Cladding strategies for building-integrated photovoltaics

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Photovoltaic cladding on the surfaces of commercial buildings has the potential for considerable reductions in carbon emissions due to embedded renewable power generation displacing conventional power utilization. In this paper, a model is described for the optimization of photovoltaic cladding densities on commercial building surfaces. The model uses a modified form of the 'fill factor' method for photovoltaic power supply coupled to new regression-based procedures for power demand estimation. An optimization is included based on a defined 'mean index of satisfaction' for matched power supply and demand (i.e., zero power exportation to the grid). The mean index of satisfaction directly translates to the reduction in carbon emission that might be expected over conventional power use. On clear days throughout the year, reductions of conventional power use of at least 60% can be achieved with an optimum cladding pattern targeted to lighting and small power load demands.

1 Introduction

The total potential resource of building-integrated photovoltaic (BIPV) generating capacity for the UK has been estimated by to be 63 GW.[1] Results from UK monitoring of a south-facing tilted array of BIPV suggests an annual mean power yield of 69.3 kWh of sustainable electricity per square metre of module surface – equivalent to a reduction in carbon emission of 9.84 kg per square metre of module surface annually. As a consequence, BIPV and other forms of renewable embedded power generation are at the forefront of moves towards electricity infrastructure migration seeking to cut greenhouse gas emissions and reduce global warming.

A central idea with BIPV is to integrate the photovoltaic modules within the building fenestration so as to form part of the rainscreen cladding. Accordingly, modules are tilted with respect to the vertical in order to maximize solar collection. General 'rules of thumb' of ideal surface orientation for maximizing the available direct irradiance have been outlined by Duffie and Beckman.[2] For maximum annual energy availability, the tilt angle of the PV array should be equal to the latitude (10° to 15° greater or lower than this for maximum winter and summer availability respectively). The azimuth angle for the northern hemisphere should be 0° (i.e., facing south), with deviations of 20° to 30° east or west having little effect on the availability.

Windows and other external wall features make a proportion of the wall area unsuitable for PV cladding. According to the Building Regulations for England and Wales,[3] the basic allowance of area for windows and doors is 40% of the total exposed wall area for an office-type building. Also, the frontal surface dimensions of most types of PV module currently manufac-

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tured are roughly 1 m by 0.5 m,[4] which influences the precise cladding pattern achievable.

As to power utilization, the low power yields available from BIPV are entirely consistent with embedded generation rather than cogeneration. At best, export power yields are likely to be very low and sporadic and therefore uneconomic in the short and medium term, though this situation may change in the future. Thus a BIPV cladding strategy needs to place constraints on the extent to which a building's surfaces can physically be clad and the maximum power yield to avoid excess power generation. The latter depends on the time-varying pattern of power demand of the subject building and the corresponding BIPV output from treated surfaces. Previous work has looked at specific case examples of matching power demand and array output.[5,6] In this work, a model of building power demand is combined with an array model to provide a general approach for BIPV load matching. A simple optimization method is included to ensure correct matching of array size with power demand, such that surface cladding densities are within practically realizable criteria and power exportation is avoided.

2 Description of a building template

As a template, this work is based on the Northumberland Building in Newcastle upon Tyne,[7] which has a 39.5 kWp nominally south facing BIPV array. The essential particulars of this building are similar to many commercial style buildings of this scale (i.e., power demand characteristics, floor-to-wall geometry, exposure), so that results based on observations from this building are expected to have some degree of generality. On the glazed south face of the Northumberland Building, there are actually 93 modules per storey (5 storeys). However, there are other surfaces on this building that could potentially support BIPV treatment and thus the algorithm proposed here has been developed with a view to all surfaces that could practically be clad but uses the Northumberland Building as a basic structural template. On the shorter and mostly unglazed east/west faces of this building, there are areas available for cladding. This is estimated at 80% of the total surface area, allowing for support structure, maintenance access and wall features. Thus 68 modules per storey may be fitted on the shorter face. This results in a potential proportion of module area to total wall area for the entire building of 37%. This value is reasonable considering the basic glazing allowance of 40% governed by the Building Regulations, leaving approximately 20% 'spare' for reveals, structural elements, etc. It is assumed that no extra module surface area is gained by tilting the cladding modules, as any proportional increase in surface area is offset by the increased requirement for support structure.

