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Tackling fuel poverty with building-integrated solar technologies: The case of the city of Dundee in Scotland

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ABSTRACT

Fuel poverty in Scotland is rising and is currently experienced in a quarter of households. Large-scale renewable generation does not reduce fuel poverty because citizens still have to pay for their imported energy. However, building-integrated solar systems do reduce the amount of energy imported into homes and have demonstrably already taken some families out of fuel poverty in Scotland. This study is of the solar potential of Dundee, a city with higher than average levels of fuel poverty. A review of the Scottish Index of Multiple Deprivation presents the deprivation status of the population in the centre of the city. The total roof area practically available for solar integration was estimated using RoofRay software. Energy efficiency measures, combined with building integrated solar systems were shown to potentially eliminate fuel poverty in central Dundee. Energetic and economic analyses of the solar systems using TRNSYS software resulted in optimal PV/inverter system sizing ratios of 1.02 and 1.06, respectively. The solar water system optimally performed with a 230 L tank of 1 m height and an inlet fluid flow rate of 40 kg/h. The study indicates that city level solar installation programmes can help eliminate fuel poverty in Scotland at an acceptable cost.

1. Introduction

The global financial crisis has increased the average cost of living today to that of a decade ago. Oil prices continue to rising making the grid supplied energy a really hard-to-buy commodity for low-income families. Consequently fuel poverty figures for UK are poor: 1 in 14 households in England, 1 in 9 in Wales, 1 in 4 in Northern Ireland are in fuel poverty [1]. In Scotland 1 in 3 are fuel poor with here 45% of rural households deemed fuel poor in 2009, and 20% in extreme fuel poverty while 30% and 8% of urban households respectively, making rural households more than twice as likely to be in extreme fuel poverty as urban households [2]. This situation in Scotland is not expected to improve by 2016 [3]. The ambitious Scottish targets for renewable energy production and for more independence from fossil fuels by 2020 are currently not linked to the fuel poverty issue.

PV and SWH markets in Scotland today are limited, not least because of the poor public awareness of the cost benefits of home-owned solar technologies and the potential for significant increases in the future cost of delivered energy. Scotland patently does not have the best global climate for solar energy and historically people have considered the weather as a barrier. However the radiation incidence available is more than adequate and an appropriately sized PV and SWH system on a typical house in Scotland can meet more than 50% of the annual needs of a Scottish household for either electricity or hot water and there are many satisfied solar system owners in the country. Across Britain a total solar PV capacity was installed under the feed-in tariff (FIT) scheme of 999,617 kW, a shade away from reaching a 1GW market [4].

A good indicator that solar technology in Scotland is sustainable is the Findhorn eco-village in Northern Scotland. Despite the high latitude at latitude 57.6°, the ecohouses use solar PV and thermal panels effectively and according to the residents they can have solar hot water for the whole summer and only use auxiliary heating during winter [5]. Moreover, the residents of Berwickshire receive the benefits of the free solar energy, after being funded by the Department of Trade and Industry in 2002 [6]. The experiences of this solar pilot are once again positive, especially because of the low income families who live in Berwickshire. As a result of the recent FIT Scheme there have been hundreds of domestic PV systems installed in Scotland and a number are described in detail on the Community Energy Scotland website [7]. An early research array was installed by Napier University of Edinburgh at Napier's Merchiston Campus in 2005. The system includes PV panels of a total 160 m^2 on a vertical wall with a power capacity of 14.4 kW_p [8]. The estimated output is about 11 MWh/year, 21% less than it would be if was installed at optimal orientation and inclination

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Table 1
Terms used in the text.

Acronyms		e_i	Economic performance of the PV/inverter system (kWh/€)
FIT	Feed-in tariff	$H^a_{G,T}$	Annual global solar radiation on a tilted plane (kWh/m^2)
FPC	Flat plate collector	n_{inv}	Efficiency of the inverter
SWH	Solar Water Heating	$P_{in,n}$	Normalised power input to the inverter
SIMD	Scottish Index of Multiple Deprivation	P_{inv}	Power capacity of the inverter (kW)
PV	Photovoltaic	P_{PV}	Nominal power of a PV array (kW$_p$)
Nomenclature		$P_{PV,tot}$	Total PV power capacity of all the arrays in Dundee (kW$_p$)
C_{inv}	Unit cost of the inverter (€/kW)	R_e	Optimal energetic sizing ratio
C_{PV}	Unit cost of the PV array (€/kW$_p$)	R_i	Optimal economic sizing ratio
E^a_{inv}	Total annual energy output of the inverter	R_S	Sizing ratio of a PV/inverter system
E^a_{PV}	Annual energy output from all the PV arrays in Dundee without considering the inverter		
e_e	Energetic performance of the PV/inverter system (kWh/kW$_p$ year)		

Table 2
Solar units installed in Scotland by different sources: Ofgem [10], Element Energy Ltd. [11] and Scottish Government [12].

Technology	Source	Number of units/stations installed	Installed capacity (kW$_p$)	Energy production (MWh/year)	Latest update
PV	Ofgem	112[a]	382[b]	n/a	31-03-2010
	Element Energy Ltd.	95	414	352	08-2008
Solar thermal	Scottish Government	n/a	9370	6666	31-03-2009
	Element Energy Ltd.	10,700–11,100	22,400–23,400	14,400–15,000	07-2008

[a] This is the number of grid-connected accredited stations which are equal or less than 50 kW. The stand-alone number of units is thus unknown.
[b] Ofgem reports that this number is by 181% increased compared to the 2008–2009 figures.

where it would have an energy output considered as average on a scale of low, average and high PV array output [9] (Table 1).

Notwithstanding the growing enthusiasm for solar installations in Scotland, there are no official technical reports on the Scottish solar market or potential and thus making it impossible to gauge the cost benefits of the wider scale application of the technology at this latitude. Moreover, it is not yet clear how big the market is today, as different sources give very different figures. Table 2 summarises the discrepancies between several reports on the PV and solar thermal markets that highlights the lack of a definitive study on the Scottish solar market making well informed policy on this technology impossible to develop let alone implement.

The technology trends of the Scottish solar market can be seen in Table 3 that resulted from a review of the regional manufacturers and suppliers of PV modules and solar thermal collectors carried out by the authors based on manufacturers' datasheets and suppliers' feedback. Table 3 only partially reports on the full survey and in Scotland the majority of the installed PV modules are made of polycrystalline silicon and have a power capacity of 190–250 W$_p$. Their cost is in the range of 1.55–3.90 €/W$_p$, depending on the manufacturer and the size of the order. On the other hand, most of the supplied solar thermal collectors are flat-plate and produce about 1000–1200 kWh/year. The cost per collector is around €856 which gives an estimated cost of energy near €0.037/kWh for flat-plate collectors in a 20 years lifetime.

Table 3
Research on the Scottish solar market (PV and solar thermal).

