Renewable Energy
on the University Estate

by

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Fourth-year undergraduate project in
Group D, 2013/2014

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signed: ______________________________ Date: _______________

Technical Abstract

Renewable Energy on the University Estate - Bryn Pickering

Purpose and Method As a result of the United Kingdom's Climate Change Act 2008 and the Higher Education Funding Council for England 2010 policy on carbon reduction, the University of Cambridge has set in place its own CO_2 emissions reduction target of 34% below 2005 levels by 2020. In light of this, it is necessary to analyse the contribution to the target from renewable energy sources situated on the University Estate (the Estate). The sources are all small-scale and have been primarily installed due to a 2006 City Council requirement to offset 10% of predicted regulated CO_2 emissions from new building developments with on-site renewable generation. The effectiveness of the Photovoltaic (PV) arrays and Ground Source Heat Pump (GSHP) installations is analysed and discussed with a view to determining the shortcomings and achievements in the practices of the University with regards to renewable energy generation. The study makes use of a number of monitoring systems used by the University as well as meetings and interviews with University staff and experts on renewable installations. A survey of University members is also undertaken to ascertain opinion and extent of knowledge with regards to energy use and renewable installations.

Report Layout Although investigating all renewable energy sources on the Estate, of which there are 13 installed at a building level, this study concentrates on 4 particular case studies due to the availability of data and background information for these particular sources - one University College renewable source is also utilised:

1. University Library Phase 6 Extension
2. Engineering Department
3. Sainsbury Laboratory
4. Robinson College

These case studies are used to analyse and discuss facets of the process by which renewable energy generation is installed and operated on the Estate; the analysis has been divided into policy, technical and social effectiveness.

Results Results found in the study relate directly to the case studies considered:

1. Predicted regulated emissions of a development on the Estate, used to size renewable installations for 10% offset, tend to be lower than the actual emissions of the commissioned building. This leads to renewable energy installations which do not meet 10% of regulated emissions in almost all cases.

2. The installed renewable energy sources provide an offset of less than 1% of the University's total emissions. This is a result of incorrect sizing in design as well as installations being non-operational. Negative attitudes exist due to lack of operation of GSHPs, leading to expected lower uptake of such sources in future developments.
3. University incentivised schemes can lead to more research based installations, which may aid future developments in on-site renewable generation.
4. When considering designing on-site PV to meet a greater emissions offset requirement than that set out by the MR, arrays cannot be optimised to provide more than one or two percentage points. Current weather data available in Cambridge is insufficient to use for monitoring such PV arrays as well as for design of arrays which advantage from the Cambridge climate.
5. Surveying University members, based on a College sample size, found low awareness of University renewable installations and a correlation between awareness of energy use and efforts made to reduce energy waste. Furthermore, display of energy in terms of kWh or number of kettles boiled is preferred.

Conclusions The study finds that current policy of the University with respect to renewable energy generation is not sufficient to incentivise a significant increase in contribution to CO_2 emissions reduction from such sources. Any new policy should aim to maximise renewable generation per new development, by use of several sources per building, or enforce the use of the limited on-site space for innovative developments that could aid research. The former approach would see a more significant contribution from renewable generation to the carbon targets of the University while the latter may be more beneficial for the future of on-site renewables on a larger scale than the Estate and would likely be monitored to a more satisfactory degree. Alongside a change in purpose and policy for incentivising renewable generation, the University does not make its membership sufficiently aware of the installations on the Estate nor energy use on a building or individual level. If rectified, the University could see an increase in support for renewable installations and more concerted efforts to reduce energy waste.

Contents

1 Introduction

Climate change due to man-made greenhouse gas (GHG) emissions, primarily CO_2, is a phenomenon widely recognised by the international community [IPCC, 2007]. The realisation that natural systems may be irreversibly damaged unless atmospheric GHGs are stabilised has led the UK, alongside other countries, to implement policy to reduce national GHG emissions. Most notable of these is the Climate Change Act 2008 which sets out "to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline." In light of this, a carbon reduction target and strategy for higher education in England has been set with a 34% decarbonisation target for 2020 against 1990 levels [HEFCE, 2010/01]. The University of Cambridge is one of many institutes to adopt a similar target; it aims to reduce 2005 emissions by 34% by 2020 as set out in its carbon management plan [UoC, 2010]. Since 2006, Cambridge City Council have also imposed a ruling that all new developments must have 10% of their CO_2 emissions offset by on-site renewable energy sources (renewables). The regulation was first imposed by the London Borough of Merton and as such is commonly known as the Merton Rule (MR). The combination of the MR and the University carbon management plan has seen several renewable/low-carbon energy sources installed on the University Estate (the Estate), primarily over the past 4 years. This report will analyse current Estate owned on-site renewable energy generation effectiveness. It aims to gain an insight into the University's practices and alignment with its mission to "contribute to society through the pursuit of education, learning, and research at the highest international levels of excellence." [UoC, 2014] with regards to renewable energy.

1.1 Literature Review

The Merton Rule (MR) is a planning policy which "requires the use of renewable energy on-site to reduce annual CO_2 emissions in the built environment" [Merton Council, 2013]. The MR was first developed and implemented by Merton Council in 2003 and has subsequently been included in the UK government's Approved Document Part L as a measure by which building carbon emissions can be offset, although emissions can be similarly met by other energy efficiency measures Building Regulation Approved Document L2A [2006]. The City of Cambridge introduced a variation on the MR in its 2006 local plan with large developments, over $1000m^2$, such that 10% of predicted CO_2 emissions must be supplied on-site [Cambridge City Council, 2006] and refers particularly to:

- Active solar thermal.
- Photovoltaic cells (PV).
- Wind turbines.
- Biomass for community heating or Combined Heat and Power (CHP).

