SOLAR ENERGY POTENTIAL OF AN URBAN HOUSING ESTATE IN LONDON

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Abstract

The high cost of power from solar photovoltaic (PV) panels has been a major deterrent to the technology's market penetration. Moderate solar irradiation levels in the UK have also contributed to the reduced number of solar installations. The built environment accounts for more than 40% of total energy consumption, with over 60% of this in the domestic sector in the UK. Considering that an estimated 90% of its population at 2008 is based in urban areas, with an annual rate of urbanization at 0.5%, it is clear that most of the energy consumption in the UK is domestic urban based. With Energy prices escalating and CO_2 emissions reductions high in the agenda adopting solar energy in urban zones appears as an essential and practicable strategy to foster sustainable development. This paper, explores the basics of Photovoltaic (PV) technology, reviews the latest scientific approaches to evaluating solar irradiation in the urban environment, and assesses the potential for PV applications in the urban environment – with a case study of the Broadwater Farms Estate London. False color images of annual cumulative irradiation on the site serve the basis to a subsequent proposal for a hypothetical grid connected PV system. Finally, a cost analysis assuming a feed-in tariff is undertaken to evaluate the economic viability and payback time for the proposed system (Iweala, 2009; Iweala and Brotas 2010).

1. Introduction

Of all forms of renewable energy known to man, solar energy offers the greatest potential with theoretical estimates of 3.9 million EJ/yr. For comparison, the global primary energy use was 418 EJ/yr in 2001 (UNDP, 2004). There is no shortage of solar derived energy on earth; indeed, the storages and flows of energy on the planet are very large relative to human needs. However, a criticism to some renewable sources is their variable nature. This variability is often referred to as "intermittency in energy source". Energy source intermittency inherently affects solar energy to certain extents. Solar radiation varies throughout the day and seasons, and is affected by cloud cover. Although current technologies allow for quite accurate predictions of the sun's availability, the production of electricity from solar radiation is also strongly dependent on local conditions, namely the obstructions, the albedo of materials and the orientation of the solar collectors.

Solar power, in particular photovoltaics, has been relatively commercially unattractive due to the moderate level of insolation in the UK, cheap grid electricity, and low financial incentives from the government. In 2006, the United Kingdom had installed 12.5 MWp of photovoltaic capacity representing just 0.3% of the European total of 3.4GWp. In this context, the European Union agreed to source 20% of the energy needs from renewable by 2020 (EU, 2007, 2009). A new scheme to encourage homeowners to generate their own electricity, which includes a feed-in tariff, was announced in the UK, in June 2008. Moreover, the country's increasing reliance on gas imports, threatens UK energy security. With the built environment accounting for an estimated 40% of total energy consumption, while arguably more than 50% of all UK carbon emissions can be attributed to energy use in buildings it is imperative to adopt non-pollutant sources of energy and contribute towards a sustainable world (DECC, 2009a).

Fig. 1: Location of Broadwater farms estate shown within Greater London.

Fig. 2: Axonometric view of the site and key buildings.

2. Background Information on Study Area

The selected study area - Broadwater Farm Estate is situated in the valley of the Moselle, approximately 10 km north of the City of London, see Fig. 1. It is situated in a deep depression immediately south of Lordship Lane, between the twin junctions of Lordship Lane and The Roundway. It is immediately adjacent to Bruce Castle, approximately 500 m from the centre of Tottenham, and 2 km from Wood Green. The construction of the Broadwater Farm Estate began in 1967; the estate contains 1,063 flats, providing homes for 3,000–4,000 people. The design of the estate was inspired by Le Corbusier, and characterized by large concrete blocks and tall towers, see Fig. 2 and Fig. 3. Conspicuous buildings within the estate are the very tall Northolt and Kenley towers, and the large ziggurat shaped Tangmere block. Broadwater Farms Estate underwent a £33 million regeneration. The study area covers approximately 1 Sq Km, and would include all buildings within the Broadwater Farms Estate.

