CAN PV OR SOLAR THERMAL SYSTEMS BE COST EFFECTIVE WAYS OF REDUCING CO_2 EMISSIONS FOR RESIDENTIAL BUILDINGS?

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ABSTRACT

This paper compares two solar systems, an actual building integrated, photovoltaic roof (BIPV) and a notional solar thermal system for a residential block in London, UK.
The carbon payback for the solar thermal system is 2 years, the BIPV system has a carbon payback of 6 years. Simple economic payback times for both systems are more than 50 years. Calculations considering the current UK energy price increase (10%/yr), reduce the economic payback time for the PV roof to under 30 years.
The costs to reduce overall carbon dioxide emissions using a BIPV roof are £196/tonne CO_2, solar thermal individual systems at £65/tonne CO_2 and community solar thermal at £38/tonne CO_2. The current spot market price for CO_2 is £15/tonne CO_2 (20). Capital costs for PV systems in particular must be significantly reduced for them to be a cost-effective way to reduce CO_2.

1. INTRODUCTION

In the UK, the domestic sector is a major consumer of energy, accounting for approximately 30% of energy consumption. Considering almost 90% of our energy is derived from burning fossil fuels, the carbon emission profile is similar (1).Energy use in the residential sector is rising more quickly than in the UK economy as a whole. Total UK energy demand grew by 7.3% between 1990 and 2003, while residential energy consumption grew 17.5% over the same period (2). Reductions made in this sector will have a significant impact on national emission rates.
The paper considers solar energy as a form of building integrated renewable energy, applied to the domestic sector. A small domestic block of 18 flats in London that incorporates a large building integrated photovoltaic roof (BIPV) is used as a case study.
The main focus is the carbon impact and economic impact of building integrated solar energy. Social impacts have not been considered.
Two forms of building integrated solar energy are considered: the PV roof as built, and a notional solar thermal roof system. Carbon and economic payback periods of the two systems are assessed using partial life cycle assessment (end of life impacts have not been considered). This is followed by a sensitivity analysis of key variables.
Possible negative environmental impacts of solar energy systems include: land displacement, air and water pollution from manufacturing, operations and maintenance, and demolition of the systems. Land displacement can be avoided by mounting collectors on roofs of buildings. This is particularly advantageous in urban environments and places the energy source close to the energy demand. Maintenance of solar energy systems is minimal and pollution due to demolition is not considered significantly greater than that for conventional systems. Pollution created during manufacture is considered later in this paper in terms of embodied energy and associated carbon emissions.
In the UK, energy is predominantly required for heating in the domestic sector during winter when solar radiation intensity is at its lowest. Similarly for electricity energy is often required when it is dark for lighting.
Currently in the UK, solar thermal collectors are more widespread than PV installations. There are over 100,000 systems in place in the UK, and this number is rapidly growing (3). Most applications are found in the domestic sector.
Space heating is the greatest energy demand in the domestic sector, and this is generally provided by hot water, therefore solar thermal systems offer an ideal way to reduce domestic energy bills as well as CO_2 emissions.
UK government initiatives such as the Major Demonstration Programme (£20 million fund launched in 2002) (4) are encouraging growth in the photovoltaic market, to try and bring costs down.
There are currently around 600 PV installations in the UK. However Germany, which has a similar climate as much of

the UK, through the introduction of policies that actively support and encourage photovoltaic technology, (mainly by support through electricity tariffs) has close to 100,000 considerably (2).

1.1 Energy and carbon payback times

Alsema and Nieuwlaar (5) reviewed energy analysis studies for thin film photovoltaic modules. They found that energy payback times for frameless a:Si modules in NW Europe varied from 1.6 to 3 years. A module efficiency of 6% and a system Performance Ratio of 0.8 to account for system losses due to wires, invertors, cell-operating temp etc. were assumed.

Crawford and Treloar (6) compared net energy requirements of solar hot water systems to conventional systems in Melbourne, Australia. Although the embodied energy of solar hot water systems were higher than the embodied energy of conventional systems, when operational energy was considered, the energy payback of the electric-boosted system was approximately 0.5 years, and around 2 years for a gas-boosted system.