- Ground source heat pumps (GSHPs).
- Passive solar design.

A later assessment in Cambridgeshire has found that it is unlikely that the policy delivers the intended 10% reduction of a building's CO_2 emissions [Letcher et al., 2012]. High levels of satisfaction and support were found for renewables provided installation had been undertaken correctly and maintenance issues were minimal. Reciprocally, incorrect installation and lack of information on effective operation led to dissatisfaction and worries. The assessment suggests a revision to policy such that University developments meet the 10% energy requirement with PV alone due to its social acceptability and ease of installation and monitoring.

In 2007, due to cost concerns, it was not recommended that the University meet its renewable energy requirements from on-site renewables, but rather from large-scale solutions such as anaerobic digestion, district CHP or wind power [Faber Maunsel, 2007]. However, a lack of available sites or resources has led to on-site renewables being the sole contributor at the end of 2013.

1.2 Scope of Study

This study will concentrate on currently installed GSHPs and PV panels situated at 11 buildings on the Estate and one Cambridge College building (Table 1). There are two biomass boilers installed in buildings on the Estate, but vibrations induced by delivery vehicles for constant wood pellet supply may disturb delicate experimental equipment in surrounding buildings. As such, the use of biomass boilers is not expected to increase in penetration within the Estate renewable portfolio and will not be considered further in this study.

Furthermore, passive solar design is a measure by which the MR can be met for a new build. Passive solar design involves designing the building to gain from solar radiative heat in the winter and to limit heating from the same source in the summer [NREL, 2001]. This measure has been utilised in a number of new builds on the Estate to meet MR requirements. However, as it is integral to the building fabric, its effect cannot be realistically measured without suitable benchmark buildings; suitable buildings would need to be identical to the considered Estate building in design and operation, except for a lack of passive solar measures at the design phase. A lack of such benchmark buildings available for this study means the contribution of passive solar design to CO_2 emissions offset will not be considered further.

The study aims to view on-site renewables as an energy generation source but also a platform from which future testing and CO_2 emission awareness can develop. This involves an assessment of each installation in terms of:

- Policy Effectiveness.
- Technical Effectiveness.
- Social Effectiveness.

Building name	Building Abbreviation	On-site renewable	Purpose for installation
Architecture studio extension	AE	GSHP	Novel heating design
Hauser Forum	HF	GSHP	City Council regulation
Kavli Institute of Cosmology	KI	GSHP	City Council regulation
University Library phase 6	UL	PV 'Trees'	City Council regulation
Department of Engineering	CUED	PV	University funding
Sainsbury Laboratory	SL	PV	City Council regulation
Alison Richard Building	ARB	GSHP	City Council regulation
Astrophysics (Battcock Centre)	BC	GSHP & PV	City Council regulation
Sports Centre	SC	PV	City Council regulation
Materials Science & Metallurgy	MSM	PV	City Council regulation
BP Institute	BPI	PV 'sails'	Gift from benefactors
Robinson College	RC	PV	Financial

Table 1: University and College buildings considered in this study.

As data is not available in full for every installation - and for each there are many fine details that would necessitate a great deal of discussion - it is impractical to consider all the installations in this report. As such, the report will make use of a number of case studies in order to analyse the detailed aspects of the different facets of effectiveness. The following case studies have been analysed in-depth and will be discussed, with respect to different aspects of the current process of renewable installations on the Estate, alongside a general overview of the entire installation portfolio:

1. Policy Effectiveness
    (a) Part L Requirements
        - **Case study 1:** University Library phase 6 extension emissions.

A study of the UK Building Regulation Part L CO_2 emission predictions process and comparison to actual emissions.

    (b) University Policy
        - **Case study 2:** Engineering Department

A study of the use of the University Energy and Carbon Reduction Project for funding renewable installations on the Estate.

2. Technical Effectiveness
    - **Case study 3:** Sainsbury Laboratory

A study of solar array design and the potential for optimisation beyond minimum requirements as set out by policy.

3. Social Effectiveness
    - **Case study 4:** Robinson College

A study of University members' attitudes towards energy use and renewable energy production on a building scale.

1.2.1 Unassigned Sources

This study utilised a range of sources, of which some are used to aid discussion or are collated to perform necessary calculations. As such, they are not referenced directly in the report. However, they are relevant to the study and are listed here:

1. Council planning application documents.

Sustainability Assessments included as part of planning applications contain details of predicted building emissions as well as the method by which 10% of those emissions are expected to be offset using renewable energy sources. Many of these assessments are no longer available.

2. University SystemsLink database.

The University works with Estate building managers in order to collate and make available monthly gas, electricity and water consumption data of buildings on the Estate. The data is sourced from manual readings and automatic monitoring of meters (via the TREND BMS). The database was the primary source for annual building CO_2 emissions and some renewable energy generation.

3. University TREND Building Management System (BMS).

The TREND BMS is used to monitor and control the hundreds of sensors installed in every building on the Estate. Data for electricity and gas consumption was acquired from the BMS when data was unavailable from the SystemsLink or a particular meter reading was required. The system usability is low because it is not possible to copy readings, such that it is not feasible to undertake large-scale data analysis.

4. Energy and Carbon Reduction Program (ECRP) Footprint Tracker metering.

In order to analyse energy meter readings in large data-sets, the footprint tracker scheme, initiated by the University ECRP, was utilised for certain pilot sites (see section 2.2). The scheme collates building energy data for online graphical display, which can be easily adapted for historical analysis.

5. Atomwide Weather Station Data.

The University weather station does not provide solar irradiation information, other than the binary output defining whether it is 'sunny' or 'not sunny' at any given point in time. As such, another local weather station was found in the City centre, provided by Atomwide network solutions, in order to provide values for irradiation as W/m^2 to the horizontal plane from 2007-2013.

