of heat leaving via the glazing (Sun et al, 2017).

4. Roof-space collectors

Roof-space solar-energy collectors employ passive solar collection combined with active distribution. A roof-space solar-energy collector is essentially a pithed-roof which is partially or fully glazed on its southerly aspect. Solar heated air from the roof-space collector is conveyed by an automatically-controlled fan via a duct, either directly into the building or as a pre-heated supply to either a warm-air space-heating system or to heat storage (Charvat et al, 2001). The roof-space collector is replenished with air, either from within the building or from outside the outside ambient environment.

When the air from the roof-space solar energy collector is at a lower temperature than the set level of the room thermostat, the air stream emerging from the roof-space collector forms a pre-heated supply to the auxilliary heating system (Lo and Norton, 1996). Warmth is stored, to some extent, within the structural elements of the roof-space collector. Ventilation is employed to prevent overheating in high summer. Examples of roof space collectors are shown in Figure 5.

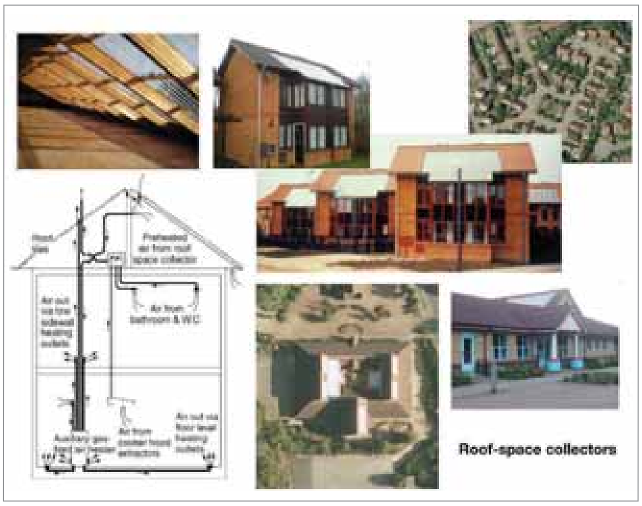


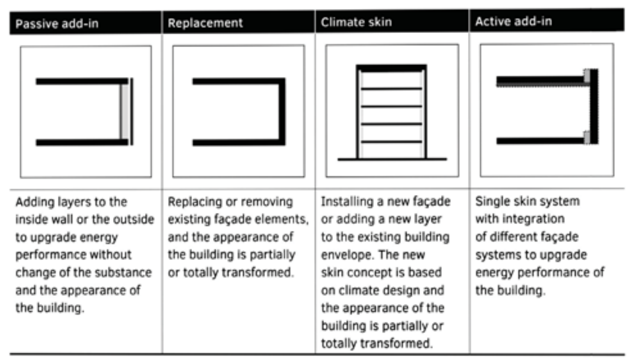
Figure 5: Roof-space solar collector diagram showing (clockwise from bottom left) operation of a domestic system; interior view of glazed loft space; exterior view of a domestic system, aerial view of a group of domestic systems; staggered row of domestic systems; system on a school building (Norton, and Waterfield, 1990); aerial view of system on a school building.

As it can be designed for more optimal heat collection design to thus attain higher air temperatures, a roof-space collector can provide more efficient and effective pre-heating of ventilation air. Neither are possible within an atrium as internal conditions in an atrium must satisfy occupant comfort requirements.

5. Atria and roof-space collectors in energy efficient building renovation

Holistic low-energy buildings use sustainable materials for construction as well as incurring low energy use in their operation. The use of materials with low embodied energy and carbon is thus essential in new construction. However, new buildings constitute only a small proportion of a building stock so, to make an impact on overall energy use and greenhouse gas emissions, it is important to prioritise the energy-efficient renovation, and if necessary re-purposing, of existing buildings.

Offices account for nearly a quarter of the total floor area of non-residential buildings in the European Union (Economidou et al, 2011). In proportion to floor area, office buildings have higher energy use intensity than houses and 60% of them were built before 1980 (Stegnar and Cerovšek, 2019). Therefore, the potential for their renovation to achieve energy saving and carbon emissions reductions is greater than for other building types. Figure 6 shows a classification of energy renovation strategies for office buildings (Kwon, 2020).



Passive add-in	Replacement	Climate skin	Active add-in
Adding layers to the inside wall or the outside to upgrade energy performance without change of the substance and the appearance of the building.	Replacing or removing existing façade elements, and the appearance of the building is partially or totally transformed.	Installing a new façade or adding a new layer to the existing building envelope. The new skin concept is based on climate design and the appearance of the building is partially or totally transformed.	Single skin system with integration of different façade systems to upgrade energy performance of the building.

Figure 6: Classification of building envelope renovation strategies (Kwon, 2020).

In reality, energy renovation of a particular office building may combine, to varying extents, elements of each of the strategies shown in Figure 6. The retrofitting of an atrium between existing buildings, as illustrated in Figure 7 (next page), is a frequently-implemented, predominantly "climate skin" strategy that enables a building to continue to meet all functional requirements. It obviates the need to make significant changes in behaviour or work patterns, while additional tempered spaces with low overall energy consumption are provided for amenity, circulation and meeting.

A roof-space collector can have a low initial capital cost as its physical construction may not differ greatly from that of a conventional pitched roof (Norton and Waterfield, 1990). In addition, a reduction in additional cost may arise from the employment of fans and controls that would already be present in an air-heating system. Being roof-located, there are often fewer constraints to a roof-space collector being less frequently overshadowed (Lobaccaro et

Figure 7: An atrium retrofitted between existing buildings at Sheffield University, UK. (Anon, 2020).

al, 2016). In contrast, harnessing solar energy features on façades in high-density urban locations may often be rendered ineffective by overshading, particularly at lower sun angles, by neighbouring buildings (Chatzipoulka et al, 2016).

Mitigating risks of cost escalation associated with uncertainly as to the extent of improvements required to achieve specific energy performance goals is critical to the successful introduction of an atrium or roof-space collector as part of a building renovation. To reduce such risks, laser scanning can be used to gather geometric data of an existing building for Building Information Modelling (Sanhuudo et al, 2020). This can be integrated with infrared thermography to precisely locate and quantify building defects (Macher et al, 2020; Shariq and Hughes, 2020).

Future energy use in buildings may be highly affected by changes in climate. For example, in southern Spain it has been estimated that global warming will increase the average percentage of indoor thermal discomfort hours during the summer by more than 35% (Escandon et al, 2019). Therefore, energy renovations need to be assessed both from a cost-optimal energy perspective and for their resilience to global warming (Ascione et al, 2017). Extreme future weather data has been synthesised for this purpose (Pernigotto et al, 2920). The controllability of heat removal from atria and roof-space collectors provides inherent adaptability to climate change as well as weather and occupancy variations.

6. Conclusion

The performance flexibility arising from an ability to be thermally decoupled from other spaces renders atria and roof-space collectors particularly suited for consideration as part of energy-efficient renovation of office buildings. The additional usable space provided has meant atria have indeed formed part of many climate-skin renovation strategies. Roof-space collectors have not found similar levels of adoption because they do not extend a building's habitable space. However, roof-space collectors merit more frequent attention as part of low-energy renovation. With careful design, significant energy saving benefits can be provided at a cost similar to traditional roof construction while incurring low embodied energy.

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