A fairly comprehensive study by Kalogirou (7) compared the pollution caused by solar hot water systems to that caused by conventional systems in Nicosia, Cyprus. Three different backup systems, typically used in Cyprus, were considered: electricity, electricity and diesel, and diesel. It was found that the solar hot water systems saved between 56% and 69% of CO_2 emissions, depending on the backup system used. When embodied energy was considered, carbon payback times for the solar hot water system varied from 1.2 years to 3.7 years, depending on the backup fuel used. It should be noted, however, that annual solar radiation intensity in Cyprus is considerably higher than in the UK, with a value of 1,840 kWh/m^2. Carbon payback times include the effects of different fuels with different carbon content used in the manufacturing process.

Under the lowest irradiation considered (1,202 kWh/m^2yr – similar to that in the UK), a frameless module has an energy payback time of around 3 to 5 years, depending on conversion efficiency.

1.2 Economic payback

A study by Mott Green Wall (8) looked at the economic implications of a building integrated photovoltaic installation in the UK, on the Alexander Stadium, Birmingham. The payback from this model, assuming a 20-year lifetime, and taking consideration of the 60% grant and the savings through awareness is 40 years.

Kalogirou (7), also found that in Cyprus, where more than 93% of houses have solar water heating systems, economic payback times were between 4.2 years and 5.6 years, depending on the backup fuel used.

photovoltaic installations. This has increased the competitiveness of the technology within the market

2. CASE STUDY: 18 FLAT BLOCK IN LONDON

The case study is a residential block containing 18 flats, made up of three wheelchair access 3-bed flats, three 2-bed flats and twelve 1-bed flats. Each flat has street level access with a maximum of 4 flats sharing the same street level door. The building, completed in 2005 as part of a regeneration project has a large 229m^2, 14kWp (BIPV) roof.

The roof is expected to cover the demand of all ground floor flats (on average). The electricity from the roof will be assigned to these flats, selected because they have been designed for disabled occupants. It was assumed that disabled occupants would be more likely to be in their flats during the day, when electricity is being generated.

At the time of design, 2002, a large UK government grant was available to encourage BIPV (4). A new grant, Clear Skies (4), is now available for solar thermal systems.

The embodied carbon of the photovoltaic roof was estimated using data from the literature, for the notional solar thermal roof, published data along with process energy data obtained from the assembly factory was used.

This has been followed by a study of the output energy for each system, using real PV system efficiencies and modelling each system using typical London weather data for the purposes of comparison.

Real installation costs of the PV and estimates for the solar thermal system have been calculated, combined with annual financial savings to generate the full cost of each of the two renewable energy systems over a conventional system.

In addition, various factors considered to influence the economic viability of photovoltaic systems have been analysed to determine their impact, with the aim of determining actions that will help create a sustainable market for photovoltaic technology on a domestic scale in the UK.

2.1 Description of notional solar thermal roof

The solar thermal system considered for this study was specified by Imagination Solar, and uses the ATON panel, (9). The lifetime of the panels is approximately 30 years.

An electric pump is required to circulate water within the system. This is operated by a 20Wp polycrystalline PV module, synchronised with the solar collector temperature to ensure the pump operates when the sky is bright enough for the collector to harness useful energy, ensuring that zero carbon emissions are associated with operation.

Since solar thermal systems cannot provide 100% of domestic hot water demands in the UK, the system is an

auxiliary system, which requires a conventional system as back up. This is assumed to be a gas condensing combination boiler.
Two system configurations were considered, 18 individual systems (12 by 1.1m^2 panels, 6 by 2.7m^2 panels), and 1 communal system (10 by 2.7m^2 panels, 2 by 700-litre unvented hot water cylinders). The two are referred to as ST (I) for solar thermal individual systems and ST (C) for solar thermal communal systems..

2.2 Description of Solar PV roof

The 13.3 kWp photovoltaic roof consists of a Uni-Solar thin film, amorphous silicon, photovoltaic laminate (PVL), which is factory bonded to a Corus Construction, Kalzip standing seam metal roof. The 2.5mm thick PVL is then adhesively bonded to 1mm thick polyvinylidene difluoride (PVdF) paint coated sheet aluminium profile.
Six inverters convert the generated electricity from DC to AC for use in flats when there is demand and for export to the national grid when supply exceeds demand.
When demand exceeds supply, electricity will be imported from the grid. Using electricity directly as it is generated reduces transmission losses, and connection to the national grid eliminates requirement for battery storage, which often uses environmentally unclean materials.