6. Meetings and interviews:

    (a) David Atkins (Head of Innovation: Ice Energy)

    A specialist in GSHPs, David Atkins provided an insight into their operation, common malfunction errors and best practice solutions.

    (b) David Green (Superintendent of Workshops: CUED) and Caston Urayai (Temporary Researcher: CUED)

    The CUED PV array was designed by Dr Urayai and proposed by Mr Green. They provided information regarding the purpose of the installation and the process by which it was realised.

    (c) Chris Lawrence (M&E Services Advisor/Project Manager: University of Cambridge Estate Management (EM))

    Chris Lawrence contributed to understanding of the Soft Landings approach taken by the University on monitoring new developments and subsequent results from recent developments, including energy use and renewable source generation.

    (d) Roger Ling (Advisory Officer: EM)

    Roger Ling provided an understanding of the University TREND BMS and the types of sensors installed in buildings for metering.

    (e) Paul Hasley (Energy Officer: EM)

    Paul Hasley outlined the process of gathering and analysing energy data on the Estate. This included compilation of the SystemsLink database from various metering sources and analysis of energy demand reduction schemes.

    (f) Building maintenance/facilities managers

    For several of the buildings considered, a site visit was undertaken. At this time, the particular building maintenance/facilities manager was interviewed.

2 Policy Effectiveness

2.1 Merton Rule

2.1.1 Part L Requirements

In accordance with Part L building regulations, the prediction of CO_2 emissions from gas and electricity use must be calculated for any new building development [Building Regulation Approved Document L2A, 2006]. This prediction is compared to a target emissions rate (TER), facilitating further design modifications if the prediction exceeds the TER. The MR 10% offset is taken from these predictions, so an understanding of their accuracy is required. Part L predictions have been found to be an inexact representation of actual emissions, averaging 14% lower than post-occupancy measured emissions [The Carbon Trust, 2012]. This disparity comes from several factors, but primarily the distinction between regulated and unregulated emissions (table 2). Part L predictions only include fixed building services - the so called "regulated" emissions. Further emissions are "unregulated", from energy use by building occupants, and are not included in the part L requirements. The addition of unregulated emissions alongside inefficiencies from poor operation & maintenance and incorrectly predicted working hours lead to unexpected additional energy requirements from a development, once commissioned.

Regulated Emissions	**Unregulated Emissions** (not exhaustive)
Space heating	Plugloads
Hot water	IT services
Cooling	Security
Mechanical ventilation	Lab equipment
Primary lighting	Task lighting

Table 2: Comparison of regulated and unregulated energy use as is defined by the Building Regulation Approved Document L2A Building Regulation Approved Document L2A [2006].

Building emissions originate from the use of electricity and gas, whether regulated or otherwise. The energy use of the building, given in kWh units, is converted to $kgCO_2$ by use of emission factors - which represent the amount of emitted CO_2 per unit of gas or electricity consumed. 2006 Emission factors are used in Part L predictions (Table 3). Electricity displaced by on-site renewables is assigned a higher emissions factor as it is assumed to displace grid coal power plant electricity. The grid electricity emissions factor changes regularly, with the 2013 average being 5.5% greater than in 2006. For the remainder of this report, 2006 values will be taken to allow for comparison with predicted values.

Predictions of CO_2 emissions, and the plan for offsetting with on-site renewables, are submitted by the building Mechanical & Electrical (M&E) contractors to the city council at the planning stage. These predictions are not necessarily kept by any of the parties concerned,

Emission source	**emissions factor ($kgCO_2/kWh$)**	
	2006	**2013**
Gas	0.194	0.194
Grid Electricity	0.422	0.446
Displaced Electricity	0.568	0.568

Table 3: Emissions factors for building primary energy sources in 2006 and 2013.

leading to the inability to compare predictions to actual building CO_2 emissions in some cases. Where predictions are available, there is a disparity between total building CO_2 emissions and building regulated emissions (Table 4) due to the omission of unregulated emissions, among other factors, as discussed earlier.

	CO_2 emissions (kg)			
Building	Predicted Regulated	Predicted Unregulated	Actual (2013)	MR Offset Target
HF	Unknown	Unknown	220,233	Unknown
KI	Unknown	Unknown	79,335	Unknown
UL	17,670	-	82,937[1]	1,767
SL	631,270	3,286,200	2,677,614	63,127
ARB	226,100	Unknown	257,868	4,350
BC	53,834	Unknown	N/A[2]	5,383
SC	Unknown	Unknown	N/A[2]	37,351
MSM	180,800	442,700	N/A[2]	17,345

Table 4: Predicted and actual CO_2 emissions from Estate developments requiring an MR offset. Actual emissions given as combined regulated and unregulated.

There is currently no policy put in place by the Government nor City Council to monitor the disparity between predicted and actual regulated CO_2 emissions, although building regulations do require that the whole building energy use is monitored (based on predictions undertaken later in development). This leads to installed monitoring equipment that does not necessarily distinguish between intended "regulated" and "unregulated" energy use, such that separating the two from the actual emissions is not possible for almost all developments.

2.1.2 City Council Requirements

As per Cambridge city council regulations, part L predictions on a new development are used to set a 10% offset requirement to be met by on-site renewables or passive solar design. Both the MSM and ARB projects had the 10% offset of regulated emissions exceeded by use of passive solar design - 10.5% and 27% respectively. This allowed for the 10% offset to be extended to include some unregulated emissions and the subsequent deficit to be accounted for with on-site renewables. The consequent emissions offset required from on-site renewables was predicted to be ~5% and ~6% of regulated emissions for MSM and ARB, respectively. In

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[1] Value calculated as fraction of whole-building emissions, see Case Study 1 for more information.