To allow for comparison between the months, all array tilt angels in this study are set at 55°, the latitude of the Northumberland Building. This is assumed to experience minimal self shading as analysis of the Northumberland Building array, which has a tilt angle of 65°, has revealed that self shading is a minor effect only experienced in June.[8]

The flat roof area of the building provides a further target surface which, after allowing for structural features, etc, could potentially host up to 1140 modules. Roof arrays are all inclined horizontally, in order to maximize usage of space and minimize shading. North facing building surfaces in the northern hemisphere also form theoretical targets, though power yields from these surfaces will be low.

3 Optimization parameters

The proportion of daily power demand which is supplied by a PV array is expressed by a mean value referred to here as the mean percentage index of satisfaction, $\bar{S}$. The load matching model (described later) is based on regression fitting to 15-min power data over a standard working day period of 09:00–17:00 (a time series of 33 data sets). The mean index of satisfaction can thus be defined as follows for these conditions:

$$\bar{S} = \frac{1}{33} \times \sum_{n=1}^{n=33} [P_o(n)/P_d(n)] \qquad (1)$$

(where $P_o(n)$, $P_d(n)$ are the overall PV power output (kW) and building power demand (kW) at the n^{th} time instant respectively).

The optimum configuration is defined as the configuration which provides the maximum mean index of satisfaction over the working day, with zero net power output at all times (i.e., $P_o(n) \leq P_d(n)$, for all n) to the grid on a day of typical clear day irradiance conditions for the time of year. Identification of the optimum configuration is achieved by incrementally increasing the amount of modules on each surface. The building surfaces are clad in order of maximum year-round solar availability given the practical mounting angles identified previously: south surface, roof, east surface, west surface and north surface.

A preliminary analysis has shown that selected clear days in May, July and November give a reasonable spread of solar irradiances that lead to a well-defined summary of annual performance.[9] The tilt angles for maximum array energy output during clear days in these months have been observed at 45°, 25° and 85° respectively which are reasonably spread about the site latitude angle as might be expected.[2]

Thus the optimization objective function for economic PV cladding is defined as the mean index of satisfaction, $\bar{S}$, and the constraints are:

- $P_o(n) \leq P_d(n), \forall_n$
- Available cladding surface areas (south/roof/east/west/north).

4 Modelling

4.1 Supply side

The supply-side model is based on an adaptation of the photovoltaic fill factor approach leading to the total power output for a surface array, j, at time instant, n ($P_{o,j}(n)$):

$$P_{o,j}(n) = N_{m,j} K C_{FF} E_j(n) \ln[kE_j(n)]/T_{m,j}(n) \qquad (2)$$

where:

- $N_{m,j}$ number of modules forming the j^{th} surface array
- K an empirical constant
- C_{FF} fill factor model constant (Km^2)
- E_j total solar irradiance at the n^{th} time instant on the surface-normal of the j^{th} array (Wm^{-2})
- k fill factor model constant (m^2W^{-1})
- $T_{m,j}(n)$ mean module temperature at the n^{th} time instant of the j^{th} surface array (K)

The fill factor model constants used in the present work were based on the characteristics of the Saturn modules used on the Northumberland Building, the values being $C_{FF} = 1.22$ Km^2 and $k = 10^6$ m^2W^{-1}. The empirical constant, K, for the Northumberland Building array was ascribed that value which brought the model results to within measurement uncertainty. This value was 0.8 and has been used in all results reported here. Further details of the array model can be found in Jones and Underwood.[10,11]

4.2 Demand side

An investigation into category-specific demand side modelling based on ARIMA time-series analysis, least-squares regression fitting to single day demand cycles, and least-squares regression fitting to half-day demand cycles concluded that the latter method gave most representative modelling predictions of power demand for lighting and small power. For machinery, HVAC and other power loads, a constant effective mean fit was found to be most representative. Further details can be found in Jones.[9]

Thus, the normalized power demand at the n^{th} time instant in the half-day cycle and for the appropriate category of power (i.e. lighting or small power), $P'_{d,cat}(n)$, will be:

$$P'_{d,cat}(n) = A_o + A_1 n + A_2 n^2 + \epsilon(n) \qquad (3)$$

where A_o, A_1, A_2 are fitting constants to the observed data and $\epsilon(n)$ is an error term.