Manufacturer	Product name	Technology	Module nominal power	Module total area	Cost per module[a]	Cost per power capacity
Kyocera International Inc.	KD240GH-2PB	Polycrystalline silicon	240 W$_p$	1.65 m^2	€416	1.73 €/W$_p$
Renewable Energy Association	REC240PE	Polycrystalline silicon	240 W$_p$	1.65 m^2	€508	2.12 €/W$_p$
SANYO Electric Co., Ltd.	HIT-H245E01	Monocrystalline silicon	245 W$_p$	1.39 m^2	€579	2.36 €/W$_p$
Schüco International KG	MPE 210 PS 05	Polycrystalline silicon	210 W$_p$	1.49 m^2	€357	1.70 €/W$_p$
Suntech Power Holdings Co., Ltd.	STP190S-24/Ad+	Monocrystalline silicon	190 W$_p$	1.28 m^2	€295[b]	1.55 €/W$_p$

Manufacturer	Product name	Technology	Annual energy output (kWh)	Collector gross area	Cost per collector[a]	Cost per energy output[c]
AES Ltd	AES Light Solar Collector, models A–L	Flat-plate, double glazing	1162 (model H)	1.20–4.40	€783 (Model H)	€0.034
Stiebel Eltron UK Ltd	SOL 27 series, SOL 23 PREMIUM	Flat-plate	1260	2.53–2.70	€765 (SOL 27 Prem.)	€0.030
TiSUN GmbH	FM-S 2,00 and 2,55 FM-W 2,00 and 2,55	Flat-plate, single glazing	1058	1.85 and 2.36	€690	€ 0.033
Viessmann Ltd.	Vitosol 200-T, 300-T	Evacuated tube	1169, 1192	1.36, 1.37	€2986, €3287/kit	€0.064, €0.069
	Vitosol 100-F, 200-F	Flat-plate, single glazing	1020, 1088	2.513	€1816, €2231/kit	€0.044, €0.051

[a] Excl. VAT. Wherever kit price is given, a 50% of it is taken as the panel price to be included in the cost of energy estimation.
[b] This price is valid for a mass purchase of about 20 units and therefore the price per module itself might be more expensive.
[c] Assumed lifetime of 20 years.

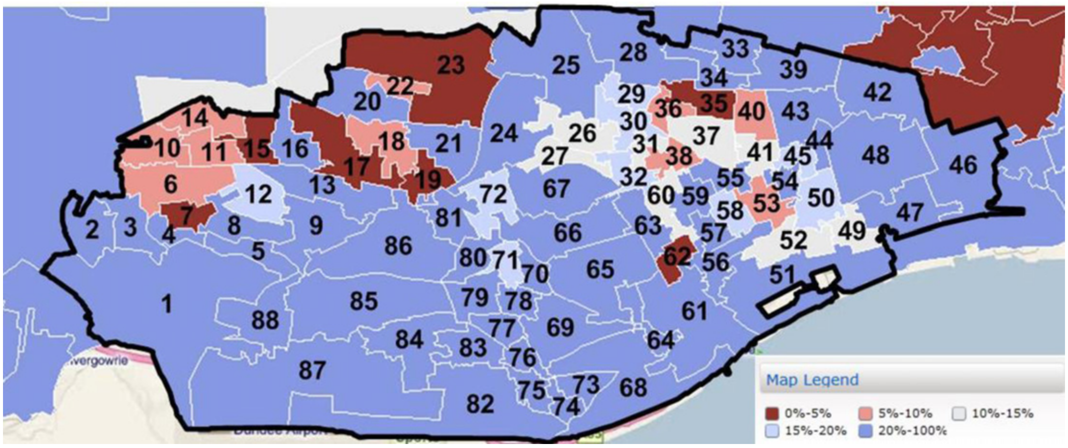

Fig. 1. The selected region for this study. The colour of each datazone represents its deprivation index as shown in the Map Legend in the right bottom. The map was taken from the official SIMD website. Each datazone is by default referenced by a code of the format S0100ABCD, where ABCD can be from 0001 to 6505. However, integer numbers have been added on the zones for making the datazone reference easier.

There have been a number of major projects developed in Scotland including the Edinburgh Renewable Heritage Housing Co-operative project to put 165 m^2 of solar collectors on the roofs of seven Grade B listed Georgian tenements in the centre of Edinburgh, providing about 74,520 kWh/year and saving up to 32,000 kg CO_2/year. This successful project was aimed at taking households out of fuel poverty and enhancing their quality of life using solar energy [13].

A driving force for the authors here was the increasing figures for households in fuel poverty in Scotland. Our focus was on Dundee, a city with high levels of deprivation and also home to the Solar Cities Scotland office. We began this exercise by exploring the potential role for building-integrated solar technologies together with the adoption of some basic energy efficiency measures as a successful and lasting solution for the elimination of such problems.

2. The SIMD and the deprivation status in Dundee

2.1. Introduction to the SIMD

The Scottish Index of Multiple Deprivation (SIMD) classifies the areas of Scotland according to how deprived the population of areas are. Deprivation here is that used by Townsend [14]: "*People are relatively deprived if they cannot obtain, at all or sufficiently, the conditions of life – that is, the diets, amenities, standards and services – which allow them to play the roles, participate in the relationships and follow the customary behaviour which is expected of them by virtue of their membership of society. If they lack or are denied resources to obtain access to these conditions of life and so fulfil membership of society, they may be said to be in poverty*". The term 'multiple' has been used to include all the types or domains of deprivation which the SIMD examines and for which Townsend believes they form the condition of deprivation and poverty. These domains are: current income, housing, health, education skills and training, employment, geographic access to services and crime. In this paper, the domains that were taken into account are those of income, housing and employment.

The SIMD produces a rank for each geographical area (datazone). Scotland has been separated into 6505 datazones and each one is ranked by a number which is between 1 (the most deprived) and 6505 (the least deprived). This ranking is taken place for all seven domains. Finally, all domains are combined and an overall index is produced which represents the final position of each datazone at the deprivation ranking list. This index can take the values of 0–5%, 5–10%, 10–15%, 15–20% and 20–100% and, similarly to the 1–6505 ranks, the 0–5% percentage denotes the most deprived percentage of the total datazone population. Analogies for the comparison of the deprivation in different datazones do not apply. For instance, a datazone ranked by 100 does not mean that it is twice deprived compared to a datazone with a 200 rank.

2.2. Geographical area of the study and presentation of the results

The area which was selected for this study was the centrally located SIMD datazones of Dundee (56.4°N, 2.9°W) that are included within the following borders: the oval-shaped region which is formed by Kingsway West and East (A90) in the North and the Riverside Avenue (A85) and East Dock Street (A92) in the South. This is shown in Fig. 1. There are total 88 datazones within the defined region and their numbering has been made arbitrarily.