[2] Building has been commissioned for under 1 year, so annual emissions cannot be measured.

other developments, unregulated emissions from IT equipment was included when calculating the 10% offset requirement, but the extent to which this occurred is unclear from analysis of planning documentation. Due to City Council policy, 5 PV arrays and 4 GSHPs have been installed on the Estate; the policy has driven 80% of the installations and, with development of the West Cambridge site continuing, is likely to contribute further.

2.1.3 Post Occupancy Obligations

Upon commissioning, actual emissions of a development are monitored by the EM. Building Regulations do not require that action be taken due to any discrepancy between predicted and actual emissions or due to the designed offset not being met by installed on-site renewables. However, the EM does analyse actual emissions and production from on-site renewables over the first 3 years after commissioning a building, as part of the development "Soft Landings" phase. The Soft Landings framework was developed for the University of Cambridge in 2002 [Roderic Bunn, 2011] and sees the University working closely with development contractors to allow for any major discrepancies to be dealt with. Post-occupancy monitoring for Building Regulations and Soft Landings involves whole-building analysis and does not aim to validate the accuracy of regulated emissions predictions undertaken at the planning phase of a development. Furthermore, only Soft Landings requires that renewable installations are monitored, such that any malfunctioning installations should certainly be dealt with within the first 3 years after commissioning a building.

As will be seen in section 3 (Technical Effectiveness), there are many post-occupancy discrepancies whereby renewable installations are not acted upon in a timely fashion, if at all, including in the Soft Landings phase of a development. These instances display a policy shortcoming that may require more action from the University to ensure that post occupancy monitoring and maintenance is adhered to in a more strict and prompt manner by building managers and EM staff. The consequence of unsuitable monitoring and maintenance policy for on-site renewables will be discussed further in section 4 (Social Effectiveness).

Case Study 1: University Library Phase 6 Extension

The University Library phase 6 extension (UL) was completed in 2010 as the final part of the Library extension program, started in 1994, and was the only part of the extension phases subject to the MR, requiring on-site renewable sources. As a result of the MR, PV panels were installed as "trees" in the Library staff car park. In order to obtain post-occupancy emissions, gas use was estimated from the University SystemsLink database and TREND BMS while cooling and ventilation electricity use was calculated using ECRP 'energy footprint tracker' metering. Systemslink provided gas data for a collection of the Library extension phases in order to obtain a trend for gas use variation throughout the year. The percentage of the Systemslink data attributable to the phase 6 extension was then calculated using TREND data for a number of months of gas data.

The 2013 gas and electricity use for the extension was calculated to be, on average, 2.5% and 4.3% of the total building use respectively. There was little variation in the extension to whole building electricity use ratio, whereas the extension compared to total building gas use varied between 5% in winter and .6% in summer (figure 1).

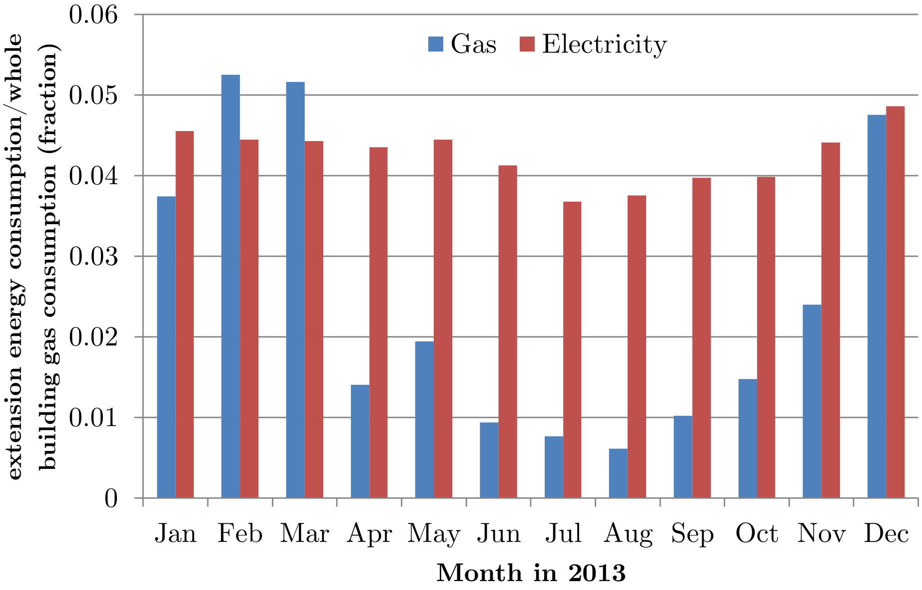


Figure 1: UL gas consumption compared to whole building consumption.

As a result of more stringent TERs in the past decade, set in place by building regulation, it is expected that the emissions intensity of the extension (per m^2) will be lower than that for the whole building. The extension has a floor area equal to 8.1% of the total building floor area and is used solely to accommodate bookstacks, without significant reading space. Bookstacks require strict control of heating and ventilation in order to ensure the correct temperature and humidity is maintained for the upkeep of the books. However, the requirement of gas use for hot water and electricity for task lighting or IT is removed.

The results indicate that the extension emissions intensity is lower than that for the whole building. Variations in extension gas emission intensity compared to the whole building seems to vary with full term - January and April emission intensities experience dips when the Winter and Easter vacations, respectively, are in effect. Visitations to bookstacks may be reduced outside full term, reducing loss of controlled temperature from opened doors.

