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Compensation for differential energy balance across a building incorporating solar energy systems

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ABSTRACT

In order to compensate for imbalance in solar energy between different sides of a building, and the resultant difference in energy availability and (heating/cooling) demand, methods using offsetting were developed to adjust occupiers' energy bills. In the case of solar electricity generation, a model was considered, in which all the power is routed through common meter(s), so that total electricity generated is recorded. Equal proportions of this metered energy can then be deducted from occupiers' individual meter readings, to give the net energy use for which each user is billed. Computer-based models were used to calculate the imbalance on those energy demands, which are affected by solar gain, i.e., space heating and cooling. The offset was calculated, such that all users pay the same bill for a given thermostat setting, and are charged more or less, for settings which result in higher or lower energy consumption respectively. Several case studies were performed, in which one building parameter was changed between successive trials. It was found that the offset was different in each case. Therefore, it is necessary to calculate the offset separately for each location, and for each building, depending on those parameters related to solar and thermal energy exchange.

1. Introduction

When a building is exposed to direct sunlight, the solar radiation is incident on one or two faces at any one time. Where solar energy forms a major component of the energy balance, this results in an imbalance in supply (where solar panels are used) and demand (heating and/or air conditioning requirements) from one side of the building to the other [1]. In a building with one owner/occupant, balancing the energy across the building can be achieved by technical measures alone [2]. However, in a multiple-occupancy building, such as a block of flats or a commercial building housing a number of small businesses, offsets can be implemented in the metering of energy use, in order to compensate for the relative advantages of those premises which have better availability of solar energy, and/or lower heating or cooling demands, as a result of differences in solar gain.

In order to increase the total area of solar collectors, many designs include wall-mounted panels or full-height façades, in addition to rooftop arrays [1,3]. In built-up areas, lower storeys may be shaded by neighbouring buildings [4,5]. Buildings in various environments may be partly shaded by trees [6]. Upper storeys may be totally unshaded, or shaded for shorter periods of time. Thus premises on upper storeys have a higher level of solar availability, and a lower heating demand or higher cooling demand, compared to premises on lower storeys. An offset is thus required, similar to that between different sides of the building.

The imbalance in solar electricity generation requires that electricity is transferred from one side of the building to the other. By routing the power cables through meters, the power generated by the solar panels can be measured, and used to calculate the quantity of electrical energy to be deducted from each owner/occupier's meter reading, and adjust the bill accordingly.

Calculating offsets, to compensate for differential solar gain from one side of the building to the other, is more complicated. Heating demand is lower, and cooling demand is higher, for the side of the building exposed to solar radiation. The extent of the imbalance, and hence the offset required, depends on local climate, the solar gain properties of the building (wall colour, window area and reflectivity, etc.) and daily cycles of occupancy. Thus case studies are performed for a range of locations, and for a number of building types (parameters as given above) for each location. The difference in energy demand is calculated over daily and seasonal cycles, to determine an offset, which compensates for the relative advantage for each side of the building, integrated over a complete annual cycle.

The mechanisms for calculating energy bills should encourage efficient use of energy, and this principle should be extended to the offsetting measures.

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Nomenclature

A_k	area of envelope component
E_{bill}	energy on which periodic bill is based
E_{CS}	energy used by communal services during billing period
$E_{FuelBill}$	energy on which fuel bill is based (generator use during loss of supply)
E_{Solar}	energy generated by solar arrays during billing period
h_0	(convective + radiative) heat transfer coefficient
I	solar radiation (direct + diffuse)
I_{gnd}	thermal re-emission from ground
I_{sky}	thermal emission from sky (atmosphere)
P_{CS}	power used by communal services
P_{flat}	power used by each flat
P_{Solar}	power generated by solar arrays
$P_{Utility}$	power supplied by utility
$\dot{Q}_{SG}$	(direct) solar gain
T_i	interior air temperature
T_0	exterior air temperature
T_{SA}	sol–air temperature
U_k	heat transfer coefficient (U-value) of envelope component – wall, window, etc.
α	solar absorptivity of exterior wall surface
ε	thermal infra-red emissivity of exterior wall surface (thermal infra-red absorptivity)

