HYBRID BIPV AS ENVIRONMENTAL PROBLEM-SOLVER - GLASGOW CASE STUDY

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Abstract – This paper summarizes a proposal to explore BIPV (building-integrated photovoltaics) as a means of solving a wide range of environmental problems in a large office building of the 1950s-1960s in Glasgow. It demonstrates the relevance and potential of an architectural problem-led design approach, with the emphasis at this stage, not on quantifying predicted building energy performance, but rather on a strategic improvement to quality which have inherent energy benefits. More detailed computer-assisted quantitative analysis will come later. The methodology is thus: identify problems; identify constraints with respect to BIPV; and develop interactive solutions where BIPV plays a strong part. The innovation lies in its holistic approach and breadth of issues tackled by BIPV. The paper concludes that this approach is viable, especially where a strong need for refurbishment would help to absorb the relatively high capital cost of BIPV. Also, as the case study is of a fairly typical urban office building, the electricity load and PV generation profiles provide a good match between supply and demand, with avoidance of spring-summer-autumn overheating playing a significant part.

1. INTRODUCTION

The underlying aim of this paper is to demonstrate that BIPV (building-integrated photovoltaics) can have a viable and useful role in the refurbishment of typical run-down urban buildings - i.e. buildings with a potentially useful extended life, but with many current problems in terms of energy consumption, thermal comfort and so forth. The first step will be to identify the problems, and then explore opportunities and barriers to BIPV, with some emphasis on hybrid PV (electrical + thermal) and where it has multiple architectural/thermal functions.

The selected BIPV case study building, named Graham Hills Building, is owned and operated by the University of Strathclyde. It is situated on a steep south-sloping site on the Strathclyde University Campus, and bounded to the south by George Street (Fig. 1). At present there is no obstruction to solar access - the site to the south of George St. is a car park. If, however, this was to be built up to a height of 27 m (7 office floors), there would still be no shading of the south facade from the end of April to mid-August. From autumn through to spring there would be some shading, implying the need for careful design of PV strings in order to minimise shading losses.

The building was built in 1957, extended in 1963, and was occupied by the Inland Revenue and British Telecom until 1988 when the University of Strathclyde acquired it. Since then, the building has been used to accommodate a mixture of teaching and administrative departments. The building has a very prominent position representing a public frontage of the University of Strathclyde Campus and forms part of the eastern gateway to the city centre of Glasgow.

The Graham Hills Building is a typical model of a "form follows function" of its time, with cellular office accommodation and corridors, mixed with open plan offices or larger teaching areas. The plan uses three and four sided courtyards to achieve a relatively narrow footprint of approximately twelve meters from wall to wall in each wing of offices, with the only deep-plan sections occurring at the base of courtyards. The construction of the building is a typical expression of early 1960s architecture with in-situ concrete frame and pre-cast concrete cladding panels (Figs. 2-4). It is eight stories high, under-insulated and over-glazed with single-glazed windows which are the sole means of ventilating offices.
The main entrance is from George Street linking the two
phases, and the building has car-park levels on the first
and second floor accessed by ramps from the rear.

Fig. 2. Graham Hills Building (front elevation)

Fig. 3. South Elevation

Fig. 4. Courtyard

2. ENVIRONMENTAL PROBLEMS

A feasibility study produced in 1993 by the University of
Strathclyde Energy Systems Research Unit (ESRU),
along with environmental questionnaires and interviews
with users, confirm that the Graham Hills Building
suffers from a wide range of environmental problems:

- Excessive heat loss (in winter, especially on north
elevation) due poor insulation, cold-bridging and
large single glazed areas.
- Severe cold-bridging on floor and cill junctions.
- Poor thermal performance of the external envelope
(U-value approximately 1.4 W/Km²)
- Poor heating controls (lack of zoning/temperature
control, and badly positioned thermostats).
- Excessive heat gain and poor glare control - in
spring, summer and autumn, especially on south
elevation due large single-glazed metal windows
(seldom opened - see below), and an inefficient sun
protection system of internal vertically slatted blinds.
- Poor natural ventilation system, coupled with high
noise level from busy George Street (this results in
poorly ventilated offices and unventilated corridors).
- Excessive use of artificial lighting (also contributing
to overheating in summer).
- Rundown internal and external appearance (existing
cladding panels have problems with water
penetration, deterioration of render finishes,
detachment of mosaic finishes and poor thermal
performance).
- Lack of servicing facilities and amenities for both
staff and students.