The deprivation results are presented in Table 4. It was found that 72,329 citizens live centrally in the city of Dundee. These are more than the half of the total population of the whole city region. The population in Dundee in 2003 was 143,090, with a net change of −0.8% compared to 1991 numbers and the estimated population was 133,325 in 2010 and will be 123,506 in 2018 [15].

2.3. Discussion

The SIMD analysis showed significant concentration of deprivation in the chosen area. From the total 88 datazones the 34 of them (39%) are ranked with a 15–20% derivation index or lower, i.e. in more than one in every three datazones there are people in the 20% of the most deprived in Scotland. The biggest concentration of the deprived datazones is located to the Eastern side of the sample region nearby Clepington Road, Dens Road, Dura Street and Arbroath Road (the Western part). There is also concentration in Lochee, Dunsinane Industrial Estate and nearby the South Road Park. Finally, there is one datazone (no. 62) directly behind the city centre and the University Abertay of Dundee with a deprivation index of 0–5%.

Unfortunately, it is not possible to identify how many people are under the fuel poverty threshold. However, there are important conclusions to be drawn concerning those people who are financially deprived and those who live in accommodations without central heating. It can be seen from Table 4 that 14,580 people (20.2%) are income deprived and 9880 (13.7%) lack of central heating in their house, while in Scotland these numbers are 806,970 (15.6%) [16] and 287,727 (5.8%) [17], respectively. Although there is no correlation between these figures (we are unable to know how

Table 4
Deprivation data from the SIDM for the 88 selected datazones of the map in Fig. 1. For households which lack of any installations of central heating in some or all rooms, central heating includes gas, oil or solid fuel central heating, night storage heaters, warm air heating and under-floor heating.

	Zone population	Total income deprived individuals	Total population living in households without central heating	Total employment deprived individuals
Total	72,329	14,580	9880	7649
Percentage of the total in the studied region	100.0%	20.2%	13.7%	10.6%

Table 5
Comparison of the deprivation status in Dundee and in another 4 cities.

City	Population considered	No. datazones considered	No. datazones ranked with SIMD 20% or lower	Percentage of total
Dundee	72,329	88	34	39%
Aberdeen	100,000	120	20	17%
Falkirk	55,000	72	18	25%
Inverness	43,000	55	11	22%
Dumfries	32,000	38	9	24%

many people are income deprived and without central heating at the same time), it is logical to conclude that the people facing financial difficulties will have trouble paying their energy bills. Hence, it is possible that the individuals in the 'without central heating' category might be in extreme fuel poverty, i.e. they spend more than 20% of their income on energy or they are completely unable to meet the energy needs of their household.

One in every ten residents in the selected region is considered to be employment deprived. The total number is 7649 (10.6%) which is analogously above the overall Scottish SIMD unemployment percentage – this is 373,100 (7.2%) [18]. It is noted that individuals who are unable to work due to disablement or other reasons also fall into this category.

Finally, the findings from the SIMD analysis in another four cities are summarised in Table 5 for comparison. Central city areas of approximately similar size as that of Fig. 1 have been examined and compared here and therefore Glasgow and Edinburgh were excluded due to their large population. However, Glasgow has the highest deprivation concentration in the whole country. It was found that the deprivation concentration in Dundee is significantly more than in the other compared cities. In particular, the number of the datazones with a SIMD of 15–20% and lower is only in the range of 17–25% of the total in the studied areas while in Dundee this is 39%. The latter, together with the fact that all the deprivation figures in Dundee presented here are higher than the totals in Scotland, implies a strong imperative to take action to cope with the fuel poverty in the city.

3. The solar plan for Dundee

3.1. Estimation of the total roof area in the selected region

3.1.1. Initial steps

Mass calculations of roof areas suitable for solar integration in large regions like cities are a very recent issue. To make these calculations feasible and reliable, the aerial photogrammetry technology must be used. Satellite images of very high resolution can give accurate information about roof size, orientation, inclination and estimate successfully how nearby buildings and other obstacles like trees have shading effects on the roof. However, commercialization of such kind of software has not started yet and therefore the authors had to find another more conventional approach for the roof potential estimation in Dundee.

In this study the online RoofRay software was used [19]. This software uses a satellite interface with 2D Google images of about 1 m accuracy. The user can draw closed areas of any shape on the interface and these correspond to roof objections that the eye can observe on the map. After the roof objections have been pointed out and the inclination and orientation have also been defined by the user, the software calculates the area of the tilted surface in which the user is interested.

There were several difficulties faced during the roof area estimation. First, it was impossible to have information about the shadings on each roof during all sunshine hours. Furthermore, most of the obstacles such as ventilation fans, chimneys, flues, dormers and roof windows and any other openings were visible on the most of the roofs, but it is possible that some hidden objects might not have been considered in the calculations. For these reasons some safety factors have been inserted in the estimation. These were 5% for the any hidden objects and 15% for any unconsidered shading effects, following the methodology of Izquierdo et al. [20] for the estimation of the shadowing coefficient by human inspection. Finally, the geographical area of the roof estimation was the same as in the deprivation analysis except for the historical city centre and its surroundings in which building density was really high and thus it was impossible to consider the shading effects and also to distinguish which buildings were of domestic use. These are shown in Fig. 2.

3.1.2. Methodology

The roof estimation process was applied to all the appropriate buildings within the geographical area of Fig. 2. The term appropriate corresponds to any building which has its roof oriented by a maximum of ±30° from 0° azimuth (South). Furthermore, the roof inclination was considered to be 45° for all the roofs (typical in the UK). After the roof area had been found, the PV capacity and energy output were calculated. For the total PV power calculation the following equation was used which derives from the determination of a PV module efficiency in Standard Test Conditions:

$$P_{\mathrm{PV,tot}}(\mathrm{kW_p}) = \frac{E^a_{\mathrm{PV}}(\mathrm{kWh/year}) \times 1(\mathrm{kW/m^2})}{H^a_{G,T}(\mathrm{kWh/m^2\quad year})} \qquad (1)$$

where $P_{\mathrm{PV,tot}}$ is the total PV power capacity of all the arrays in the city, E^a_{PV} is the annual energy output from all the PV arrays without considering the inverter and $H^a_{G,T}$ is the annual global solar radiation on a tilted plane (kWh/m^2).

The global solar radiation in Dundee was taken by the METEONORM software and is shown in Table 6. For the calculation of the annual energy output of all the PV/inverter systems some further performance factors were used. These are:

- 15% off for shading effects as discussed in Section 3.1.1.

Fig. 2. Geographical area considered (white-collared) for the estimation of the roof potential.

- 5% for any hidden objects and another 10% off for roof unsuitability due to the roofs shape (e.g. corners).
- 15% efficiency for a typical commercial PV panel.
- 95% for the inverter's efficiency.
- 7% off for transmission (cable) losses.

The combined factor is thus 9.58%.