2. Offsetting solar electricity generation

The imbalance in solar electricity generation varies throughout the day. This is illustrated by considering a building, with walls facing east, south, west and north, as shown in Fig. 1a. In the late morning, the sun illuminates the east and south sides of the building, resulting in higher power generation for panels mounted on those walls. Similarly, in mid-afternoon, the panels adjacent to the south-west flat generate the highest power. At any given time, the imbalance in power can be compensated by cables on each storey, routing power from one side to another. Imbalances in power between east and west largely cancel over a daily cycle. However, there will be a net imbalance between the south and north-facing sides of the building. The simplest wiring system would be to route cables from each set of panels through the flat, on whose wall they are mounted, and through the meter for that flat. This would lead to a greater reduction in electric bills for occupants of south-facing flats – compared to north-facing ones – even for equal electricity consumption.

The alternative cable-routing system – shown in Fig. 1a – allows the power generated by the arrays, and the reduction in electricity bills – to be shared equally by all occupants. Power cables from the arrays are fed – via inverters – to a single feed point. A meter at this point records total solar electricity generation, for that storey. Power cables then connect to the service cable from the mains, and to each flat, via its own meter. Signal cables from the solar generation meter transmit the total generation to the meter in each flat, to allow the deductions from the billed electricity to be calculated.

To allow for differences in shading between storeys, signals are sent to a central meter for the whole building – for instance, the meter at the service cable entry point, as shown in Fig. 1b – to record solar generation for the whole building (including the rooftop array.) This signal is then sent to the meter for each flat, to calculate the deduction. Communal services, e.g., lifts and stairwell lighting, can also be metered, so that usage can be billed equally to each flat.

The power from the utility, entering via the service cable, is:

$$P_{Utility} = \left(\sum_{flats}^{n} P_{flat} + P_{CS} \right) - P_{solar} \quad (1)$$

The power in brackets is total consumption for the building – including n flats and communal services (CS). Over the billing period, each flat is charged according to its individual energy consumption (recorded by its own meter), corrected for solar generation and communal services.

$$E_{Bill} = E_{Meter} - \frac{1}{n}(E_{Solar} - E_{CS}) \quad (2)$$

Some of the communal services, notably landing and stairwell lighting, are distributed throughout the building. In practice, this will make it difficult to meter their energy consumption at a single point. However, it is possible to calculate the power being consumed by communal services, by measuring power at existing meters (at each flat and at the entry point to the building). This can be illustrated by rearranging Eq. (1).

$$P_{CS} = P_{Utility} + P_{Solar} - \sum_{flats}^{n} P_{flat} \quad (3)$$

This can be converted to energy equivalents.

$$E_{CS} = E_{Utility} + E_{Solar} - \sum_{flats}^{n} E_{meter} \quad (4)$$

Substituting the energy for communal services into Eq. (2) gives

$$E_{Bill} = E_{Meter} - \frac{1}{n}\left(E_{Solar} - \left(E_{Solar} + E_{Utility} - \sum_{flats}^{n} E_{meter} \right) \right) \quad (5)$$

The solar energy cancels from the equation, which thus reduces to

$$E_{Bill} = E_{Meter} + \frac{1}{n}\left(E_{Utility} - \sum_{flats}^{n} E_{meter} \right) \quad (6)$$

This requires metering of the power/energy of each flat and the building as a whole. Thus, in addition to avoiding metering of communal services, this option removes the need to meter the power generation of the solar arrays (although power cable routing will remain as in Fig. 1). A functional block diagram of the meters, and the signal routing between them, and to/from the utility, is shown in Fig. 2. In practice, this could be implemented as programmable logic, and thus integrated with other functions performed by smart meters, which may be installed in coming years [7].

In the event of loss of mains power, the photovoltaic array may (in the future) be operated in islanding mode, thus continuing to provide power [8]. A back-up generator will generally be installed, to provide power to essential loads – communal services, refrigerators, etc. – when solar energy is insufficient. For this period, the occupants of the building will be charged for the fuel used by the generator (which may be provided by a different supplier than the electricity). Similar offsets can be calculated for solar generation and communal services, with this total being recorded separately by the meters. For the first metering option described above, the calculation is:

$$E_{FuelBill} = E_{Meter}(F) - \frac{1}{n}(E_{Solar}(F) - E_{CS}(F)) \quad (7)$$

The suffix (F) indicates that the measurements are recorded over the fault period (loss of grid supply), separately from the normal recordings, for separate billing by the fuel supplier.