2.3 Photovoltaic embodied energy

Keoleian & Lewis (10) calculated the embodied energy for a Uni-Solar tandem junction a:Si module. As in most studies, they have not looked at end-of-life energy requirements due to lack of data. They have stated, however, that assuming photovoltaic modules are disposed of according to current methods: either in landfill, or shredded in hammer mills (as cars and white goods are currently disposed of), an end-of-life energy requirement of ~97 J/kg for shredding can be assumed. The embodied energy for a framed version of this cell (UPM880) was reported as being about 572 MJ (1400 MJ/m$^{2)}$ and without frame about 349 MJ (850 MJ/m^2). Alsema and Nieuwlaar (5) suggest an embodied energy of 20MJ/Wp for PV cells. In the same paper they calculate an energy payback time of between 2.5 – 4 years and 50-60 gCO_2/kWh. Their calculations use 1999 data, annual solar radiation of 1700 kWh/m^2 yr and a system lifetime of 30 years. This compares to current US electricity grid emissions of 636g CO_2/kWh (11).
The full embodied energy of the roof includes the module and the BOS components, the total was found to be 1262.6 kWh/m^2, (289,000MJ 80,315.6kWh, 5.6kWh/Wp), further details found in (13).
Transport energy has not been considered here due to lack of data. This may, however, be significant since the constituent materials are sourced from the US, then bonded to the aluminium roof profiles in the UK, before being transported to the site location.

2.4 Solar thermal embodied energy

Kalogirou (7), calculated the embodied energy of a 1.9m^2 flat plate collector. Including process energy, total embodied energy was 3,540 MJ per module, with a total embodied energy value for a 2-panel installation coming to 8,700 MJ.
Here the 2.7m^2 ATON panel (9) was considered, the embodied energy for each configuration was found as follows, individual systems 1291.2 MJ/m^2, (37960.7 MJ, 10544.6 kWh), communal system 1097.2 MJ/m^2, (29623.5 MJ, 8228.8 kWh). Further details can be found in (13).
Parts of the system that would be required in a conventional heating system (such as hot water cylinders, insulation and pumps) are discounted, as they would be present in all cases.

2.5 Modelling of solar radiation

Incident solar radiation falling on the inclined roof (12º slope) in London is calculated to be 1003 kWh/m^2, (Kew 1966 data) using equations in (12).

2.6 PV system efficiency

Actual electricity production was measured from the installed PV roof and was found to be closely related to global solar insolation. Readings were taken at weekly intervals and from these it was found that the total system efficiency including balance of system components was 5.8%.

2.7 Solar thermal system efficiency

The system efficiency of 34% for the solar thermal system was assumed by making comparisons between the manufacturer's own tests for annual energy output - and the government's side by side test of eight solar water heating systems (21).

2.8 Energy Output of Solar systems

Annual PV output for 229m^2 of PV with a system efficiency of 5.8% was calculated as 13327.6 kWh (47979.2 MJ).
Output for the individual solar thermal (29.4 m^2) was calculated at 10027.0kWh (36097.2 MJ) and community solar thermal (27.0 m^2) system was calculated at 9208.5kWh (33150.4MJ) . More detailed results can be found in (13).

2.9 Energy demand for the building

In the UK, energy use for heating dominates domestic demand, with on average 82% of energy used for space and water heating. However, energy used for lights and appliances is the fastest growing end use, having risen 157% between 1970 and 2000. The rise is mainly due to multi-source lighting, and the increase in household electrical appliances (14).

Electricity demand was estimated based upon national average figures, 3,300 kWh/household (14). For the case study an average annual electricity demand of 3,000 kWh/household has been assumed. The average UK household size in 2003 was 2.32 (16), giving an electricity demand of 1,293.1 kWh/person.

Space heating and annual domestic hot water demand for each flat type was estimated using (17). Overall total annual consumption is calculated at 128,343.3 kWh/yr. See (13) for further details.