In the end, every roof area found was multiplied by the total solar radiation to find the available energy for harvesting and then all the factors above were applied to calculate the annual total net energy of the suggested investment.

3.1.3. Results and discussion

It was found that there are about 1300 domestic buildings suitable for solar integration, all of which have tilted roofs with a maximum deviation of ±30° from South. It has also been estimated that there might be about 300 more suitable buildings in the rest of the city. The City Council of Dundee has made a different investigation and concluded that this number is 1500 for the whole city and therefore the two estimations concur. The 1300 buildings reported here do not correspond to same numbers of households, because there were many blocks of flats included, the roofs of which seemed suitable for solar integration.

The total roof area was found to be 88,313 m^2 which can receive 97,914,848 kWh of total solar radiation per annum. According to these outcomes the methodology described in Section 3.1.2 gave 9.6 MW_p total PV capacity and 9,380,242 kWh/year of net electrical energy.

To have a clear idea about the size of the electricity output we have to consider the current energy consumption in the city. According to the University of Strathclyde, the typical annual electricity consumption of a Scottish household is [21]: (a) 3084 kWh for a single person, (b) 4117 kWh for a working couple and (c) 5480 kWh for a four-member family (parents at work and children at school). Furthermore, there is also analytical information (derived from real meter readings) about the electricity consumption in specific zones, the Intermediate Geographical Zones, in the city of Dundee [22]. According to this reference the average annual household electricity consumption in 32 zones is 3601 kWh for the ordinary domestic (78.5% of the total) and 5697 kWh for the Economy 7 tariff (21.5% of the total). If these two averages are combined according to their weights (% of total) an annual average 4052 kWh for the city of Dundee is derived.

It is also suggested that the unsuitable parts of the roof areas can further be usable if bespoke solar thermal collectors are going to be installed. For instance, bespoke AES Ltd. model L of a trapezoid shape can effectively cover roof corners and contribute more to the solar potential in the city. Therefore if another 8% of the estimated roof area can be usable this can bring about 2,500,000 kWh of solar hot water and improve importantly the renewable energy portfolio of the proposed investment.

Concerning the environmental benefits, if we take into account a total 11,880,242 kWh of free solar energy the total carbon savings per year could be up to 4,443,781 kg of CO_2.

3.2. Energy efficiency

It is generally considered that the most important policy to avert fuel poverty is to first reduce energy consumption and increase the energy efficiency in buildings. Typical domestic energy demand reduction measures included in this study are:

(1) Replacement of old boilers with new ones of 85–95% efficiency.
(2) Extra insulation to the solid walls.
(3) Usage of energy saving fluorescent lamps.

Every financially vulnerable household in Dundee can currently receive two types of support for: (1) free energy from the solar installations described in Section 3.1 and (2) one or more of the energy measures discussed above. What is more, proper energy demand management through say consumer's behaviour (wiser use of energy) and load shifting to use day time PVs electricity can reduce the energy consumption of imported energy significantly. There have been several cases in which demand management measures in end-users saved up to 40% of their energy consumption [23] and had a rebound effect of 10–30% in space heating [24]. It is

Table 6
Total solar radiation at different orientations and at 45° inclination for the city of Dundee, taken from the METEONORM software.

Azimuth, deviation from south, negative sign denotes South-East	−30°	−25°	−20°	−15°	−10°	−5°	0°	5°	10°	15°	20°	25°	30°
Annual global solar radiation on a 45° tilted plane (kWh/m^2)	1079	1090	1099	1107	1112	1115	1116	1115	1111	1106	1099	1089	1077

thus concluded that if a 10–15% reduction in energy consumption can be brought by such measures, the deprived families of Dundee can be taken out of fuel poverty once and is this was achieved for all homes, 100% elimination of fuel poverty would be possible.

3.3. Economics

A recent report by Ernst and Young [25] proposes that PV prices are going to halve and reach a cost of $1/$W_p$ by 2013. It also claims that PV investments are already financially sustainable in UK for the domestic sector without subsidy. Today a fully installed PV system of 4 kW in UK ready to operate costs €9053, according to Microgeneration Certification Scheme (MCS) accredited PV installers in UK. According to Solar Cities Scotland experts working for the organisations this can drop to €6117 with a large scale installation as described below in Section 3.1. Therefore, the total budget for a 9.6 MW_p PV installations could cost around €14,680,800.

According to information gathered from AES Ltd, bespoke model L of a trapezoid shape costs about the double the standard panel. An AES Ltd. model H (typical flat-plate, gross area 3.3 m^2) costs €783 and the rest of the system €1533, making a model L total of €3099. If trapezoid panels of gross area 3.3 m^2 were used to cover the uncovered 8% of the roofs, there would be space for about 2141 solar hot water systems which usually cover more than 50% of the annual needs of a Scottish household for hot water. The total cost of these installations would be €6,634,959.

Concerning the rest of the energy measures:

- A typical condensing boiler of 24 kW_{th} in UK cost about €887 in 2008 [26].
- Internal insulation of solid walls costs €6729–10,399 [27].
- Purchase of modern fluorescent lamps is negligible compared to the total solar plan budget.

If a further average €9175 funding is given to 5000 households, that is the estimated number of fuel poor households in the white-collared region in Fig. 2, and the e prices above held, this would cost €45,875,000. Adding up the running costs for solar systems and energy efficiency measures, the total budget of the suggested solar plan for Dundee would be €67,190,759 as is summarised in Table 7.

Finally, an energy balance for the proposed investment and a cost-benefit analysis per fuel poor household and in total for the studied area is given in Table 8. The main assumptions and figures behind the analysis are:

- Household annual income. Two cases have been considered here: a household in fuel poverty with an annual income of €7500 and a household in extreme fuel poverty with an annual income of €4000. According to Ref. [3] the first household has to spend more than 10% of its income to pay the fuel bills and the second more than 20%. If these values were dropped below 10% then the households would no longer be considered as deprived and therefore the mitigation of fuel poverty would have been achieved.
- Half of the households use electricity to heat the water; the rest use gas and all use gas for space heating.
- From the electricity produced from the PV systems, 50% is consumed by the households and the rest 50% is exported to the grid.
- As a simplistic and indicative domestic energy economics management, from the total revenues from the PV generation and export tariffs the households in extreme fuel poverty will receive a 10% increase in their income and the rest will be distributed to the remaining households.
- The revenues from the PV tariffs will be spent on the households' fuel bills to re-calculate the final fuel poverty ratio.
- Current prices of electricity and gas (in UK) used are 0.135 and 0.061 €/kWh, respectively.
- Current generation tariff 0.196 €/kWh and export tariff 0.055 €/kWh, for PV systems equal or less than 4 kW_p [28].
- Annual electricity consumption 4052 kWh per household according to Section 3.1 and annual gas consumption 14,891 kWh per household [29].
- Total number of fuel poor households in the studied area: 5000, of which 10% (500) are assumed to be in extreme fuel poverty.