Typical values of the constants for both lighting and small power were found to be $0.25 < A_o < 1.0$; $-0.01 < A_1 < 0.1$; $-0.0035 < A_2 < 0$. The applicable model for machinery is of the same form but with A_1, A_2 set at zero. Best-fit models were found to have regression standard deviations that were in general comparable or less than measurement uncertainty (normalized measurement uncertainty being 0.035 for lighting, 0.038 for small power and 0.038 for machinery). Thus $\epsilon(n)$ was modelled as a normally distributed random error with zero mean and a standard deviation set at the appropriate normalized measurement uncertainty for the power category of interest.

4.3 Optimization procedure

The procedure for identifying the optimum configuration is shown in simplified flowchart form in Figure 1.

The initial configuration defined is a commonsense underestimation (i.e., south facade half-clad) for a single storey building. The output power to grid will be zero for an under-clad building, the number of modules is incrementally increased until the configuration is found to create excess power to the grid. Once one surface reaches its full capacity of modules (93 per storey, south face; 1140 roof; 68 per storey east and west), cladding of the next surface is begun. The number of modules on each surface is increased from zero until the optimum configuration is identified. The incremental increase is decreased when the procedure has located the approximate optimum size to obtain precision of module numbers in the optimum configuration, to within an accuracy of 2 modules (smaller configurations) or 10 modules (larger configurations). If cladding the entire building is not sufficient to generate excess power, the number of south facing modules is increased until a hyopthecated optimum is identified.

5 Results and discussion

The profile of the optimum configuration power output will fill the maximum amount of area beneath, whilst never exceeding, the power demand profile. Sample results are illustrated in Figures 2–4, based on the profiles for a single storey building's lighting demand for the representative three months considered. It is important to note the variation of power demand magnitudes between months. The lighting and total power demand profiles share the double curved shape. The differences in the array output profiles of the individual clear days are obvious. The detail of the smooth or jagged output curves are due to differences in the climate character of the individual days, differences which are not unique to any particular month. Only the overall magnitude of the power demand and time of sunset are attributable to individual months.

The results of the optimizations are summarized in Tables 1–3 for May, July and November data respectively. For each configuration, the two columns show the index of satisfaction achieved and the optimum configuration. The configurations, as previously, are described in terms of the number of modules on each surface with the target surface order being south, roof, east, west and north (denoted S/R/E/W/N). In cases when all target areas have been clad, a hypothecated excess number of modules is added to the south face array in order to illustrate the additional cladding needed to reach optimum cladding within the other constraints defined.

The increase in storeys increases the lighting and office power demands proportionally, in turn requiring proportional increases of modules for the optimum configurations. In May and July, office power demand is met by south facade cladding only. The lighting optimum configuration is similar, except roof modules are required to meet the demand in May. In November, more modules are required; for the ten storey building all roof space is used, and extra modules are required on the east facade to satisfy the lighting power demand. The maximum indices of satisfaction obtained lie between 59% and 77%. The