3. CARBON PAYBACK TIMES

This is total embodied energy of each system divided by the carbon savings per year, (table 1). The value for the solar thermal panels is lower than some quoted as the actual process energy for the assembly factory is used, it operates with green electricity (assumed emissions = 0g CO_2/kWh) and natural gas. (0.194g CO_2 /kWh). The energy in the materials themselves is assumed to be from non-green electricity.

TABLE 1: CARBON PAYBACK TIMES FOR EACH OF THE THREE SYSTEMS CONSIDERED.

	PV System	Solar thermal individual	Solar thermal community
Embodied energy (exc transport) (kWh)	80315.6	10544.6	8228.8
Embodied carbon (ex. Transport) (kg CO_2)	33893.2	4340.4	3362.0
Energy saving (kWh/yr)	13323.2	10027.0	9208.5
Carbon saving (kg CO_2/yr)	5622.4	1945.2	1786.4
Carbon payback excl transport (yrs)	6.0	2.2	1.9
Lifetime (yrs)	30.0	30.0	30.0

4. ECONOMIC PAYBACK TIMES

The overall costs of the different systems are given in table 2, information about assumptions and values used are given in the sub sections below

4.1 Capital costs PV

The total cost of the 229m^2 photovoltaic roof including installation costs was £123,231. However, a 60% grant was obtained (4). Payback times with and without the grant are considered. As the photovoltaics are building integrated, all of the costs for the roof itself are incorporated into this amount. It is assumed the standard roof cost without the PV element would be approximately £11,660. This is approximately 9.5% of the total cost for the BIPV roof and is removed from the calculations.

4.2 Annual operating costs PV

Maintenance for the photovoltaic system is assumed to include the replacement of inverters approximately every 10 years, and an electrical inspection of the system every 5 years. At today's prices, replacement of the inverters would cost approximately £9,000, and an electrical inspection would be about £200. Over a conservative estimate of a 30-year lifetime, this brings the operating costs to an average of £640 per year, (18).

In terms of lifetime savings, it has been assumed that electricity generated by the photovoltaic roof is sold to the national grid at the same rate that it is bought from the national grid. Solar electricity is presumed to replace grid electricity with an assumed cost of 0.075£/kWh (14)

4.3 Capital cost solar thermal

For the individual solar thermal option, calculating only the cost of the extra equipment required for the auxiliary solar system the net cost excluding VAT is assumed to be £25,728 (9). The UK Government Clear Skies grant has a maximum contribution of 50%, the total cost including this would be £12,864, (4).

The community based system is significantly cheaper at an estimated installed cost of £13,900 excluding VAT and grant.

Not included in this quote are: roof mounting systems, and work done in connecting the cylinders to the domestic hot water or boiler systems.

4.4 Annual operating costs solar thermal

The solar thermal systems are designed to require very little maintenance. Over a 30-year design life, pump replacement after approximately 15 years would be required Over the lifetime of the individual system this amounts to an operating cost of £48.60/yr.

When replacing the pumps on the community system, only four large pumps will be required, amounting to £14/yr.
It is assumed that all hot water used from this system replaces mains gas heated water, where a price for mains gas of 0.0199£/kWh has been assumed (14).
As the results for the 30 year system lifetime, in table 2 show, the simple payback for the photovoltaic system is long. Both solar thermal systems also have long simple payback periods, even with a 50% grant.

TABLE 2: SIMPLE PAYBACK FOR EACH SOLAR ENERGY SYSTEM (30 YEARS)

	Install. cost (excl. grant) (£)	Install. cost (incl. grant) (£)	Ann. Saving (£)	Ann. maint. and running costs (£)	Pay back (excl. grant) (yrs)	Pay back (incl. grant) (yrs)
PV	111631	39071	666.2	640	4267.5	1493.6
ST (C)	13900	6950	144.6	14	106.5	53.2
ST (I)	25728	12864	157.4	48.6	236.4	118.2

4.5 End of Life Net Present Value calculations

The net present value (NPV) of a system represents the worth of the financial investment, including future maintenance costs and a social discount rate. The net present value was calculated for each system. A social discount rate of 3.5% has been assumed throughout as this is the current rate used by the UK treasury, (19).Current uncertainty over future fuel price calculations indicate that it is important to factor in possible fuel price rises. Two different price rise scenarios are considered; (a) fossil fuel prices rise at the same rate as the social discount rate, ie 3.5%, table 3 (b) they rise at the current rate, 10%, table 4. If the value for EoL NPV is positive then the economic investment is not paid back over the lifetime of the system. At a fuel price rise of 10 % even without a grant the solar thermal community system has an economic payback of less than 30 years. For the PV roof to be considered cost effective an annual fuel price rise of 10% is required along with the large capital grant before payback occurs within the lifetime of the system.