4. Optimisation of the solar systems

4.1. The PV/inverter system

4.1.1. Methodology and system parameters

Optimisation of the PV system can be looked into different ways such as optimising balance of system performance, yield, and/or optimal performance based on individual performances. Several of these studies have been explained by Norton et al. [30]. The analysis here follows standard PV/inverter optimisation methodologies like those of Refs. [9,31–33]. At the end, the collected results will be compared to those in literature to testify if they are in agreement. The ultimate aim was to maximise the output of a grid-connected PV-inverter system by examining which sizing ratio gives the best energetic or economic performance. The sizing ratio is defined as:

$$R_s = \frac{P_{PV}}{P_{inv}} \tag{2}$$

where P_{PV} is the nominal power of the PV array (kW_p) and P_{inv} is the nominal power of the inverter (kW). In this paper, the sizing ratio is symbolised with R_e when it maximises the energetic performance and R_i when it maximises the economic performance. The energetic performance is also defined as:

$$e_e(\text{kWh/kW}_\text{p}\ \ \text{year}) = \frac{E^a_{inv}}{P_{PV}} \tag{3}$$

where E^a_{inv} the total annual energy output of the inverter. The economic performance is:

$$e_i(\text{kWh/€year}) = \frac{E^a_{inv}}{C_{PV}P_{PV} + C_{inv}P_{inv}} = \frac{E^a_{inv}}{C_{inv}P_{inv}(1 + R_i(C_{PV}/C_{inv}))} \tag{4}$$

where C_{PV}/C_{inv} is the cost ratio of the unit cost of the PV array (€/kW_p) to the unit cost of the inverter (€/kW). According to current inverter costs, this ratio has been considered to be about 5:1.

The primary system, as pointed out in Table 7, is a 4 kW_p PV array directly connected to a DC/AC inverter. Three different inverters (of 97%, 95% and 92% efficiency, the most common in domestic applications of this PV capacity) and several sizes were used in each simulation in the TRNSYS software to find the optimum one. The technical characteristics of the chosen PV module and the characteristic curve of the input inverters are shown in Table 9 and Fig. 3, respectively. The produced circuit in TRNSYS is shown in Fig. 4.

4.1.2. Simulation results

The simulations in TRNSYS gave the results listed in Table 10. They show that the energetic optimum falls in the range of 1.01–1.12 and the economic optimum in 1.06–1.20. The best energetic and economic performance can be achieved for the 40° slope and South (0°) orientation, as expected, in which the optimum ratios are 1.02 and 1.06, respectively. Due to the fact that the maximum possible energy output is desired for the solar plan the sizing ratio 1.02 has been selected for the optimisation.

Table 7
Summary of the costs needed for the suggested solar plan in Dundee.

Action	Primary system	Aggregation	Cost per unit	Total cost
PV installation	4 kW_p building integrated	9.6 MW_p	€1,529.25/kW_p	€14,680,800
AES Ltd. bespoke model L solar thermal collector	One 3.3 m^2 solar panel plus the rest of the system[a]	2141 SWH systems	€3099/system	€6,634,959
Energy efficiency measures	Any combination per household	5000 households	€9175/household	€45,875,000
			Total	€67,190,759

[a] Pipes, pumps, antifreeze, expansion vessel, solar controller and anything related to a full SWH system kit.

Table 8
Energy balance for the proposed solar plan in Dundee and cost-benefit analysis in total and per household in the studied area. All figures are shown in an annual basis.

Energy balance		Cost-benefit analysis for all the households in fuel poverty	
Imported energy needed		**Costs**	
Electricity	−20,260,000 kWh_e	Electricity	−€1,539,794
Gas	−74,455,000 kWh_{th}	Gas	−€3,791,867
Energy benefits		**Revenues**	
Electricity from the PV systems used for local consumption	4,690,121 kWh_e	PV generation tariff	€1,838,527
		Export tariff	€257,957
Electrical energy savings from the SWH systems	1,125,000 kWh_e	**Totals**	
Electrical energy wise savings of 15%	3,039,000 kWh_e	Electricity	€556,690
Thermal energy savings from the SWH systems	1,125,000 kWh_{th}	Gas	−€3,791,867
Thermal energy efficiency savings of 15%	11,168,250 kWh_{th}		
Totals			
Electricity	−11,405,879 kWh_e (43.7% reduction)		
Gas	−62,161,750 kWh_{th} (16.5% reduction)		

Cost-benefit analysis for two individual households

	Household in fuel poverty		Household in extreme fuel poverty	
	Amount	% of annual income	Amount	% of annual income
Income				
Annual income	€7500	100%	€4000	100%
Initial costs				
Electricity bills	−€547	7.3%	−€547	13.7%
Gas bills	−€**908**	**12.1%**	−€**908**	**22.7%**
Sub-total	−€1455	19.4%	−€1455	36.4%
Energy bills after the solar plan				
Electricity	€79	−1.1%	€400	−10%
Gas	−€758	10.1%	−€758	18.9%
Sub-total	−€**647**	**8.6%**	−€**358**	**8.9%**

As a general observation the sizing ratios have a tendency to increase while moving towards western azimuths, lower inverter efficiencies and slopes lower than 40°. For instance, the R_e for the inverter 1 at 30° slope and −30° azimuth is 1.03, increases to 1.07 for inverter 2 and ends up to 1.09 for inverter 3. Similarly, the R_i of inverter 1 and 2 at 20° slope and 0° azimuth is 1.12 and takes the maximum value of 1.20 for inverter 3 at −30° azimuth. The last example also denotes that many values remain unchanged among several variables. During the simulations it was also noticed that the energy output from the inverter remained the same regardless the PV array configuration. For instance, the 5 × 4 array had the same output with the 2 × 10 one and therefore it was impossible to investigate whether there are any differences between different configurations.

The results of Table 10 are in agreement with those in the Refs. [9,33]. More specifically, in Ref. [9] there is a guideline suggesting that for e_e = 1000 kWh/kW_p the R_e falls in the region of 1.0–1.1 for high to average inverter efficiencies and cost ratio 5:1. In Ref. [33] a PV/inverter system located in Copenhagen (55.7° latitude) and

Table 9
Technical data of the PV array used in the simulations in the TRNSYS software.