During the extension design and planning stages, the predictions of energy use were calculated using thermal and ventilation programs certified for use with Part L, which gave a preliminary value of $20.02\text{kgCO}_2/\text{m}^2$ in April 2008. In September 2008, after refinement of the model and measures in design to meet the given TER, the emissions intensity was predicted to be $6.90\text{kgCO}_2/\text{m}^2$. Both these values are regulated emissions. The final prediction of emissions is almost 5 times lower than the actual extension emissions, calculated in this case study to be 32.38kgCO_2/m^2 (figure 2). The actual emissions intensity also refers to regulated emissions as there is minimal building occupant controlled energy use in the extension. As a result of low predictions, the emissions offset provided by on-site PV is only ~2% of actual emissions. This estimate does not include electrical requirements from lighting, so the PV offset is likely to be an underestimate.

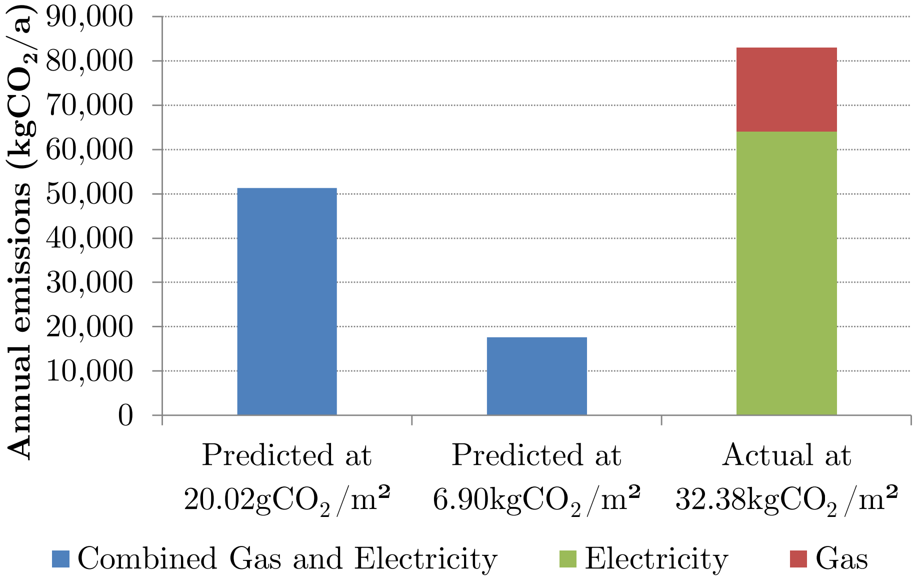


Figure 2: UL actual compared to predicted CO_2 emissions.

This case study provides an example of a building with CO_2 emissions far higher during occupancy than were predicted. Erroneous estimations increase running costs and lead to a negligible renewable offset, which is considerably lower than required. It also demonstrates the difficulty in analysing metering data from University buildings in more detail than the accumulated gas and electricity use for a building.

Additionally, There is more space available for PV panels in the UL car park, which could have been utilised had the installation been designed to the available space rather than the need to meet a requirement based on underestimated values. Equally, the financial outlay of the PV installation will have been disproportionally high due to the steel 'tree' structure used to keep the panels above excessive shading; use of the finances for energy saving measures may have been more beneficial, leading to an emissions intensity closer to predicted. Information on the cost of Estate installations due to the MR were not available so a financial analysis, to compare PV 'tree' emissions offset to building fabric energy efficiency measures, is not possible in this study.

2.2 University Policy

The only University Policy which explicitly refers to renewable energy generation is set out in the University carbon management plan UoC - University of Cambridge [2010]. The document refers to compliance with the MR for small scale on-site renewable schemes and a review to be undertaken for large scale off-site renewable generation. There have been no large scale reviews published since 2007 [Faber Maunsel, 2007], which may raise concern of inaction from the University with regards to large scale installations. The ECRP was established in 2011, in order to support delivery of the aims and targets set out in the carbon management plan, and currently has a 2m p.a. budget until 2020. It does not directly involve itself in MR incentivised on-site renewables, but has seen small-scale PV installed at CUED and hopes to continue efforts for further on-site installations.

Case Study 2: Engineering Department

CUED is one of four pilot sites being studied by the ECRP, the others being the Gurdon institute, the department of Chemistry and the University Library. The study has involved the use of a publicly available web page to view energy use in the buildings, as part of the Workplace Footprint Tracker scheme (http://www.environment.admin.cam.ac.uk/what-are-we-doing/energy/energy-dashboards), as well as energy use reduction initiatives. The need to refurbish the roof of the CUED Inglis Building provided a timely opportunity to install PV panels, with the hope of producing an “energy roof” which would integrate the PV panels with the roofing material. The energy roof was funded by ECRP and is currently their largest single expenditure, with other funding going to several energy efficiency and demand-side management initiatives [ECRP, 2012].

The system was modelled in PV*SOL by CUED, software whose purpose is to model PV systems, and optimised for predicted shading. Unlike installations in new developments, the system was not optimised for cost efficiency or to offset a particular quantity of CO_2 emissions; most of the available space was used with high efficiency panels and a section was installed in order to test the viability of costly micro inverters for widespread use across the Estate.

PV Inverters

The purpose of inverters in a PV array system is to connect the Direct Current (DC) output of PV panels to Alternating Current (AC) devices or to the AC electricity grid [Amaratunga and Hiralal, 2013]. Conventional string inverters are connected to a number of panels in a series and all those panels must produce the same output current. Any disparity between panel currents will lead to energy being lost as heat, for all current which is above the minimum current of the panels, or a low current panel being bypassed - either case results in a lower electrical output than the optimum. The current imbalance is primarily caused by varying solar irradiation incident on each panel, which is a result of disproportionate shading over the panels. Due to the I-V characteristic curve of a solar panel (figure 3), there is a unique value of current and voltage which provides the maximum output power. Varying irradiation changes the curve shape which consequently changes the unique value of I and V for maximum power. The shading which can vary incident irradiation may come from cloud cover or obstacles (such as a chimney stack in the case of CUED).