The excessive overall energy consumption (1991 Annual
Energy Figures) expresses in numerical terms some of
these problems. Total annual thermal (gas) and electric
energy consumption is 2,566,420 kWh for an occupied
floor area of 10,527 m² - i.e. 244 kWh/m². This
compares, for example, with a target of 83 kWh/m² for
the Building Research Establishment’s 1996 naturally
ventilated office block built in 1996 (Evans 1996). It is
also worth stating that the three times higher Glasgow value, attributable to the poor standards of the 1950-60s, does not necessarily convey the impact of lack of comfort, inconvenience and qualitative poverty of the working environment.

3. POTENTIAL FOR BIPV AS ENVIRONMENTAL PROBLEM-SOLVER

3.1 South Elevation (1957) - second skin construction

The Graham Hills Building has its long front elevation south oriented overlooking a noisy street. Environmental problems, as stated above, include excessive summer overheating, a poor natural ventilation system, excessive winter heat loss and high noise level. The architectural ideas and energy strategies involve a range of passive solar and BIPV applications aimed at reducing, or where possible solving, the problems cited above.

Moreover, the proposed solution has an aesthetic dimension which acknowledges this building’s role and prominent position. The concept employed was to exploit possibilities of BIPV and related passive solar techniques to target problems, and in doing so, to integrate BIPV systems clearly expressing their aesthetic compatibility rather than attempting to create a sense of ‘invisibility’.

For example, the architectural proposal for the facade facing George Street is a secondary glazed skin, set forward 800 mm from the concrete frame structure, from first floor upwards. An important aesthetic feature of the existing external envelope is pre-cast concrete panels positioned in a chessboard order. This has been ‘translated’ into the second-skin design as a combination of glass and vertical opaque BIPV panels in a chessboard formation set in front of concrete panels. This new structure will provide an aesthetic of transparency, openness, and clarity, whilst at the same time tackling the most serious practical problems. The buffer zone will act as a noise barrier, permitting the inner skin to be freely opened, as well as preheating air for ventilation in winter, obviating cold-brudging and improving U-values, assisting with glare-free daylighting, cooling the facade in summer, simplifying maintenance etc.

Second skin construction - winter mode

The incoming cold ambient air will enter through the louvred base of the twin-skin void or ‘solar chimney’ at first floor level, then naturally convect upwards through maintenance grilles, being joined by vitiated or partly vitiated air from offices according to window opening regimes adopted by occupants (Fig. 5). The opaque parts of the facade, now insulated, will act as solar absorbers and air will be further pre-heated as it passes behind PV panels. The grilled walkways at each floor level will be reflective, with a special section and positioned vertically to help the distribution of daylight in offices in conjunction with new suspended ceilings. New double-glazed inner windows will have thermally-broken, slim metal frames; while the outer skin is single-glazed, partly with solar absorbing glass and partly with PV.

At roof level the pre-warmed air will be ducted horizontally to a number of new air handling plant ‘pods’, where it will be exhausted through an air-to-air heat exchanger. The fresh supply, taken in at roof level to minimise ambient pollution, therefore gains much of the energy from the facade, and can be further heated as required. New vertical shafts will transport the warm fresh air down to horizontal ducts over corridors (i.e. above existing suspended ceilings). Fresh air entering the corridor zone is then distributed to the office spaces on either side (through fanlight louvres, door grilles or directly in open plan areas); and then back into the solar chimney in the case of the south facade to George St.