Technical characteristic	Value
Nominal power	200 W_p
Module efficiency	13.4%
Number of cells	52 (6 × 9)
V_{max}	26.80 V
I_{max}	7.43 A
V_{OC}	32.70 V
I_{SC}	8.22 A
Module total area	1.5 m^2
Array considered	5 × 4 modules of a total 4 kW_p (30 m^2)

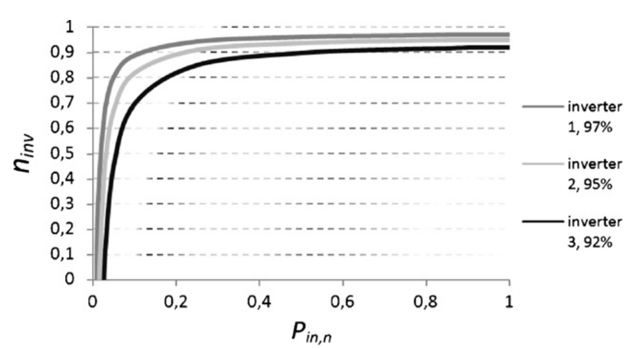

Fig. 3. Characteristic curves of the simulated inverters. The *y*-axis represents the inverter's efficiency (n_{inv}) and the *x*-axis the ratio of the normalised power input to the inverter ($P_{in,n}$).

Table 10
Optimum sizing energetic and economic ratios for a 4 kW$_p$ grid-connected PV/inverter system in the city of Dundee.

Azimuth	Slope	Inverter 1 (97%)		Inverter 2 (95%)		Inverter 3 (92%)	
		R_e	R_i	R_e	R_i	R_e	R_i
−30°	20°	1.11	1.11	1.11	1.11	1.11	1.20
	30°	1.03	1.09	1.07	1.08	1.09	1.10
	40°	1.02	1.10	1.04	1.11	1.10	1.11
	50°	1.01	1.10	1.04	1.10	1.05	1.10
0°	20°	1.08	1.12	1.08	1.12	1.12	1.18
	30°	1.03	1.08	1.05	1.08	1.10	1.08
	40°	1.02	1.06	1.03	1.08	1.06	1.11
	50°	1.01	1.07	1.04	1.07	1.07	1.11
30°	20°	1.11	1.11	1.10	1.11	1.11	1.18
	30°	1.10	1.10	1.10	1.10	1.10	1.10
	40°	1.01	1.09	1.04	1.09	1.09	1.09
	50°	1.01	1.08	1.05	1.09	1.09	1.09

Helsinki (60.3°) was simulated and the results for a 90% inverter efficiency and cost ratio of 5:1 indicated that R_e = 1.01 for both locations with 45° inclination and South orientation and R_i = 1.23 for Copenhagen, R_i = 1.15 for Helsinki.

Last, the operation of the system in optimal conditions, i.e. R_e = 1.02 (P_{inv} = 3921 W), slope 40° and south orientation, gave an inverter energy output of 4060 kWh/year (e_e = 1015 kWh/kW$_p$) and an economic performance of e_i = 0.3694 kWh/€. The latter would be 0.3714 kWh/€ if simulated for R_i = 1.06. The inverter operated for 4147 h and the maximum power output of the system was 3.78 kW in April. If all the systems in Dundee were considered (9.6 MW$_p$) then the total inverter output with a cable loss of 7% (Section 3.1.2) according to TRNSYS would be 9,061,920 kWh/year. This is 318,322 kWh less than that of Section 3.1.3 and the most possible reason for this difference is the PV temperature coefficient which was not included in that estimation.

It must be noted that the studied PV system here does not include an annual net metering/debating scheme. Although net energy metering is a regulatory obligation in many countries and especially in the USA, its implement in the UK faces many obstacles mainly because of the issues arisen concerning the payment and the refunding of the Valued Added Tax in electricity trading. For this reason its use has not been considered in this analysis.

4.2. The SWH system

4.2.1. Analysis of the procedure

Here, the aim of these series of simulations is once again to maximise the overall performance of the SWH system. The parameters under examination were the tank's volume and height and the circulating fluid flow rate in the collector. After this process, the operation of the system will be checked and all the results will be discussed and compared to those in literature and market. The optimisation procedure has as a guideline the methodology of Ref. [34] in which the same simulations were made for a SWH system in Montreal, Canada by using the TRNSYS software.

Table 11
Calculated mean monthly cold water temperature.

Month	Cold water temperature (°C)	Month	Cold water temperature (°C)
January	4.53	July	12.07
February	5.04	August	11.56
March	6.38	September	10.17
April	8.27	October	8.27
May	10.16	November	6.38
June	11.56	December	5.01

The size of the system considered is the primary system of Table 7, which is a 3.3 m^2 flat-plate collector from AES Ltd (model H). Although the collector's area must be a subject under investigation, the findings of the case study in Section 3 were taken as a datum for the simulations. Therefore, the collector's area and the fluid characteristics were the constants of the simulations. For the latter, AES Ltd suggests that a glycol/water mixture is used of up to 40% by volume, with about 1000 kg/m^3 density and 3.8 kJ/kg K specific heat for operating temperatures. The water consumption, according to AES Ltd., was considered to be 50 L/person and the household profile that of a 4-member family (Fig. 5).

The most important barrier for the inputs in the simulations was the knowledge of the cold water temperature. The authors faced difficulties here, as even the Scottish Water utility does not keep records of water temperatures. To overcome this problem, it was assumed that the supply of the inlet cold water in the bottom of the tank had the same temperature as the ground at 0.5 m depth. Hence, the mean monthly cold water temperature was calculated approximately by using Labs's equation [35] and is listed in Table 11. The daily consumption profile was also not available and was defined empirically (Fig. 6).

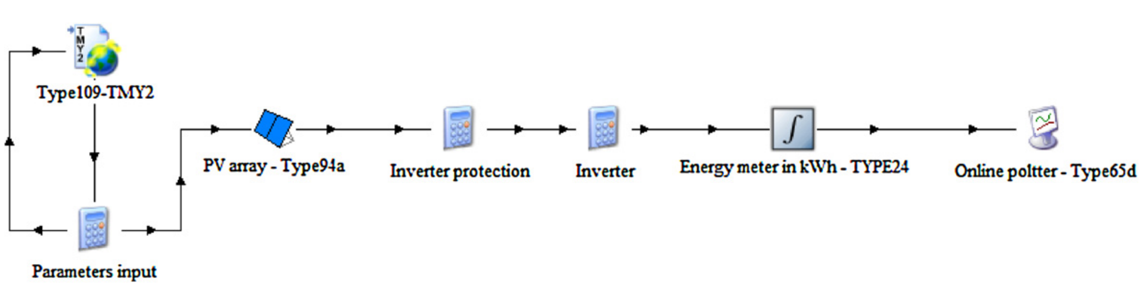

Fig. 4. The simulated circuit in TRNSYS–IISiBat interface. The Inverter protection block cuts off any power values above the inverter nominal power. The Inverter equation block has been used instead of Type 135 to include the curves of Fig. 3, based on Eq. (2) of Ref. [33].

