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Comparative Performance of BAPV Systems in Scotland: 4 Case Studies with Differing Energy Contexts

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Abstract

The paper compares the performances of four building-added photovoltaic (BAPV) systems, one located in a North-East maritime location, one in a North-West maritime location and two in East Central Scotland. Each BAPV system will be described within the overall energy context of its host building, all with varying functions – a refurbished further education campus, a new-build community centre, bespoke new offices and an existing factory and company headquarters. The last two are concerned with solar branding, while the first two place BAPV discreetly within a wider energy strategy that exploits solar energy thermally by various means, some less directly than others. The paper confirms respectable outputs from each of the PV arrays, ranging from 705 to almost 900 kWh/kWp, but with varying output significance, partly due to PV array area and configuration range from 72 to 647 m^2, relative to the overall energy demand.

Keywords: BAPV comparative performance; Scottish case studies; solar thermal context.

1. Introduction

The comparative performance of building-added photovoltaic (BAPV) systems in Scotland seems self-explanatory, but 'differing energy contexts' require explanation. Of the four case studies assessed, two set their photovoltaic (PV) arrays within an overarching design strategy that exploits solar energy in a number of ways, essentially in terms of heat and light in such a way as to engender a holistic 'environmental architecture'. One of these buildings is a new-build community resource, Sporsnis in the township of Ness on the Island of Lewis, and the other a retrofit of a 1970s Further Education (FE) campus, Banff and Buchan College, in Fraserburgh, a northeast coastal fishing town. The complementary solar techniques used in addition to BAPV arrays include active solar thermal (Ness only), enhanced day-lighting, ground heat (heat pump at Ness and air-preheat labyrinth at Fraserburgh) and solar-assisted roof vents (Fraserburgh only). The BAPV and associated solar features are visually discreet in both cases (Figures 1a - b and 2a - b). In other words, a passer-by would be unable or unlikely to notice them. By contrast, the other two projects, new-build bespoke offices at Bilston to the south of Edinburgh and a retrofitted factory and company headquarters (HQ) in Inverkeithing, Fife, use the visual dominance of BAPV as part of their corporate promotion. They have fewer other features of renewable energy significance. However, the placing of BAPV at Bilston means that office windows face north and west, hence mitigating solar overheating (Figure 3); while existing roof-lighting at Inverkeithing regulated the location of the added BAPV arrays (Figure 4). Although Scotland is a relatively small country, with a temperate, marine-influenced climate, the four case studies also vary significantly in terms of their geographical context, and hence each has distinct climatic nuances.

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Figure 1a: External view of new-build community resource, Sporsnis, Ness, Isle of Lewis. Solar PV array, solar thermal and rooflights visible from higher ground near the site.

Figure 1b: Roof of new-build community resource, Sporsnis, Ness, Isle of Lewis, indicating building added PV, solar thermal and rooflights.

Figure 2a: External view of Banff and Buchan College, Fraserburgh. Solar installation not visible from ground level.

Figure 2b: Solar PV on the roof of Banff and Buchan College, Fraserburgh.

Figure 3: PV clad south facade at Survey Solutions Ltd., Bilston Glen, Loanhead, near Edinburgh – office windows on north and west façade shielded.

Figure 4: Building added PVs mounted either side of roof lights on roof of Muir Group HQ, Inverkeithing, Fife. Roofscape is visible from the road (position of the photographer).

2. Aim

a) To compare the PV performance in the varying building-added contexts of four case studies, each different building types in differing regional locations, by means of: firstly annual output in kWh/kWp; secondly in kWh/m^2 of net PV collection surface; thirdly, total annual output (kWh) relative to total electric demand (approximate demand in two of four cases).

b) To compare the overall energy contexts for the BAPV, elaborating on solar-thermal (some less direct than others) and day-lighting strategies in two of the case studies per Introduction.

c) To compare practical constructional issues associated with the BAPV arrays in each case.

d) To compare the functional and/or aesthetic intentions in each case, and discuss relative success of such intentions for each case study.