Thus the serious thermal shortcomings have been met by a very simple hybrid passive-active system of ventilation in conjunction with insulative measures to the existing facade, in turn weather-protected and further insulated by the outer skin. The electricity produced by the BIPV panels will be used to run fans distributing preheated-air, for artificial lighting, and office appliances. Since the heat generated by the BIPV is captured, its hybrid winter efficiency in Glasgow should exceed 40% (Clarke, Johnstone and Strachan 1997). The risk of compromising daylight is met partly by glazing specification, partly by the reflective devices in conjunction with new ceilings, new luminaires and switching, and partly by better fine-tuning in term of control - e.g. modern venetian blinds within double-glazing. Indeed, while there is much more ‘active’ sophistication in terms of heating and ventilation, the user is also left with greater ‘adaptive opportunity’ (Baker and Standeven, 1995). Apart from new-found freedom to open windows, a refinement could be to include a vent below the radiator (in its present location).

Second skin construction - summer mode

The second skin construction is particularly well suited to solve overheating problem of the south elevation. In summer the rapid upward flow of ambient air will help to cool vertical PV modules (limiting reduction in their efficiency due to module high temperature) as well as the inner facade, before being exhausted at the top - large openings here will facilitate the increased flow rate compared with that in winter pre-heating mode. The refinement suggested at the end of the previous section will also allow air to enter offices having passed over ‘radiators’, now filled with cold water at around 12 C°.

The air in each office will be warmed by internal gains (people, computers, and lighting). As warmed, it will exit rooms through upper office windows into the accelerated solar chimney. Offices will still have a fresh supply of air through ambient air being sucked in to the air-handling unit, passed over cool-water coils and distributed as in winter via ducts in corridor ceilings. Sun shading in the form of reflective blinds mounted outside double glazed windows will serve to screen off unwanted solar gains and glare.

### 3.2 South Elevation (1963) - second skin construction

The east wing of the Graham Hills Building was built as an extension in 1963. It has the same structural grid, an open office plan, and suffers from the same environmental problems as the rest of the building. The architectural proposal to tackle existing problems includes integration of BIPV modules as a rainscreen over-cladding system on a solid south wall, over-cladding spandrel modules placed below windows, and a second skin construction in front of former single glazed windows as in 3.1 above.

The rainscreen PV system will have a ventilated cavity behind to eliminate potential for summer overheating. Here the application is not for PV hybrid (electrical-thermal) modules because of problems of linking generated heat with an air-handling unit. But, apart from generating electricity, the rainscreen PV modules will enhance the winter U-value level on the installation wall by radiating accumulated heat back to the wall behind.

The second skin construction will have parts with ‘translucent’ BIPV panels - i.e. where the modules are spaced out in the glass sandwich at such a density that they will provide some shade, while maintaining sufficient office daylight levels, and still generating useful electricity.

### South elevation (extension) - winter mode

This is in a sense a ‘dead-leg’ which invites a slight variant on the approach adopted for the south facade of the much larger 1957 part. In winter, the supply of air will now be directly pre-heated behind the second-skin glass. It will enter offices through low level openings below windows, and behind radiators, and due to stack-enhanced cross ventilation will enter the stair tower on the north side of the open plan office. The existing tower is at present partially enclosed and the proposal is that it be enclosed on all sides and its height extended. The height of the extended tower will move the neutral zone closer to the roofline and will create negative pressure at the top of the tower enhancing the vertical air movement. Thus there is heat recovery in a very basic form within the solar chimney, while conducted heat loss is again radically tackled. It is anticipated that the completely natural system of ventilation may result in somewhat higher heating loads compared with the main
building, but this would have to be offset against the capital saving in plant.