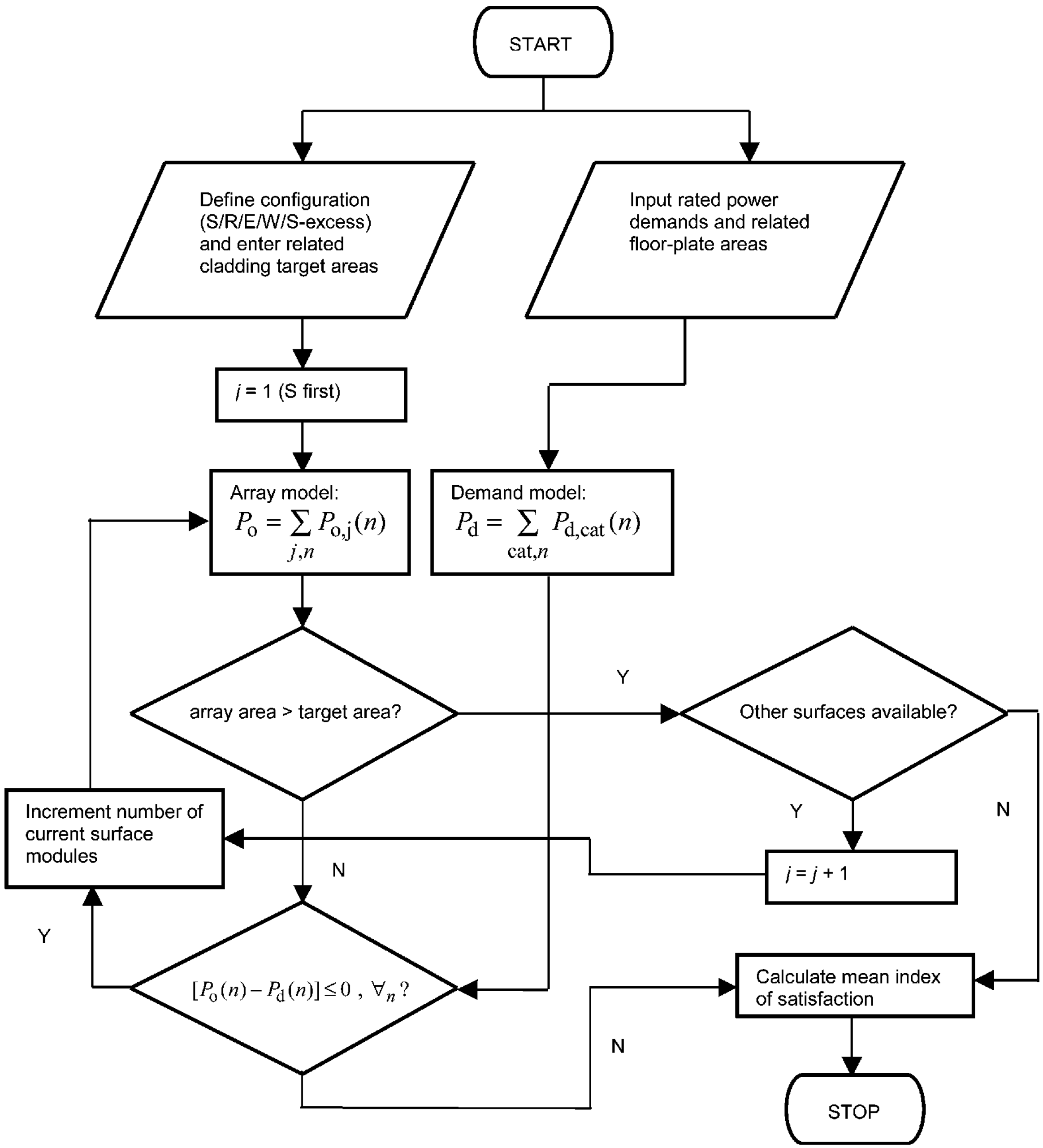

Figure 1 Flowchart of the optimization procedure

final two columns in each table show the optimum configuration to power the entire building. In November, all available surfaces are clad and excess south facing modules are required for all building sizes: around 400 modules for a single storey building, 1000 for five storeys and 1500 for ten storeys. This could only be achieved by a PV installation in addition to the fully clad

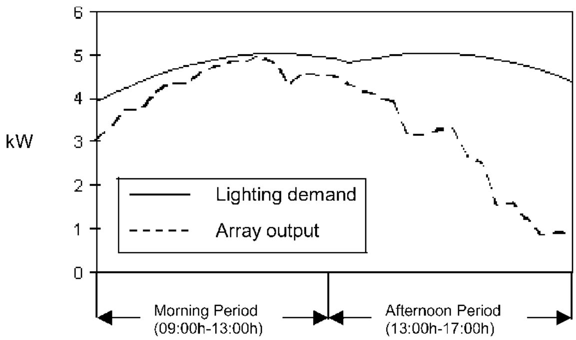

Figure 2 Load matching of optimum configuration for lighting (single storey building in May)

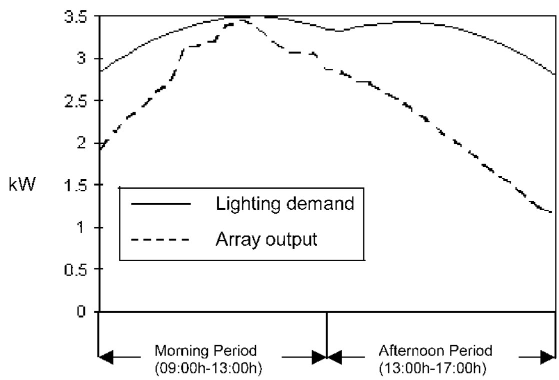

Figure 3 Load matching of optimum configuration for lighting (single storey building in July)