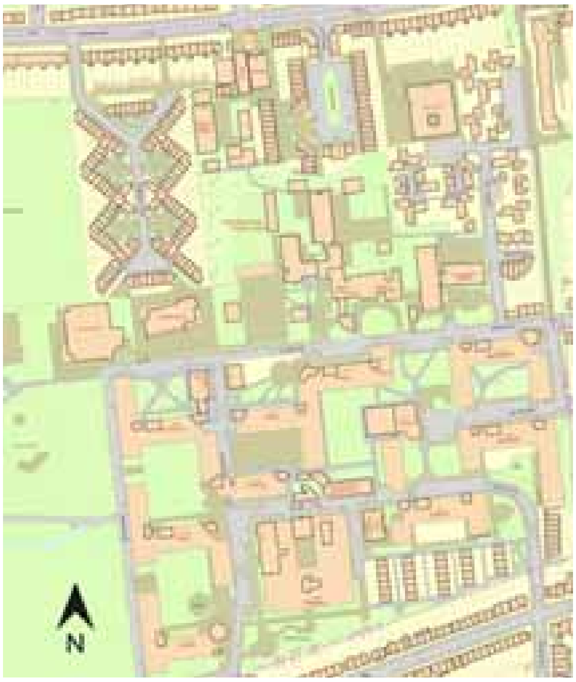

Fig. 3: Digimap survey map of study area.

In creating a digital study model of the buildings, small-scale construction details are omitted since the main objective of the method is to assess the potential for solar energy application in an urban neighborhood where the influence of volumetric and relative building layout largely overweigh the importance or relevance of aesthetic details on building's envelope. The completed digital study model was exported to RADIANCE, where materials reflectance were corrected or added if missing. Amongst corrected parameters are roofs, building façades reflectance and glazing ratios that may significantly affect solar radiation penetration and reflection in the urban context. However, these parameters do not directly depend on the urban form but on their on-site characteristics. Due to time constraints, a conservative reflectance value ($\rho = 0.2$) was assumed, but was adjusted for various urban elements such as roads and vegetation, where corresponding data was available. This low reflectance value is an estimated average between the facades reflectance. Although light colored buildings may have values up to 0.8, measurements of reflectance on old painted surfaces and concrete finishes in exterior surfaces have shown much reduced values around 0.3. Moreover, a previous study has shown that reflectance of materials in urban areas tend to be overestimated. High levels of pollution, reduced maintenance and window reveals and setbacks casting shadows make a conservative value of 0.2 more realistic (Brotas, 2004).

3. Assessing solar Potential in an Urban Built Environment

To assess the solar potential of any object, it is necessary to quantify the amount of insolation received by the object. Insolation is a measure of solar radiation received on a given surface area in a given time. It is commonly expressed as average irradiance in watts per square meter (W/m^2) or kilowatt-hours per square meter per day ($kWh/(m^2 day)$). In the case of photovoltaics it is commonly measured as kilowatt-hours per year per kilowatt peak rating ($kWh/(kW_p y)$ (BSI, 1995). Some of the solar radiation received by an object will be absorbed and the remainder will be reflected. The proportion of radiation reflected or absorbed depends on the object's albedo.

Atmospheric attenuation, the rotation and revolution of the earth, as well as shadowing effects from terrain features modify the total radiation reaching the surface within the site area. In the urban microclimate, in which the site is located, shadowing effects can be attributed to buildings and other urban structures, whilst atmospheric attenuation can be caused by polluted urban air. These groups of factors determining the level of shading can be modeled at reasonable levels of accuracy. The subsequent effects of afore mentioned factors on the quality of radiation reaching the surfaces on site is the break up of solar irradiation into direct and diffused components.

By definition, the urban built environment is not just a collection of buildings in large cities; it is also the physical result of various economic, social and environmental processes, which are strongly related to the standards and needs of society (Gaiddon et al. 2009). Today it is well accepted that urbanization leads to a high increase of energy use. Recent investigation showed that a 1% increase in the per capita GNP leads to an almost equal (1.03%) increase in energy consumption. Conversely, an increase of the urban population by 1% has been reported to increase energy consumption by 2.2%, i.e. the rate of change in energy use is twice the rate of change in urbanization [8]. Any future extensive PV application in urban areas will require an in-depth analysis of spatial and temporal distribution of solar resources; this is because spatial and temporal variations in solar radiation patterns are key amongst the problems affecting the wider use of solar energy. For example, the basic patterns of seasonal and daily variations given by astronomic factors are strongly modified by atmospheric conditions (e.g. clouds, water vapour, ozone e.t.c.). At localized scales, the patterns are further affected by local conditions (e.g. sky-view obstructions, temperature e.t.c.). Horierka and Kanuki (2009) argue that the assessment of solar energy resources in urban areas at local scale requires a combination of general/regional solar resources and the analyses of local conditions that affect solar availability. The current irradiation mapping for complex urban environments (ICUE) method for assessing the solar potential of an area takes into account:

- An accurate prediction of the incident irradiation on building facades based on hourly (or sub-hourly) basic data, e.g. test reference year (TRY);
- No practical limits placed on the scene complexity;
- Shading of and inter-reflection between buildings;
- Realistic sky radiance patterns to model non-overcast sky conditions;
- Results presented as irradiation images;
- The possibility of automating the quantification process (Mardaljevic and Rylatt, 2003).

A similar method has been adopted based on RADMAP [v.01c/2004-05-14] – a RADIANCE based software tool that is able to produce one or several irradiation maps, using a "cumulative sky" algorithm developed by Francesco Anselmo in 2004. Generated High Dynamic Range (HDR) pictures of the sky for each time step, according to the specified weather data file are then cumulated, added the sun descriptions and rendered as a final irradiation map for each view specified (Anselmo and Lauritano, 2003). Global solar irradiation maps were determined for south, south-east and south-west oriented facades. For the Broadwater Farms Estate study, the Gatwick weather file from the Energy Plus software was used.

The final energy is a combination of the solar resource available on the building envelope and the technical characteristics of the solar collectors. (Compagnon, 2001; Kaemfp, 2004) However, this research focuses on the effects of building geometry, layouts and orientation, on the potential for solar energy utilization in an urban area. The major interactions that occur between the incident irradiation (direct and diffuse), the reflected from the built environment (ground, buildings and obstructions), including shadowing and inter-reflections have been calculated. Further details of the research methodology to carry out an assessment of the global solar irradiation reaching the facades of buildings in an urban area are presented elsewhere (Iweala, 2009; Iwaela and Brotas 2010). Parameters associated with the characteristics and installation of PV collectors can be consulted in Weller et al. (2010).

4. Results

Within the study area, there is a higher diffused component of 60% solar irradiation falling on a unit area over a period of time (Iweala, 2009). Yet the results from the study allude to a reasonable potential for solar urban planning; meaning the integration of energy efficient and solar energy in urban planning via; urban renewal.

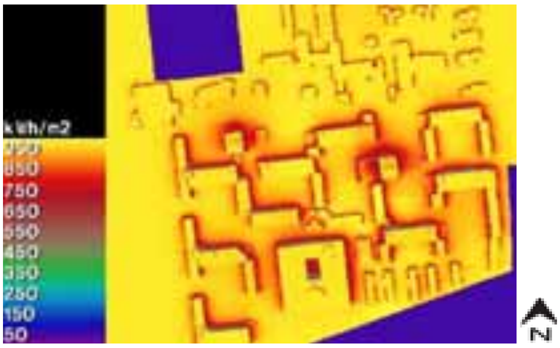

Fig. 4: Annual cumulative irradiation on the site as seen from top view.

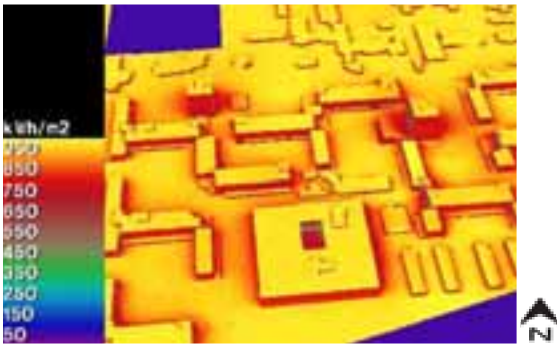

Fig. 5: Annual cumulative irradiation on the site as seen from an aerial south view.