South elevation (extension) - summer mode

In summer, the natural ventilation system will shift from south to north (Fig. 6). The ambient north-side air will enter through window openings on the stair tower (controlled by the Building Management System) and will cross-ventilate to the south side of the offices. When reaching the solar chimney, it will exit through upper windows and move upwards via stack-effect and again exit through glazed rooftop openings. When relying on natural ventilation strategy, the expectation is that the passive system will provide sufficient air-change and a comfortable summer thermal environment in offices.

Fig. 6. South Elevation (Extension) – Summer Mode


3.3 Atria

As stated, the Graham Hills Building has three large light-wells or courtyards. There is a 3-sided court marking, but at present not celebrating, the main entrance from George St. Their appearance is dismal and rundown, providing an unpleasant sight to the offices which overlook them. It is proposed to cover the second and third of these light wells with glass construction and create attractive atria. These spaces will provide weather protection, improve thermal performance of offices in a similar way to the twin-skin south facade, this time with the opportunity for planting to oxygenate and freshen the air, and provide much needed amenities for staff and students. These amenities will be in a form of a space for social interaction, including a cafe, planting and water features.

The entrance atrium roof glazing will be covered with a combination of clear glass and translucent PV-glass modules to varying densities as used at the Academie Mont-Cenis in Herne, Germany (Kaltenbach, 1999), where PV densities varied from 58% to 86%. This will provide an appropriate degree of shade inside the atrium in summer, as well as an interesting play of light. It will also generate electricity which will be required for appliances, artificial lighting and mechanisms to open glazing. To further limit any potential problem of radiant overheating/discomfort, the atrium’s south oriented glazed wall will have a system of horizontal (perhaps automatically movable) louvres with integrated PV panels. The remodelled entrance area will have a positive impact on clarity of expression and position of the entrance. A part of two garage levels next to the main entrance will be converted into offices and/or cafe with galleries providing a view over the main entrance foyer. Reducing the car-park space is an environmental measure to reduce the number of cars used in urban areas (Local Agenda 21). The atrium floor will preserve the existing concrete material acting as a thermal mass with the addition of new hard finishes as appropriate.

The enclosed light-well will again be covered with a glass structure, serving as a weather protection and creating a ‘micro-climate’ for oriented offices. What is important to note is that the entrance atrium and the central atrium are linked by a wing of offices which will now overlook both. These offices will not then be exposed to outdoor weather and temperature conditions, and therefore, their heating and cooling requirements are expected to fall significantly.

As stated, the atria will function thermally in a very similar way to the twin-skin facade, with the exception that offices may now face south, east, west or north into an atrium. In winter, warm fresh air supplied to offices via the system of corridor ducts will leave via the host atrium, and convect upwards to the roof, with its temperature boosted by the sun in good weather, where it will be ducted to heat exchangers in the plant ‘pods’ as previously. The third floor pool offices below the floor of the atria constitute special cases. Again they will now receive a mechanical supply, and their existing roof-lights will be remodelled to serve as ‘solar-chimneys’ passing their vitiated air into atria.
In summer it will also be possible to take air from the atria into offices through lower window openings and to exit through upper window openings (Fig. 7). The glazed roofs will also have generous opening sections (controlled by the Building Management System) to exhaust warm air in summer, effectively enabling breezes inside the atria.

3.4 South facade of north-west wing

It is proposed that the south-oriented elevation of the office wing parallel to the front wing at its west end will have a solar protection strategy with a system of tilted, horizontal louvres covered with PV modules. This system would be mounted outside, close to windows to provide maximum shade in summer, while matching the sun angle for maximum PV output efficiency. It should create a powerful visual statement, but in terms of performance, variable shading may present problems.