Micro inverters allow for each panel to operate at its own maximum power based on the lighting conditions they individually experience - the panels can therefore be considered as connected in parallel to the electricity grid [Green, 2013]. Alongside a clear advantage of micro inverters over string inverters in variable shade conditions, micro inverters also allow for a panel to be monitored allowing troubleshooting to take place on an individual panel level [Energy Saving Trust, 2014]. However, there is a higher capital cost incurred by micro-inverters, per installed Watt, and they are a relatively new technology without a significant quantity of research undertaken into lifetime and in-use efficiency. Whether the reduced efficiency and increased capital cost of micro inverters is enough to negate the increased output from separated panels producing maximum power at varying currents is currently a subject of study within CUED and the on-site PV array has the capability to aid this study.

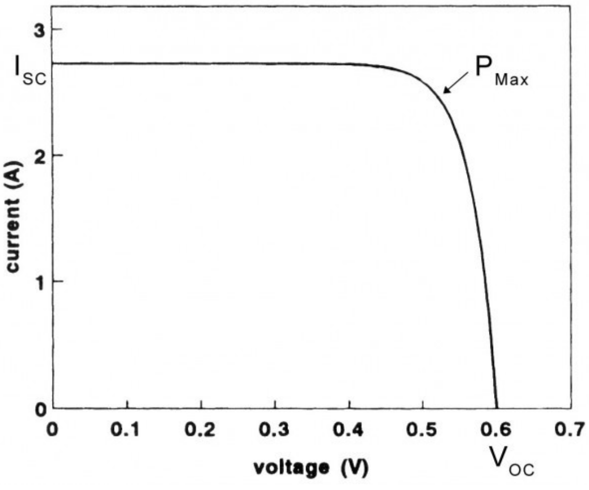


Figure 3: example of a Silicon solar cell I-V characteristic curve, which derives from the characteristic curve of an ideal diode. V_{OC} refers to the open circuit voltage, I_{SC} to the short circuit current and P_{MAX} to the point of maximum power on the curve.

As part of the initial proposal, CUED have considered the viability of DC connection of a further array in the next installation phase. This will test the capability of using PV panels for DC equipment supply, such as LED lighting. A direct supply of DC removes the need for inverters, which can reduce system cost and increase system efficiency. However, without an inverter it is not possible to connect to the electricity grid, such that the installation is incapable of exporting excess supply and eligibility for the FIT is lost.

The motivations behind the CUED array differ from those installed as a result of the MR, demonstrating a different purpose for on-site renewables, driven by University members. As part of the University Living Lab initiative, a testing approach to installations provides the capability for further study and research - the CUED approach, if successful, may lead to the development of further installations to analyse features such as new PV materials or GSHP systems.

2.3 Financial Incentive

The Feed-in Tariff (FIT) and Renewable Heat Incentive (RHI) are both Government led schemes to promote the installation of renewable or low carbon energy sources, for electricity and heat respectively. The FIT was introduced in 2010 to "support organisations, businesses, communities and individuals to generate low-carbon electricity using small-scale (5 megawatts (MW) or less total installed capacity) systems." while the RHI, specific to non-domestic installations, was introduced in 2011 and "pays participants of the scheme that generate and use renewable energy to heat their buildings" if the equipment was installed on or after 15 July 2009 [DECC, 2014]. The schemes provide a shorter time for return on investment by paying the producer for each kWh of energy produced and, in the case of the FIT, for each kWh of surplus electricity exported back to the grid. The FIT has resulted in a greater number of UK PV installations [DECC, 2011] but is not discussed in development planning stage sustainability assessments - which outline the reasons for choosing a particular technology to meet the MR offset target. All the Estate PV installations since 2010 could benefit from the FIT, although it is currently unknown how many are doing so.

The HF, BC and ARB GHSP installations are eligible for the RHI as they were installed after July 2009, but the installations have not been signed up for the scheme as they lack the eligible monitoring equipment. The lack of incentive to take advantage of Government policy of this kind raises questions as to whether the University is truly committed to installing CO_2 offsetting devices or whether these are installed purely for the purpose of fulfilling the MR requirements. Installations which are likely to provide a positive cash flow before the end of their lifetime might lead to larger initial installations, to provide a greater return on investment, and better monitoring and maintenance of the installations.

The RC PV array was installed following a financial assessment, which took into account the FIT. The installation did not exceed 30kWpeak (kWpeak given as the rated output of the array at nominal operating cell temperature and $1000W/m^2$ irradiation) as there are limits to array size, after which the FIT repayment reduces per kWh produced. This shows an installation driven by financial gain in order to gain approval and it is closely monitored by maintenance staff at the College to ensure it is operating as intended. If it proves to be as financially beneficial as predicted, further proposals for PV panels are expected to be presented.

3 Technical Effectiveness

Of the 12 considered installations, only 10 have sufficient data to analyse technical performance. The MSM building is occupied but not completed; as such, metering of the PV array does not exist. The RC installation is too recent to have sufficient data and there are also no available predictions. For the 10 installations being considered for technical effectiveness, it is possible to compare the emissions offset between installations and to the whole building emissions (figure 4).