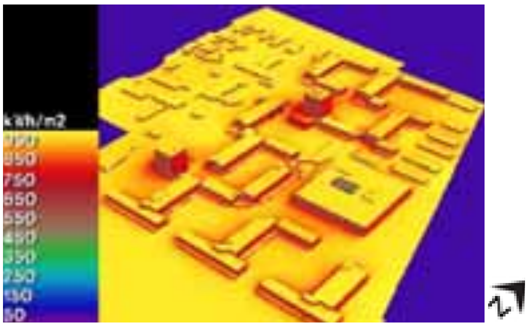

Fig. 6: Annual cumulative irradiation on the site as seen from an aerial west view.

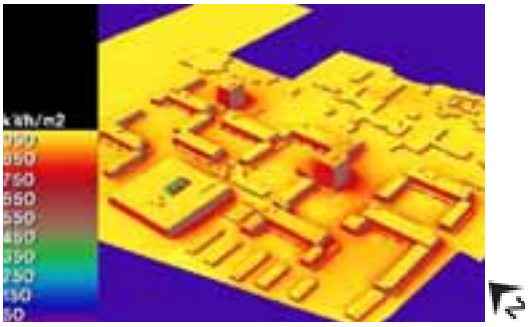

Fig. 7: Annual cumulative irradiation on the site as seen from an aerial east view.

Figures 4 to 7 present annual cumulative false colour irradiation maps produced by RADMAP. The site shows good potential for solar capture in particular on unobstructed roofs. SE and SW façades have lower solar irradiance than south ones but still have potential to receive vertical PV panels.

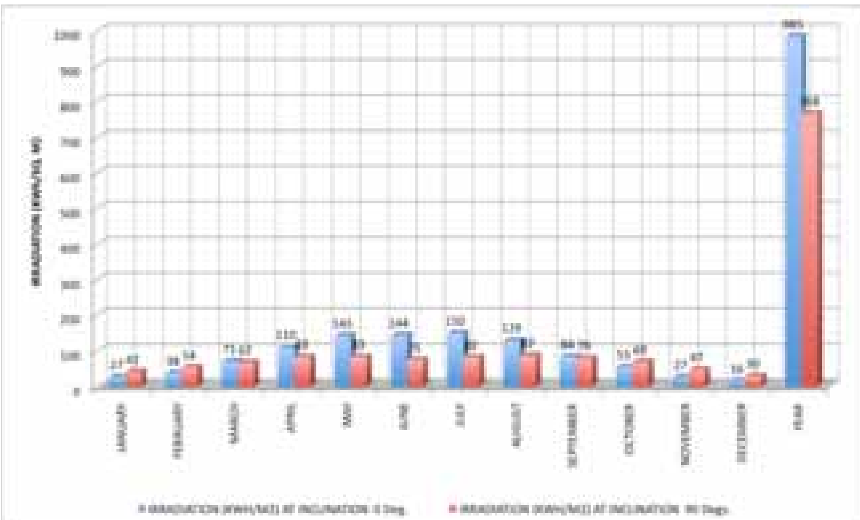

Fig. 8: Annual and monthly solar irradiance on roofs and south façades.

Fig. 8 presents solar irradiation values on a monthly basis for vertical surfaces and roofs. The latter receive higher amounts from April till September. During the summer period the frequency of sunny days is higher, daylight hours are extended and the sun reaches high altitudes. As a result, horizontal surfaces are more exposed. Conversely, in winter months vertical surfaces benefit from low altitude solar angles, if not obstructed, but the sun's intensity is weaker and for reduced hours. This results in much lower monthly irradiance values but favouring vertical façades. Overall, the annual irradiance is significantly higher for roofs, 985 KWh/m^2, than for the vertical facades, 768 kWh/m^2.

5. Photovoltaics design

In reality, typical PVs peak electricity demand seldom coincides with peak production, warranting the need for storage or sale to the main grid. The amount of PV electricity usable on site is related to the size of the array and the magnitude and pattern of demand (Randall, 2006). In this study dwellings are occupied everyday in the weekday and night, warranting a steady demand for energy.

Assumptions of typical annual electricity consumption for residential households in the UK were adopted from research studies conducted by the University of Strathclyde for average electricity consumptions of different residential types in Scotland.

The electricity consumption is assumed as:

- Working couples - 4,117 kWh;
- Single person - 3,084 kWh;
- Family with two children - 5,480 kWh (parents working, children at school).