3. Technology and Design Intent

3.1. Sporsnis Ness Community Facility, Isle of Lewis by Anderson Associates Ltd, Stornoway

Sporsnis is a community-cum-sports centre, which has been grafted on to the existing Lionel primary and 2-year secondary school in Ness. The principal accommodation is a 27 x 18 m multi-purpose hall, the long axis aligned 10º south of due west and north of due east (approximately WSW to ENE), the ridge of its 26.6º pitched roof aligned in this direction so that its southerly face is oriented 10º east of due south. Also since the apex internally is some 11.0 m high, and the ridge of the parallel block of the existing school is approximately 2.7 m lower and 27 m to the south, the roof of the new hall is unshaded even at the winter solstice. Further, the roof slope is simply continued downwards to enclose a viewing gallery at first floor level and ancillary accommodation at ground level. Advantage has been taken of this form and alignment to mount 72.36 m^2 net area of PV panels on the SSE surface, as well as a smaller solar thermal array. The functional design strategy might appear to be somewhat compromised by a roof pitch that is 12º lower than normally recommended for optimising PV at this extreme UK location – 58.5ºN, but a high proportion of diffuse solar irradiation from the sky vault is relevant.

The solar installation comprises 60 BP Solar BP5170S 170 Wp (10.2 kWp total), high efficiency mono-crystalline modules, each with a net PV surface area, excluding frames, of 1.206 m^2. These are fixed to the upstand seams of a proprietary metal roofing system, thus enabling a cooling air circulation behind the panels. There are three Sunny Boy inverters. Monitored data was available for four years commencing 08/01/2008 (see 4. Results and Discussion). Although only visible from certain viewpoints higher up on the site, the solar PV array is visually integrated with two rows of roof-lights (the latter mirrored on the northerly face of the roof); one close to the apex of the hall, the other above the first floor gallery adding light to the hall via viewing windows (Figure 5). A bowling alley to the west of the hall is also naturally lit from above. This tactic both utilises the passive solar resource of daylight to displace electricity for artificial lighting, and provide a means of exhausting vitiated air (or smoke) naturally by combined thermal buoyancy and wind pressure (supplemented by two mechanical extracts). Another less direct exploitation of solar energy is the use of two ground source heat pumps for heating (solar energy having a delayed impact on ground temperature, which

Figure 5: Internal view of first floor gallery, roof lights provide daylighting to gallery and ground floor. The windows on the right allow borrowed daylight in to the main hall.

assists winter performance). The required electricity is partly resourced by the PV and partly by two 6 kW Proven wind generators sited to the north of the complex. The latter together have averaged over 24,000 kWh each year from January 2010 to January 2013 – more than two and half times more than the PV (see 4. Results and Discussion), with a symbiotic supply-demand relationship. Overall, the compact nature of the plan and sectional form adopted relative to the existing school has undoubtedly contributed to keeping the overall demand for space heating low, with the encircling ancillary accommodation effectively buffering the much larger volume of the main hall. Since many of the activities taking place inside are energetically vigorous in conformity with the project's mission strap-line 'building a healthy lifestyle for all', comfort air-temperatures will be relatively low and low-temperature radiant heating is an ideal source. Ground source heat pumps are not only well suited to such heating, their coefficient of performance (COP) inherently minimises the power required to meet the demand. Doing without mechanical ventilation or artificial cooling in all main spaces further limits power demand, as does the strategy for natural daylight. In other words the roles of solar energy – in its visually overt active and passive forms, plus its invisible ground-heat and indirectly as a wind force – together make a strong contribution to the social, environmental and economic sustainability of Sporsnis.

3.2. Banff and Buchan College, Fraserburgh, by Comprehensive Design Architects (CDA), Glasgow

An important aspect of the architectural result for CDA was to present a smart, 21st Century public image. This was done by stitching together a series of shabby, windswept 1960s-1970s buildings on an exposed northeast Scottish site with a new, sleek public façade; its impact heightened by a projecting canopy announcing the entry leg of a T-shaped and light-filled atrium. The Solyndra 100 PV array is neatly concealed on top of the roof of this due north-south leg. It is a completely new concept, with 15 mm diameter tubes of thin-film PV round the entire circumference, contained in 20 mm diameter horizontal glass tubes aligned north-south in 101 racks, with 40 tubes per rack and mounted above a reflective flat roof. In addition to invisibility from ground level, the roof membrane is not pierced by fixings – the PV offers so little wind resistance gravity is adequate to hold the racks in place. This is clearly a major advantage, especially for retrofits of flat-roofed buildings, and offsets the less than optimal geometry of the PV collecting surface and some overshading by high parts of adjacent accommodation. Indeed, the departure from a flat surface that is optimally oriented and tilted seems to defy functionalism. However, in Scotland, much of the useful radiation falling on collector surfaces is in any case diffuse, and, seen literally in this light, the idea of maximising reflected irradiation from the roof surface has a logic. Such logic would nevertheless make the task of calculating the peak capacity significantly harder than normal. However computed, the Solyndra installation was intimated to the architect and client at 20.2 kWp with a predicted annual output of 16,000 kWh or 792 kWh/kWp at design stage (see 4. Results and Discussion).