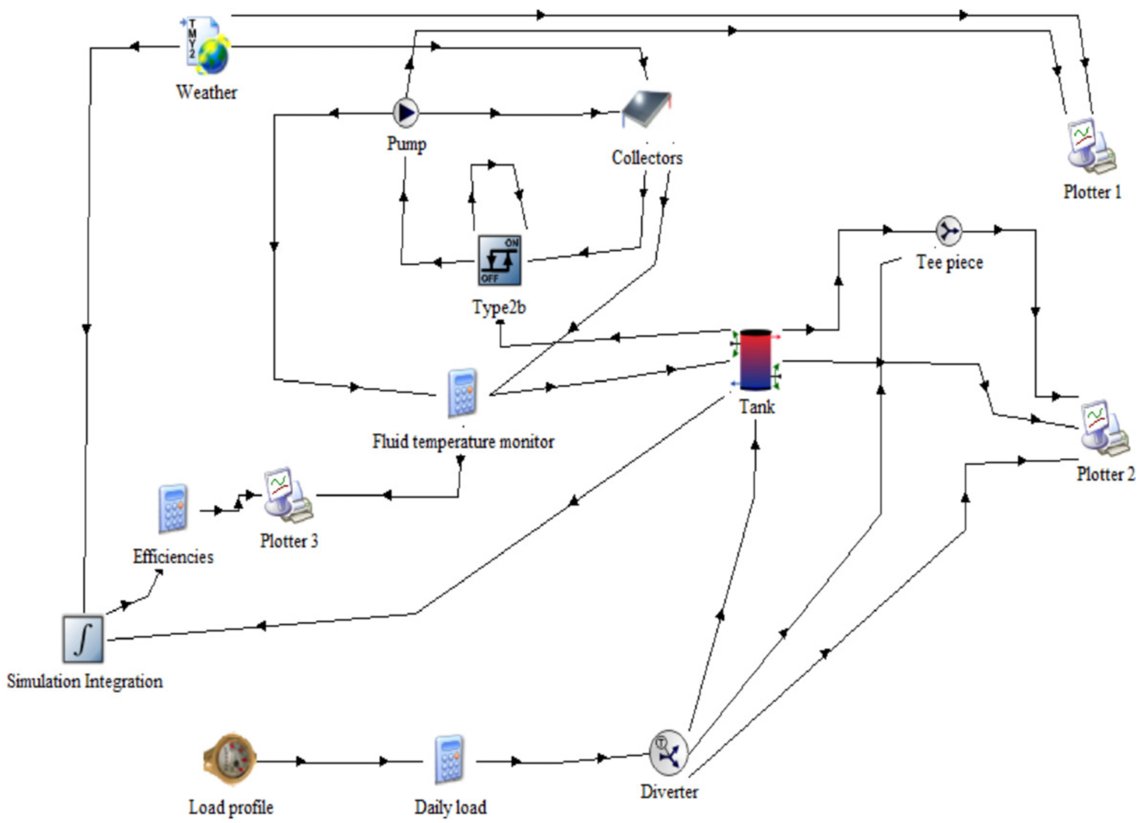

Fig. 5. The simulated SWH system in TRNSYS.

4.2.2. Results

The order of the simulations was as follows: first the tank volume was simulated with a flowrate of 72 kg/h (the nominal flow rate for which the AES FPC was tested) and a tank height of 0.9 m, then the tank height with the same flow rate and the optimal tank volume and finally the flow rate with the optimal values of the volume and the height of the tank. The results are given in Fig. 7. During the simulations the factor that was able to define the optimal values was the solar fraction, i.e. the ratio of the energy rate from the collector to the total energy supplied to the load. This was calculated for every hour and the annual average value was considered at each simulation. During the hours that there was no solar radiation (e.g. at night) the auxiliary heat source (electrical for the TRNSYS storage tank) was turned on to keep the water temperature constant to 55 °C throughout the whole year.

The simulations showed that the optimal tank volume is 350 L. However, the size of 230 L (or 70 L/m^2) was chosen for cost-effectiveness reasons. This results in a solar fraction of less than 2.5% away from the optimal one. The solar fraction increases exponentially for gradual changes in the tank volume and after the 200 L it has a limited sensitivity to further volume changes. After the 200 L threshold it can be seen that the water's thermal mass is enough to keep it warm for longer periods but not for infinite increases in volume due to the occurrence of more heat losses at larger values.

The other two parameters have a similar profile. The optimal tank height is 1 m which is a very common value for storage tanks. An interesting point in Fig. 7(b) is that after the 1 m the changes in the solar fraction are negligible and the curve is almost horizontal. This means that many sizes are accepted with actually no impacts on the system's performance.

The optimal flow rate is 40 kg/h, a relatively low value compared to the tested one (72 kg/h). This happens probably because the collector's area is not enough for the consumption defined in Fig. 6 and thus a slightly larger area might be needed.

Comparing the results with those in literature, AES Ltd suggests a 200 L storage tank for a 4-member household or 60 L/m^2 of

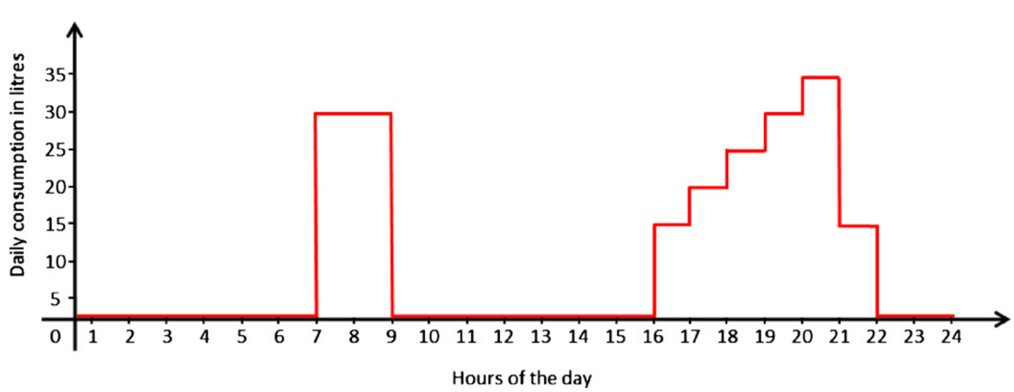

Fig. 6. Daily water consumption profile in litres.