Electricity consumption figures were measured over the winter months, November to March. This means that these figures are slightly higher than normal as during winter more electricity is used, as lights may be on for longer, more time is spend inside, generally using more appliances. An annual figure taking into account a lower summer electricity use can consider 95% of the initial value.

The study area is a mixture of all above dwelling's types, therefore an annual average electricity consumption of 4,300 kWh/yr for each household is assumed. This implies that the electricity consumption is approximately 358 kWh/month and 12 kWh/day. The area in study includes 1,063 dwellings. The estimated total annual electricity consumption for all residential housing is 4,570,900 kWh/yr, 382,696 kWh/month and 12,522 kWh/day.

A 15% efficacy monocrystalline silicon module and a 0.8 balance system loss to account for cable, PCU, inverter, metering and interface losses were assumed in the calculations. The annual solar irradiance on a vertical south façade and roof is taken as 768 and 985 kWh/m^2, respectively, see Fig. 8. The annual energy production for 1 m^2 of the PV system is 92 and 118 kWh/m^2/yr, accordingly. The basic systems of integrating PVs into buildings are: roof-based systems and façade based systems. For the proposed system, either a roof-based or façade based system is explored.

In order to have a functioning PV system in a location, the product of the system loses, solar irradiation received by the arrays at the location and the system power rating should equate to the system load (energy required), i.e.:

$$Total\ system\ load\ = System\ loses\ \times Global\ solar\ radiation\ \times System\ power\ rating \quad \text{(eq.1)}$$

To get the value for the systems' power rating, the system load is divided by the product of the system loses and global solar radiation at location i.e.:

$$System\ power\ rating = \frac{Total\ \ system\ \ load}{system\ \ loses\ \times global\ \ solar\ \ radiatio\ n}$$

(eq. 2)

For a facade based PV system, the required power rating for the system will be:

$$\frac{4{,}570{,}900}{0.8\times 768} = 7{,}440\ kWp$$

(eq. 3)

For a roof based PV system, the required power rating for the system will be:

$$\frac{4{,}570{,}900}{0.8\times 985} = 5{,}801\ kWp$$

(eq. 4)

Broadwater Farms needs a 7,440 kWp (7.4 MWp) facade based PV system or a 5,801 KWp (5.8 MWp) roof based PV system in order to produce on average, 12,522 kWh per day (382,696 kWh per month) of PV electricity to offset 100% of the yearly electricity demand from all 1063 dewllings.

To calculate the PV area needed to provide the required electricity to offset all electricity in all dwellings in Broadwater Farms, the yearly electricity demand is divided by the approximate power produced by the PV array.

For a roof based PV system, the required area for the system will be:

$$\frac{4{,}570{,}900}{118} = 38{,}736\ m^2 \quad \text{of PV array}$$

(eq. 5)

For a facade based PV system, the required area for the system will be:

$$\frac{4{,}570{,}900}{92} = 49{,}684\ m^2 \quad \text{of PV array}$$

(eq. 6)

The PV array area required to produce enough electricity to cover the annual demand for each dwelling has been calculated as being 47 m^2 of façade or 37 m^2 of roof. Based on the architecture of the buildings in the study, most roofs are flat and façades are simple glazed and un-shaded. This provides an opportunity to incorporate free-standing PV arrays on the roof and PV solar shades on the windows. The following areas were obtained from the 3D model:

- Total area of roofs: 273,270 m^2
- Total south façade area: 248,896 m^2

Façade and roof areas available are almost five and seven times the areas required to mount PV arrays to produce 100% of the electricity demand of all 1063 dwellings.