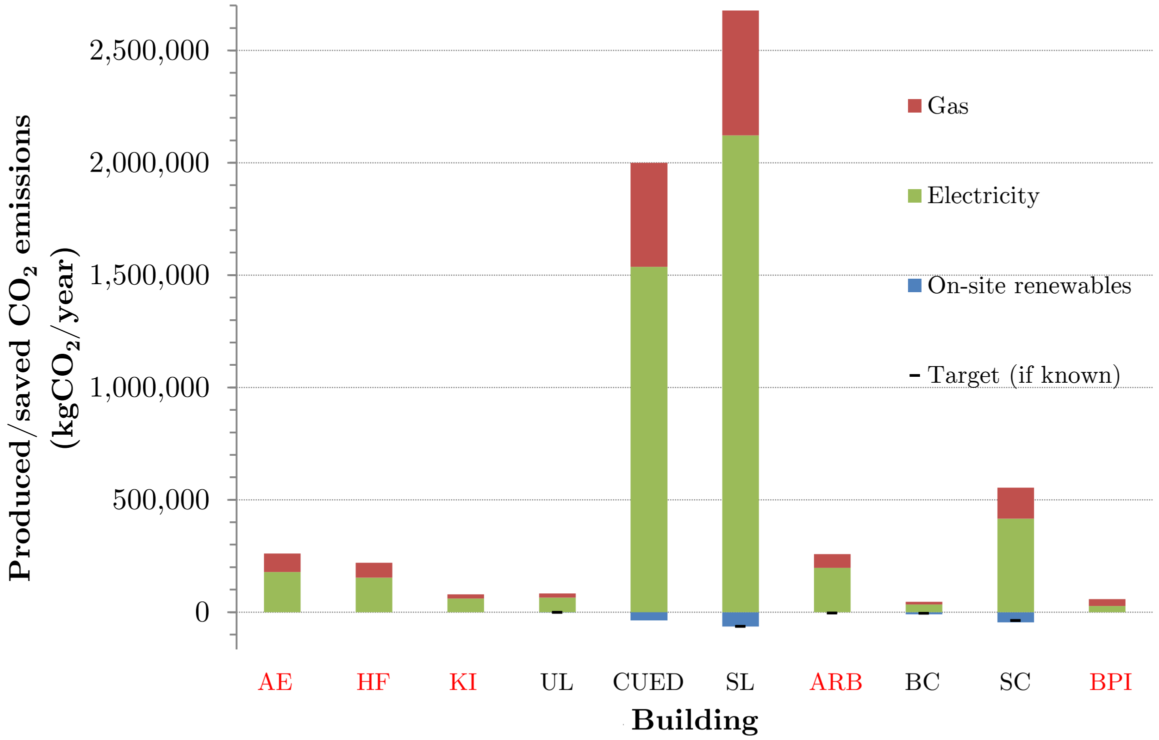


Figure 4: Comparison of 2013 annual emissions reductions for on-site PV arrays and GSHPs installed on the Estate (for installations commissioned for less than one year the outputs have been extrapolated based on current performance and predicted output).

3.1 PV installations

Ignoring the inaccuracies considered in Section 2.1.1 with respect to development emissions predictions, the PV arrays installed on new developments performed as well as or better in 2013 than their design targets. This occurred despite the irradiation to the horizontal in Cambridge being lower than the average irradiation predicted for the City from 1998-2010 and compared to available actual irradiation data (figure 5).

Over a period of 10 days, 1-10 March 2014, the daily output of the PV installations was collated from various sources and compared to global horizontal irradiation (figure 6). The global horizontal irradiation is defined as the combination of direct irradiation and diffuse irradiation onto a horizontal surface at a point on the surface of the Earth (discussed further

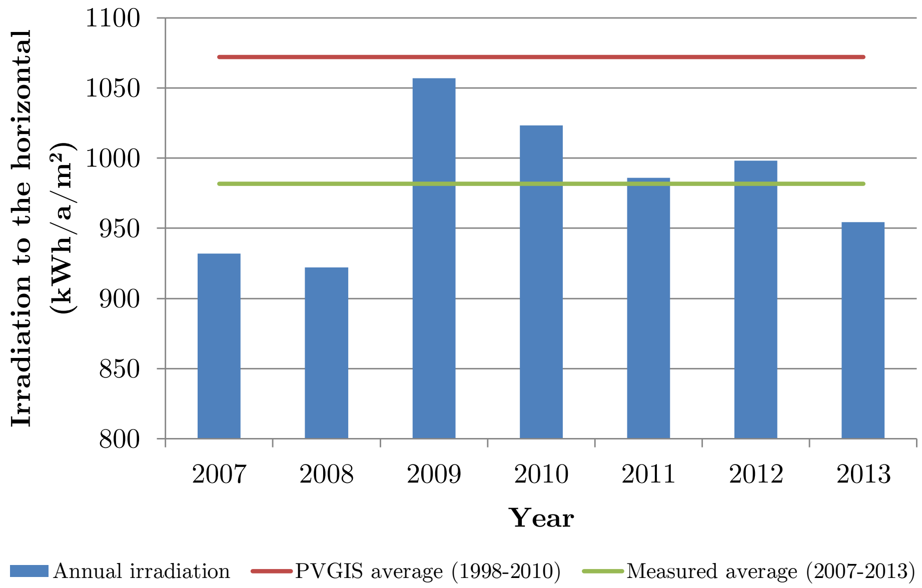


Figure 5: Comparison of annual global horizontal irradiation from 2007-13 to the average over those years and the average as estimated by PVGIS data (as used by PV*SOL).

in Case Study 3).