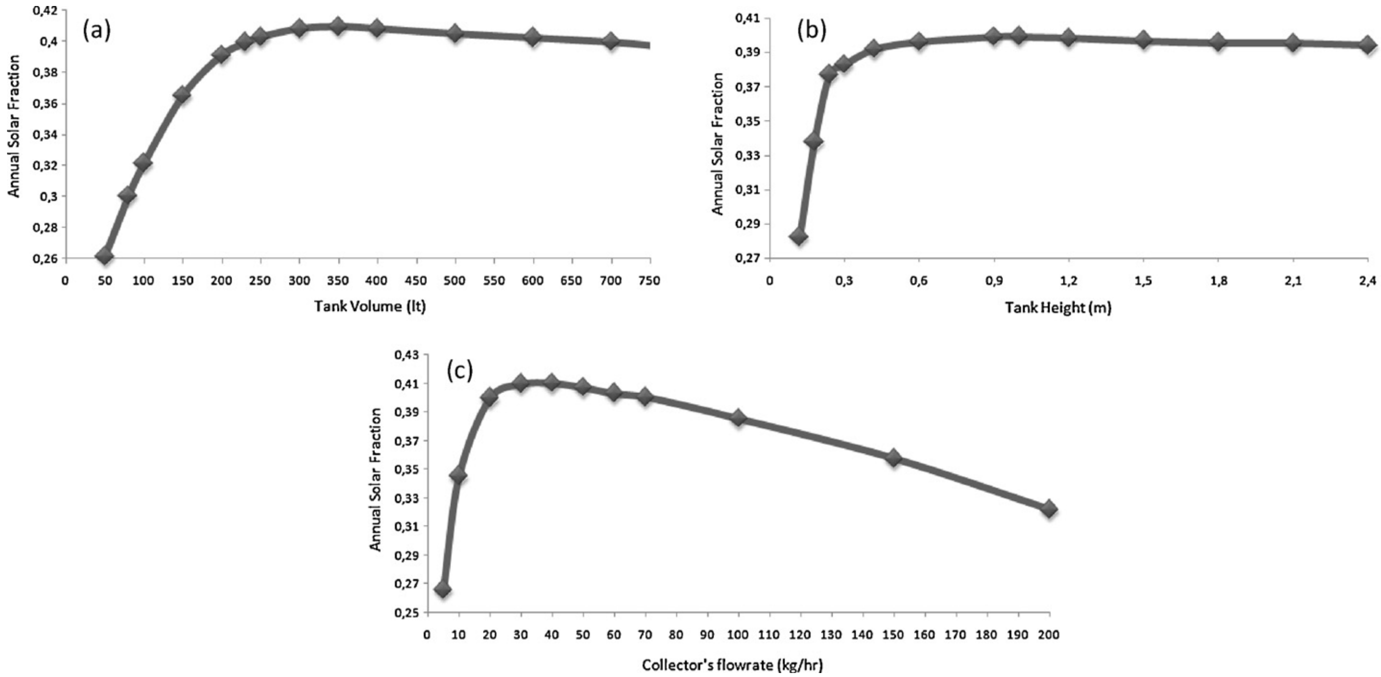

Fig. 7. Optimisation results for the SWH system: (a) optimal tank volume 350 L, (b) optimal tank height 1 m and (c) optimal flow rate 40 kg/h.

collector area, which is close to the one found here. In Ref. [34], the simulations were made for a 6 m^2 collector and a consumption of 246 L/day and the authors suggested an optimal storage tank of 55–65 L/m^2, a range of values in which, AES Ltd. and the findings here, fall successfully. The 1 m tank height was also used in Ref. [36] for the simulation of a 200 L stratified hot water tank and the results showed higher energy output compared to a conventional one. Finally, the optimal flow rate in Ref. [34] was found to be 20–30 kg/m^2 h, a comparatively higher than that the one here (12 kg/m^2 h). Nevertheless, it must be noted that the water daily consumption per collector area in Ref. [33] was 41 L/m^2 and in this study 61 L/m^2 and this difference can account for the discrepancy above.

The optimal values (230 L of tank volume, 40 kg/h flow rate and 1 m tank height) gave the following operational conditions: solar fraction 0.41, solar energy 1455 kWh/year and energy from the auxiliary heating 2435 kWh/year. The maximum and minimum recorded temperatures of the water in the tank occurred in July and were 72.1 °C and 50.2 °C, respectively. The reason for the lowest temperature occurred in the summer is because of the effect of the tee piece, which mixes the hot water with cold in order to supply it at bearable temperatures when high water temperatures are produced by the system. The circulating pump operated for 2743 h/year. The solar collector can supply constantly 41% of the hot water needs for the whole year. This fraction can be even higher if the consumption is reduced. For the remaining 59%, of the year if the condensing boiler suggested in Section 3.2 is used as auxiliary heating, a very high efficiency can be achieved from the whole system and therefore the optimised system significantly improves the level of deprivation experienced in the studied households.

5. Conclusion

A solar plan for the city of Dundee was proposed which showed clearly that a solar potential exists in Dundee capable of contributing dramatic reductions in fuel poverty in the city if appropriate State funding is applied. In the study it was found that the city contains a significant concentration of deprived households. A sample of 72,329 people was examined and according to the SIMD the 14,580 of them are income deprived, 9880 live in households without central heating and 7649 are unemployed. It was impossible to estimate how many of them operate under the fuel poverty line, but 5000 households were taken into account for the final energy calculations.

It was estimated that there are about 1300 domestic roofs in the studied area of central Dundee which can hold 9.6 MW_p of solar PVs and generate 9,380,242 kWh/year. Further energy measures, which include the production of 2,500,000 kWh of solar hot water and also energy efficiency actions like wall insulation and modern boilers, can be used to eliminate, forever, the entrenched problem of fuel poverty there. The total carbon savings from PV and solar hot water installations, but not insulation and energy efficiency, would be up to 4,443,781 kg of CO_2. A total budget of €67,190,759 was estimated as necessary to support the proposed action plan in the deprived areas studied in Dundee.

The most basic problem of the methodology used was the limited accuracy of the RoofRay software images, because Google Map satellite view was used. These images are not perfectly suitable for a detailed solar report because:

- They have a resolution of maximum 1 m accuracy, while advanced aerial photogrammetry can provide 5 cm accuracy.
- They are 2D. For studies like this one or more 3D geographical images must be used to perfectly estimate the shading effects of nearby buildings and trees.
- They are not updated frequently. Google Maps usually delay to update the satellite photos of cities worldwide resulting in buildings taken into account that no longer exist or are recent new-built which are not shown in the current Google version.

Despite the imaging problem, it is believed that the numbers presented in this paper provide a robust indication of the solar potential in Dundee and if the energy efficiency measures are applied in conjunction with the solar investments it is feasible that a 100% elimination of the fuel poverty in the city can take place.

The solar systems were optimised at the end by using the TRNSYS software and standard applied optimisation methodologies. The optimal sizing ratio which maximised the energetic performance of the PV/inverter was found 1.02. The optimal values for SWH system were 230 L for the tank volume, 1 m for the tank height and 40 kg/h for the flow rate. These are in agreement with the literature, with some differences which do not cancel their overall validity.

This paper provides a novel calculation method for quantifying the broader social and economic value of roof integrated solar systems in taking vulnerable populations out of fuel poverty in Dundee. A key Scottish Government policy driver is now the need to increase the resilience of the population in the face of challenges such as rising fuel prices and more extreme climate events, including colder winters when the issue of fuel poverty becomes one of life and death in some households.

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