There are two other notable renewable energy systems. Firstly, small integrated PV cells on roof-mounted wind catchers automatically operate an exhaust fan above motorised control dampers if the air quality in deep-plan rooms below without openable windows falls below a satisfactory level. For example, this might occur in calm, sunny weather, when the combination of thermal buoyancy and wind pressure is inadequate to exhaust enough air naturally. Typically, one catcher serves a 25-person training room. Secondly, a less direct solar application is using the energy absorbed at a 1.5 m depth in the ground to temper a 16,000 m^3/h supply to the large volume of the atrium. This is a Rehau Awadukt 42 x 30 m underground labyrinth 'thermo-grid' ground-to-air heat exchanger, with the inlet some distance away across a playing field. It is designed to pre-warm outside air by up to 9 K (ºC) in cold weather and cool by as much as 14 K in warm weather. Although the fresh air is introduced to the atrium with the help of a fan, it leaves naturally via high-level windows opened by electric actuators. As a consequence of this dual solar-assisted ventilation strategy, there is very little reliance on artificial cooling within the entire complex. What is very visible, and critical to the viability of this substantial upgrade, is the light-filled atrium. In particular, the air quality in the atrium with its continuously fresh air supply system was perceptually excellent, as was the quality of natural light provided by a fairly modest area of fenestration. Although its preheated/precooled air system and artificial lighting are environmentally superior, this floor-heated college hub (Figure 6a) nevertheless bears comparison with the overtly functional activity space at Sporsnis (Figure 6b). And although the PV array's output is small relative to the inherently large electricity loads of machines and catering in this a vocational facility, its innovative potential is high and can certainly make a useful contribution in relation to smaller electrical loads within the control of the architect. For example, the artificial lighting in the atrium is carefully designed to maximise reflected light from the ceiling as is the natural daylight.

Figure 6a: Internal view of Banff and Buchan College, daylit using high level clerestory (right of image) and glazed façade.

Figure 6b: Internal view of the main hall at Sporsnis. Borrowed daylight from the first floor gallery enters the hall through high level glazing (left of image). While the roof lights allow natural daylight. (The daylight sensing for the artificial lighting system was still to be commissioned at the time of the photograph).

3.3 Survey Solutions Ltd, Bilston Glen, Loanhead, Midlothian by JGM Engineers/Sustainable Renewable Technologies (now JGM Renewable & Energy Solutions Ltd.)

At Bilston, the image for this commercial building within an industrial estate is bound up with the formal potency of the pyramid (with its metaphysical associations). The entry and two vertically fenestrated office façades are carved out of the northwest quadrant, and the PV an overt visual message, cladding the entire sloping equilateral triangular façades orientated east and south – simultaneously converting the sun's energy to electricity and avoiding solar overheating of both the PV and the interior on these two elevations. Together, the pyramidal form and its highly visible PV cladding provide a strong branding message. The removed northwest quadrant then allows vertical triangular fenestration, one facet to the north and the other west, but partially self-shaded, while the remaining triangles of sloping roof covering to north and west (each one eighth of the total pyramid) are opaque.

To assist in the efficiency of the panels themselves, they are mounted above trapezoidal metal cladding, with air circulating upwards in the space within the troughs behind the PV. A practical problem with this geometry was that all triangular panels adjacent to the ridges had to be blank, since it was not possible to cut toughened-glass PV panels. A 'cherry-picker' was used to facilitate fixing of the panels, using special 'Metasol' aluminium clamps, overall quite a challenging construction process given the geometry of the building. The number of full panels, JT250 SBb mono-crystalline panels by Jetion Solar, is 192, each with a net PV surface area within the frames of 1.559 m^2, totaling 299 m^2. Four Danfoss inverters were used, giving a proportion of 48 panels per inverter. The roof pitch according to elevations drawn up at the time of building is approximately 50º from horizontal, thus steeper than ideal for due south for PV at this location at 56N latitude, as well as for the east-facing surface (Page and Lebens, 1986; Thomas, 2001). The total annual predicted electrical output at design stage was over 41,000 kWh, with a total capacity estimated as 48.25 kWp. However, this was based on 193 panels, rather than the 192 installed, each at 0.25 kWp. The system was commissioned by 1st August 2012.