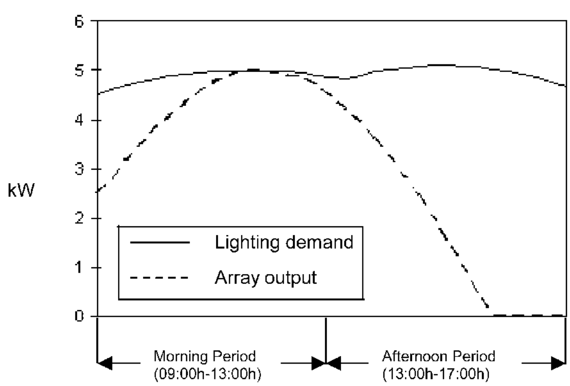

Figure 4 Load matching of optimum configuration for lighting (single storey building in Nov)

building. By contrast, in July the reduced total demand can be met by cladding only the south face and roof. In May, intermediate sized configurations are required optimizing the array for the total power demand, leaving only the north face unclad on the five and ten storey buildings.

The differences in the value of the optimum index of satisfaction are due to the change in shape of the PV profile of the individual days already observed. The May output appears to favour the flatter profiles of lighting and total power demand, whereas the November output favours the more curved office power demand. However, overall indices are reduced in November due to the earlier sunset time. The combination of high demand and lower irradiance in November means more surface requiring cladding, to the extent of requiring additional surfaces beyond the building. This is strikingly clear in the total power demand column for November.

6 Conclusions

It has been shown that for an unshaded building of up to ten storeys, office and lighting power demands individually can easily be met on clear days by photovoltaic cladding at least the south face and roof. The magnitude of lighting and office power demands, apart from the slight variation with the seasons, are at an appropriate level for efficient targeting of PV power by cladding only the surfaces that receive the greatest irradiance: the south face and the roof. There is not enough area to construct optimum configurations for total power demands during the winter period. The optimum configurations for the May and July periods may be achieved by cladding the surfaces available, although May demands do require cladding those areas that receive lower irradiance.

In this study, the optimum configurations for particular times of the year have been identified. However, the angle of tilt has been set as equal to the latitude, the ideal angle for maximum annual energy conversion, 55° in this case. With this restriction on tilt angle, it is possible to define the annual optimum configuration as the

Table 1 Optimum configurations for May working days

No. of storeys	Lighting		Office		Total power demand	
	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N
1	72%	93/9/0/0/0	60%	82/0/0/0/0	76%	93/850/0/0/0
5	72%	465/45/0/0/0	60%	410/0/0/0/0	76%	465/1140/ 340/204/0
10	72%	930/90/0/0/0	60%	820/0/0/0/0	73%	930/1140/ 680/630/0/0

Table 2 Optimum configurations for July working days

No. of storeys	Lighting		Office		Total power demand	
	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N
1	75%	64/0/0/0/0	75%	55/0/0/0/0	77%	93/550/0/0/0
5	75%	320/0/0/0/0	75%	275/0/0/0/0	77%	465/10/0/00
10	75%	640/0/0/0/0	75%	550/0/0/0/0	77%	930/860/0/00 680/630/0/0

Table 3 Optimum configurations for November working days

No. of storeys	Lighting		Office		Total power demand	
	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N	Optimum index of satisfaction	Optimum configuration S/R/E/W/N
1	60%	93/116/0/0/0	65%	93/116/0/0/0	59%	480/1140/68/ 68/93
5	60%	465/580/0/ 0/0	65%	475/580/0/ 0/0	63%	1480/1140/ 340/340/465
10	60%	930/1140/30/ 0/0	65%	930/1140/20/ 0/0	65%	2580/1140/ 680/680/930

configuration that achieves the maximum index of satisfaction on a clear day during the period of the year for which the ideal tilt angle is equal to the latitude. In this case, May is the month with ideal angle closest to 55°. Thus the optimum configurations for May are additionally the annual optimum configurations for the buildings described. The annual optimum configuration may be achieved by all three building types for all building demands, without cladding the north side of the building (Table 3).

Many other optimization scenarios might be envisaged, for example changing the building shape, variable tilt configurations, calculation of net total energy to grid rather than gross total energy, adding additional local power sources, power storage and so on. These form possible areas of further work.

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