Cost of carbon savings

By taking the above figures and expressing them in terms of cost per tonne of CO_2 saved over the lifetime of the system then this gives a measure of how effective each method is for governments to target their CO_2 saving measures more cost effectively. Again the costs are different depending on the rate of fuel price rise. Table 5 gives total carbon savings, table 6 gives cost per tonne under the two different scenarios. It is important to note that without the grant and a 10% fuel price rise, the cost of carbon reductions over the lifetime of the PV roof never drops below 261£/tonne CO_2.

TABLE 3: END OF LIFE, NET PRESENT VALUE CALCULATIONS

	Fuel Price rise = 3.5%			
	Present value of savings	Present value of maintenance	End of Life NPV (excl. grant)	End of Life NPV (incl. grant)
PV	29977.14	11770.91	93424.77	26445.77
ST (C)	5497.45	257.49	8660.04	1710.04
ST (I)	5986.11	893.85	20635.74	7771.74

TABLE 4: END OF LIFE, NET PRESENT VALUE CALCULATIONS

	Fuel Price rise = 10%			
	Present value of savings	Present value of maintenance	End of Life NPV (excl. grant)	End of Life NPV (incl. grant)
PV	88217.81	11770.91	35184.10	-31794.90
ST (C)	16178.09	257.49	-2020.60	-8970.60
ST (I)	17616.14	893.85	9005.71	-3858.29

TABLE 5: COST OF CARBON SAVING

	Embodied Carbon (t)	Carbon Saved (t/yr)	Total carbon over 30yrs (t)
PV	33.89	5.62	134.78
ST (C)	8.23	1.79	45.36
ST (I)	10.54	4.34	119.67

TABLE 6: COST OF CARBON SAVING

	Fuel rise = 3.5%		Fuel rise =10%	
	Cost of carbon (excl. grant) £/t	Cost of carbon (incl. grant) £/t	Cost of carbon (excl. grant) £/t	Cost of carbon (incl. grant) £/t
PV	693.17	196.22	261.05	-235.91
ST (C)	190.90	37.70	-44.54	-197.75
ST	172.44	64.94	75.26	-32.24

(I)				

5. CONCLUSIONS

Using a newly built block of flats in London as a case study, it was found that building integrated solar energy systems, both thermal and photovoltaic, have the potential to contribute significantly to residential energy supply and to reduce CO_2 emissions. Both technologies studied in this report had carbon payback times that were no longer than 20% of the system lifetime. Carbon payback for the PV roof was found to be 6.0 years, while payback for the solar thermal system was found to be 1.9 – 2.2 years.
The economic payback times for both systems, however, remain very long, despite the availability of substantial grants. Simple payback time for the photovoltaic system was in the thousands of years. Simple payback for the solar thermal system can be estimated in the 100's of years. However simple payback misses the changing value of energy savings in this era of increasing fuel prices.
Using end of life net present value calculations with different energy price rise scenarios indicates that with an annual projected fuel price rise of 10%, the BIPV roof has an economic payback time within the 30 year life of the system when the capital grant is included.
It was found that a solar thermal community system had an economic payback time easily within the lifetime of the system even with a projected 7% annual fuel price rise (13).
No individual factor is likely to make photovoltaics economically viable on its own; however, a combination of reduced capital costs and increased system efficiencies, coupled with rising conventional electricity rates are expected to bring economic payback times down to well within the lifetime of the system. UK PV prices may be significantly higher than elsewhere.
Some of the economic costing used is very sensitive to the input figures used, fuel price rise, social discount rate, and the replacement cost of the inverters in 10 years time. These numbers are very difficult to estimate accurately and it is acknowledged that the calculations are dependent on them. All of these calculations fail to include any concept of the value of security of supply. In an uncertain world this may be a very important feature.

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