3.4 Muir Group HQ, Inverkeithing

In this last case study, there is, as at Bilston, an issue of overt visibility of the PV arrays in order to convey a company message. But in this case there is also no architectural form-making involved, the placing of the panels following a completely commonsense rational approach. Here 400 Hyundai mono-crystalline type 1 panels are mounted in 20 arrays, each with 20 panels, in between strips of existing translucent corrugated roofing that help to illuminate the main factory space of the Muir Group's complex. The southern-tilt is relatively shallow at approximately 22.5º, with orientation approximately 4.5º east of due south. There is some winter shading from woodland to the southwest on ground that rises above the main road, from the verge of which it is possible to look down on to the roofscape of the factory. In this case the arrays are mounted on horizontal rails fixed to the projecting trapezoidal seams of the existing industrial metal roofing, hence providing similar ventilation behind the panels to those in Ness and Bilston. Each panel is 250 Wp, providing a total of 100 kWp and a net PV surface area of 646.8 m^2. The Muir Group's straightforward system has a single Eltec inverter (cf. four Danfoss inverters at Bilston and one at Fraserburgh). As much as possible of the electricity generated is used directly in the factory, where electrical demand is normally considerably greater than maximum output from the PV, with an average of approximately one sixth contribution to demand expected over a year.

4. Results and Discussion

This section addresses each of the aims. Key data is summarized in Table 1 below:

Table 1: Summary of PV Performance Data for Four Case Studies

Project	Latitude (°N)	PV Type	Capacity (kWp)	PV Area* (m^2)	Annual Yield (kWh/kWp)	Annual Yield (kWh/m^2 PV)
Sporsnis, Ness, Isle of Lewis	58.5	BP Solar BP5170S	10.20	72.4	893	126
Banff and Buchan College, Fraserburgh	57.7	Solyndra	20.20 18.38	189.6	836 918	90
Survey Solutions HQ, Bilston, Loanhead	55.9	Jetion JT250 SBb mono-crystalline	48.00	299.0	741	119
Weir Group HQ, Inverkeithing, Fife	56.0	Hyundai mono-crystalline type 1	100.00	646.8	705	109

*Net surface area of photovoltaic cells within enclosing frame.

The output results in Table 1 require further explanation. The output for Sporsnis, Ness, is based on the annual average of four years data from January 2008 to January 2012 (9,109 kWh) ranging from 9,240 to 8,932 kWh. The equivalent annual output at Banff and Buchan College in Fraserburgh, is based on 18 months data from March 2011 to September 2012, totaling 27,133 kWh. Unfortunately the total after one year was not available, and therefore an annual estimate has been found by multiplying the 18-month total by 0.622; this factor based on theoretical monthly incident irradiation on a horizontal plane in Aberdeen (Page and Lebens, 1986). The resultant 12-month figure of 16,877 kWh is comfortably, but not unreasonably, above the predicted yield of circa 16,000 kWh. Then, there are two figures given for peak capacity, 20.20 kWp based on the total of 101 racks at 200 Wp per rack of 40 tubes approximately 1.0 m long, this figure provided to the client by the installers; and 18.38 kWp based on a laboratory measured value of 182 Wp for a single rack (Spitalny et al, 2013). The standard conditions described in the latter case are radiation of 1,000 W/m^2, a cell temperature of 25ºC, with copper-indium-gallium-diselenide (CIGS) thin-film covered Solyndra tubes mounted above a white polymer layer; CIGS a specific variant of the more generic CIS (Weller et al, 2010). The inner, thin-film covered tubes were measured on site at Fraserburgh – diameter 15 mm and net length of each tube 996 mm. A highly reflective membrane was also tested by Spitalny et al and found to increase efficiency by 9.8% over a 9-month period. If one assumes this percentage improvement were to be maintained over a full year, it would increase the peak capacity to approximately 200 Wp. However, the reflective 'Solar White Sarnafil G410-20ELF' membrane used at Banff and Buchan may not match the 'Zeffle' product used in Spitalny et al's experimental set-up; and, whichever value is used for peak capacity, the resultant annual output in kWh expressed per kWp is proportionately significantly greater than that per m^2 of net PV collection surface compared with the other three case studies. To complete the set, The Survey Solutions HQ at Bilston, uses measured data from 31st July, 2012, to 5th August 2013, with a downward adjustment made for the extra 5 days to give a total of 35,557 kWh; and that for the Muir Group HQ in Inverkeithing is for a single year measured from 13th July 2011, 70,500 kWh, this reportedly meeting 95% of the expected output.