3.5 Roof-mounted PV modules

The Graham Hill Building as a typical representative of early 1960s architecture which has a large flat roof area. This is suitable for installation of freestanding tilted roof mounted photovoltaic arrays. It is not necessary to penetrate the surface of the roof to attach the support structure, but the roof will require additional insulation. Arrays of PV modules will be mounted on roof areas of three office wings perpendicular to the front office wing. The location choice is because of existing outside stairs access (mounting and maintenance) and position of air-handling 'pods' which exclude other two flat roofs areas. Here, the BIPV is at its most basic, producing electricity only, with the only other positive environmental spin-off perhaps being the shading of the roof surface. Nevertheless, there is the great advantage that the roof is much less prone to shading, and the lack of other benefits at least reduces the number of interactive problems to be addressed.

3.6 Other energy efficiency and environmental measures

The "whole building approach" to reduce/solve environmental problems, apart from emphasis on BIPV systems as an integral part of this, naturally embraces other traditional energy conservation measures. For example, improvements on the north, east and west elevations will include over-insulating and over-cladding concrete panels and high-performance window replacement. This will address the problem of excessive...
heat loss occurring on this elevation, its rundown appearance and water penetration in cladding panels.

4. CONCLUSIONS

The simplest way to present conclusions at this stage is to pose questions within the framework of the underlying aim - i.e. do the opportunities for BIPV, within the terms of the interactive, environmental problem-solving 'drivers', outweigh the barriers? This question also implies reasonable load matching of supply and demand. It is also helpful to set this within the context of some 'ball-park' energy values. We have a value for existing consumption. A reasonable target would be to try to get the new net annual energy load (for gas and electricity purchased over and above that generated by PV) down to one-third of the present value or close to 80 kWh/m$^2$. At present it will not be possible to quantify the potential PV contribution except in the most rudimentary way, but at least this can bear a relationship to the overall picture. In addition one may postulate a tentative conclusion regarding the range of qualitative benefits and the role of BIPV in this respect.

- In terms of the principal question, it has been shown in the proposals described above that the opportunities do significantly outweigh barriers (ignoring capital cost). In addition there are significant opportunities for hybrid PV, or if not wholly hybrid as in the case of the twin-skin south facade, hybrid to the extent that there is some thermal benefit in addition to electrical generation - e.g. the rain-screen cladding. The barrier of intermittent shading by obstructions is not critical for this particular case study, except perhaps the proposed PV-louvres to the south facade of the north-west wing. Most of the applications are also able to make a positive visual contribution in addition to the functional ones, but this is moving on to qualitative attributes (Fig.8).

- In terms of quantity, if we give an annual value of 80 kWh/m$^2$ to electrical generation, just over 2,400 m$^2$ of PV would provide a total of 193,840 kWh or 18.4 kWh per m$^2$ floor area. In terms of the thermal contribution, based on work in Glasgow (Clarke, Johnstone and Strachan 1997), if we use a value of 40 kWh/m$^2$ in winter (November-February) and 100 kWh/m$^2$ in the autumn (September-October) and spring (March-May), nearly 1,600 m$^2$ hybrid PV will yield a total of 223,160 kWh or 21.2 kWh per m$^2$ floor area. The total predicted contribution of almost 40 kWh/m$^2$ floor area is then approximately one sixth of existing energy consumption.

- The range of qualitative benefits of the Graham Hills Building starts from an improved overall appearance. The second skin construction with integrated BIPV will enhance the aesthetic appearance of the building, improve environmental performance and should also introduce a new 'feel-good' factor for users with respect to their working environment. Greater personal control, physical comfort and visual quality will all be relevant in this respect. It will be a building representing the front of the University of Strathclyde property and the east gateway to city centre of Glasgow. Aside from personal workspace, the covered light-wells will be new 'green lungs' for the complex, providing a high-quality internal environment as well as saving energy. Their quality and attraction lies in their aesthetic and social potential, the atmosphere of well-being supported by the play of sunlight and shadow, good quality of air and so forth. If people start to associate the prominently visual PV with the improvements, and this brings in aspects such as individual perception and marketing, then it is reasonable to attribute at least some of the this qualitative gain to the PV.

REFERENCES