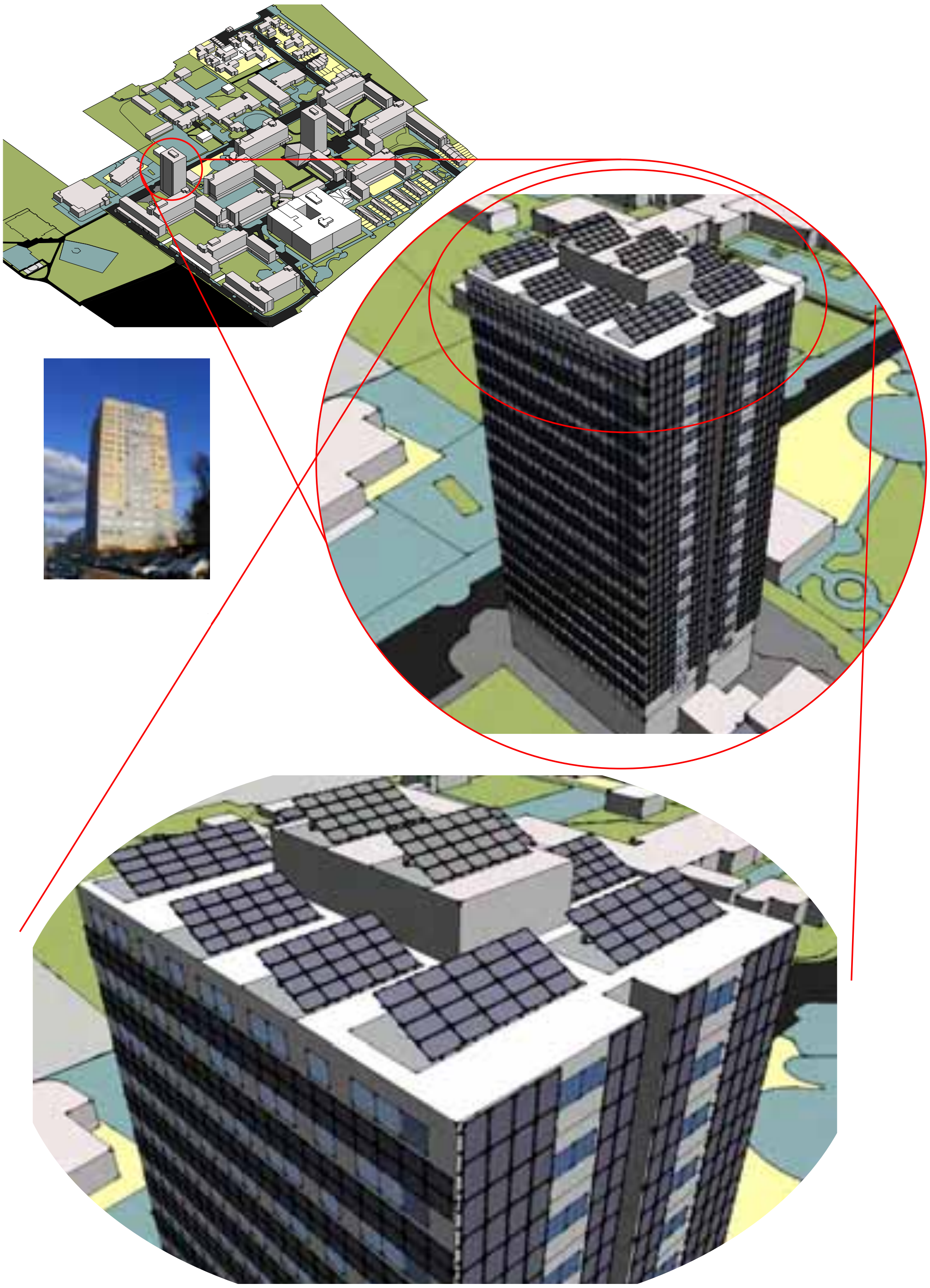

Fig. 9: Possibilities of PIBV on a housing block. South west aerial view

6. Cost Implications and Feed-in Tariffs

The installation cost of a PV system is between £4,500-£6,000 per kWp installed. The UK Government has introduced a feed-in-tariff (FITs) to incentivise small scale, low carbon electricity generation to homeowners with a premium for electricity generated from a solar PV system on their property. The incentive became available in Great Britain from 1st April 2010 (DECC, 2009b).