Although annual kWh/kWp values are commonly used as a performance indicator, the set of values in column 6, Table 1, demonstrate that they can be deceptive, with the juxtaposition relative to that in column 7 for kWh/m^2 in the case of Banff and Buchan appearing anomalous. However, if peak capacity is divided by net PV area (column 4/column 5), the values for Banff and Buchan of 106.5 or 96.9 Wp/m^2, like the kWh/m^2 ratio (column 7), are significantly lower than the other three case studies: In other words, although the Solyndra system, which is no longer available in the marketplace, offered distinct advantages for flat-roof installations in that no fixings were required through the waterproof membrane, its yield per unit surface area of thin-film PV is significantly lower than for flat, high-performance, crystalline panels. In the latter group of case studies, it is also of note that the highest performing system was at the highest latitude (58.5°N). This appears to confound expectation in a similar way to that found for solar heating (Porteous and MacGregor, 2005), but the high latitude provides long summer days, and the marine location will boost albedo to an often diffusely radiating sky vault, this favoured by the relatively low pitch with zero over-shading from obstructions. At the very least it indicates that solar collection by means of BAPV is not a lost cause in Scotland. However, in absolute terms, with smallest array of the set of four buildings, it had the lowest output at 9,109 kWh, while the factory, with a certain amount of over-shading at 56°N and 100 kWp, has highest at 70,500 kWh. The latter was still only some 16% of the industrial electrical demand, while the total at the FE campus (57.7°N), 16, 877 kWh is a token 1.4% of a very high overall demand of over 1,200 MWh (80.5 kWh/m^2 floor area), this reflecting heavy duty electrical equipment at the college. On the other hand, this modest contribution may be meeting a large proportion of the loads attributable to the new atrium.

Table 2 includes additional columns compared with Table 1, indicating further variance in ranking of performance. Firstly, expressing the peak capacity per unit area of PV, Banff and Buchan College's Solyndra system is now ranked last as in the final column of Table 1 (see also previous paragraph). However, the ranking between Sporsnis, Survey Solutions and the Weir Group is different compared with the Annual Yield (kWh) per unit area of PV (last column, Table 1). Secondly, the data in Table 2 uses a performance ratio (PR) for comparison of each of the PV arrays. The reference yield defines the theoretical electrical energy production for each array specific to its location, orientation and tilt where the total in-plane irradiance (calculated using PVGIS) is divided by a reference irradiance of 1 kW/m^2 (IEC, 1998). Dividing the actual PV system yield by the reference yield gives the PR to allow comparison of system performance (Marion et al, 2005). This method of analysis indicates the Solyndra system fares better with an average rating of 0.72-0.79. The PV system at Sporsnis has an excellent PR of 0.92 despite its northerly latitude; and the PV system covering two façades on the pyramid office building was found to have a poorer PR of 0.51; the lowest of the four case studies. Although the actual yields were derived from different reference years, the comparative results highlight an inconsistency with system performance using two different PV performance indicator methods; thus supporting the requirement for development of a consistent performance parameter for comparing PV systems (Marion et al, 2005).

Table 2: Summary of PV Performance for Four Case Studies

Project	Capacity (Wp/m^2)	Annual Yield (kWh/a)	PV System Yield (kWh/kWp)	Reference Yield* (kWh/kWp)	Performance Ratio
Sporsnis, Ness, Isle of Lewis	140.9	9,109	893	968	0.92
Banff and Buchan College, Fraserburgh	106.5	16,877	836	1160	0.72
	96.9	16,877	918	1160	0.79
Survey Solutions HQ, Bilston, Loanhead	160.5	35,557	741	1440	0.51
Weir Group HQ, Inverkeithing, Fife	154.6	70,500	705	993	0.71

*Irradiance figures derived using Photovoltaic Geographical Information System (PVGIS) website (European Commission, 2001-2012).

It is evident from above that energy contexts between the case studies are highly variable. While associated solar techniques such as displacement of electrical lighting loads by day-lighting, pre-heating and pre-cooling of air by means of solar tempered labyrinths, and so forth, may be considered as an intrinsic part of good passive architectural design, applications of BAPV are inherently more controversial. Are they investments, advertisements of an ethos, research experiments or a means of offsetting a significant proportion of electrical demand? All of the above motives may come into play at different levels of priority for clients in these cases, while, for architects, visibility is a key issue.

5. Conclusions

In general, the BAPV in the four different typological case studies, indicated creditable performance. Although market forces intervened negatively, the lowest ranked and most novel application of Solyndra thin-film CIGS applied to tubes in racks above a reflective membrane could theoretically have had commercial advantage due to the lack of need for mechanical fixings. Results also indicate that the ratio of peak capacity to PV surface area, together with electrical output in kWh per unit of PV surface area, are more reliable as performance indicators than kWh/kWp and PR. The varying attitudes to solar visibility and to BAPV inclusion within wider environmental design thinking are also noteworthy and indicative of strong architectural diversity within a renewable energy spectrum.

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