Tab. 1: FIT for Photovoltaic Systems with an installed capacity not exceeding 50 kW (DECC,2011)

	FIT Year in Which the Eligibility Date of an Eligible Installation falls									
Description	**FIT Year 2 2011/12**	**FIT Year 3 2012/13**	**FIT Year 4 2013/14**	**FIT Year 5 2014/15**	**FIT Year 6 2015/16**	**FIT Year 7 2016/17**	**FIT Year 8 2017/18**	**FIT Year 9 2018/19**	**FIT Year 10 2019/20**	**FIT Year 11 2020/21**
Solar photovoltaic with total installed capacity of 4kW or less, where attached to or wired to provide electricity to a new building before first occupation	37.8	34.6	31.6	29.0	26.4	24.0	21.8	19.9	18.1	16.4
Solar photovoltaic with total installed capacity of 4kW or less, where attached to or wired to provide electricity to a building which is already occupied	43.3	39.6	36.3	33.2	30.2	27.5	25.0	22.7	20.7	18.8
Solar photovoltaic (other than sand-alone) with total installed capacity greater than 4kW but not exceeding 10kW	37.8	34.6	31.6	29.0	26.4	24.0	21.8	19.9	18.1	16.4
Solar photovoltaic (other than sand-alone) with total installed capacity greater than 10kW but not exceeding 50kW	32.9	30.1	27.5	25.2	22.9	20.9	19.0	17.3	15.7	14.3
Export Tariff	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1

The scheme introduces a payment for all the electricity generated in the system (generation tariff), which can be complemented with an export tariff, for the electricity fed into the national grid. The power companies are obliged, by government legislation, to buy the renewable electricity from an eligible installation at a corresponding rate specified in Tab. 1 (DECC, 2011). The additional costs are passed onto the consumers. For electricity generated from PVs the scheme guarantees a payment for 20 years. Homeowners can also benefit from using the energy generated in-situ saving on the fuel bill.

The Broadwater Farms State London study assumed that each dwelling was generating its demand of electricity, therefore mainly benefiting from the generation tariff of 37.8 p/kWh and saving on import price of 11.46p/kWh, a conservative value of unit price from SAP (2009). Some marginal surplus energy is sold to the grid (export tariff at 3.1p/kWh). See Tab. 1. Higher tariffs are applicable for lower power capacities installed in refurbishments (DECC 2011).

The PV façade system generates 4,547 kWh/yr of clean energy for an individual dwelling and 4,833,461 kWh/yr for all dwellings. An overall reduction of carbon dioxide emissions of 2,498,899 Kg CO_2, with a payback time of 16 years was estimated. An emission factor 0.517 Kg CO_2 per kWh of standard tariff electricity was adopted from SAP (2009). A roof based PV system generates 4,570 kWh/yr for one dwelling and 4,857,910 kWh/yr for 1063 dwellings. This is reducing CO_2 emissions by 2,511,539 Kg CO_2. These installations have a payback time of 13 years. See Tab. 2 for a summary of the results obtained.

Tab. 2: Cost analysis of facade or roof based PVs systems per dwelling assuming an FIT Year 2 2011/12

Per Dwelling	Façade based PV system	Roof based PV system
Installation cost of PV system (£/kWp)	5000	5000
Power rating of PV array (kWp)	7.4	5.8
Installation cost of PV system (£)	37,000	29,000
Area of PV (m^2)	50	39
PV electricity produced (kWh/yr)	4,547	4,570
Annual electricity demand (kWh/yr)	4,300	4,300
PV generation tariff >4-10kW (£/kWh)	0.378	0.378
Export tariff (£/kWh)	0.031	0.031
Standard mains electricity tariff (£/kWh)	0.12	0.12
Annual income from PV generation tariff (£)	1,719	1,727
Annual savings from using electricity produced (£)	516	516
Annual income from export tariff (£)	8	8
Annual savings (£)	2,243	2,251
Estimated PV system payback time (Years)	16	13

7. Conclusions

Presently, it may be argued that PV electricity is unlikely to be a good investment, given UK sunlight levels, current electricity prices and the capital cost of the equipment. The introduction of appealing feed-in-tariffs (clean energy cash back) may result in a payback time of 13 years for a roof or 16 years for a façade mounted systems in London, making PV installations a potentially good investment for homeowners. Furthermore, large variations and current unpredictable costs of conventional electrical power, based on the type of fuel used, its production and distribution, create situations in which the use of renewable energy may not only be more economically sound but a requirement to a sustainable society.

The use of renewable energy generated in-situ should be complemented with energy efficient measures. The energy consumed would be lower, and more energy would be sold to the grid.

A study of the Broadwater Farms State in London was presented as a good example of urban PV-generated electricity.

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