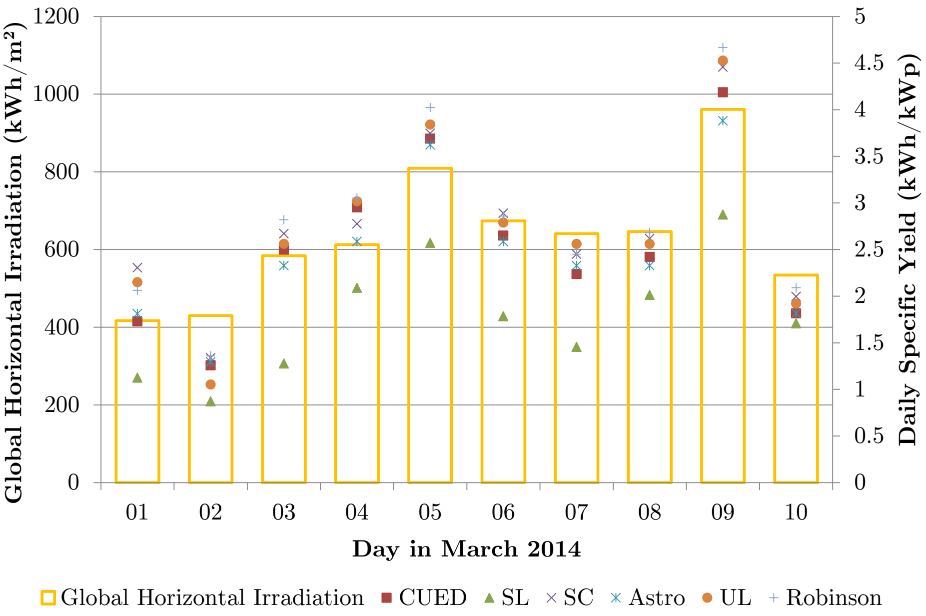


Figure 6: Comparison of daily specific yield for various considered PV arrays alongside the global horizontal irradiation on those days.

Most of the installations had a similar specific yield (kWh per day/kWpeak of installation), with the array installed at RC performing slightly better overall. The SL array showed a significantly lower specific yield than the other installations, which prompted an investigation into the operation of the installation. Upon undertaking a maintenance check, the SL facilities manager was able to conclude that two of the 7 inverters were not functioning correctly due to insulation errors, caused by a current leak between the PV modules and ground [Mastervolt, 2014]. This error had been present for almost two months without any maintenance personnel noticing and relates to the ineffectiveness of post-occupancy policy discussed earlier (section 2) and is discussed further in section 4 (Social Effectiveness).

Case Study 3: Sainsbury Laboratory

The SL was opened in 2010 and has the largest PV array on the Estate installed on its roof. As seen in table 4 of the previous section, the predicted CO_2 emissions are not consistent with actual emissions and predicted unregulated emissions are five times greater than regulated. This means that any on-site renewable source designed to the predicted regulated emissions will only be offsetting $\sim$2% of the total CO_2 emissions. The initial intention for the on-site renewables was to offset 10% of the entire development predicted emissions using PV panels and a GSHP. Due to environmental concerns with regards to ground temperature levels close to the University botanical gardens, the GSHP did not go further than the conceptual stage. It is not possible to ascertain as to whether the ground conditions would vary with a GSHP installed as no assessments were made at the design stage, by the M&E contractor nor the Environment Agency, which leads to the case study concentrating on the PV installation. Once PV panels had been chosen, the array designers were limited by the architects in their design, on visual grounds, to low inclination panels. 25° was the initial design inclination, which was reduced to 5° by the installer, chosen as the lowest possible inclination whilst maintaining the ability for panel "self-cleaning", whereby rain run-off is sufficient to keep the panels clear of dirt build-up. The following section analyses whether the SL PV array is providing its intended supply and whether that design was limited in its output by architectural constraints. Optimisation strategies will then be considered to attempt to find the optimum PV array setup to offset the largest quantity of CO_2 emissions.

Theory

The performance of a solar panel in-situ depends on two factors: the incident irradiation and panel temperature. The incident irradiation onto a panel is a combination of direct and diffuse irradiation (I_d and I_{diff}, respectively) which is usually lumped together as global irradiation to the horizontal (G_h) [NREL, 2014]. Direct irradiation, as the name implies, comes directly from the sun and is maximised on a surface facing normal to the sun's zenith. The proportion of direct irradiation that a solar panel will receive is dependent on how closely matched the normal of the panel is to the normal of the direct irradiation from the sun's current zenith and azimuth (figure 7).

Diffuse irradiation is solar radiation whose direction has been distorted by particles in the air and may have come directly from the sun or has reflected from the Earth's surface. As a result, diffuse irradiation can be considered to be isotropic, existing in equal measure

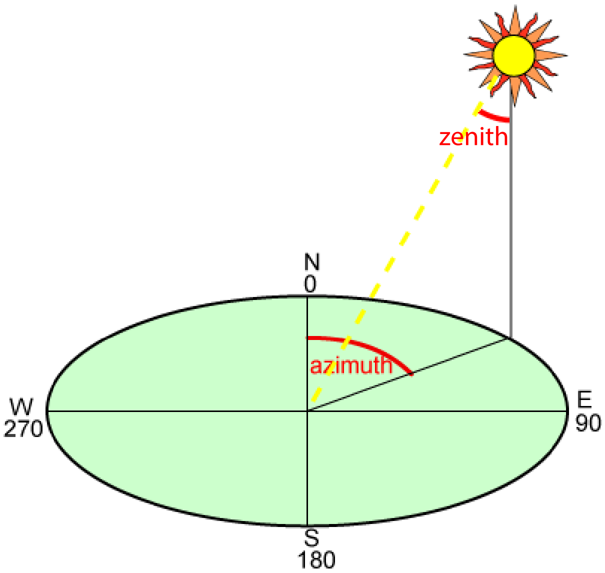


Figure 7: Visualisation of zenith and azimuth angles, defining the position of the sun as seen from a point on earth. Adapted from 'Azimuth.gif' by Honsberg, C. and Bowden, S., Available at `http://www.pveducation.org/pvcdrom/properties-of-sunlight/azimuth-angle`.

throughout the hemispherical zenith and azimuth range from a considered point (figure 8).

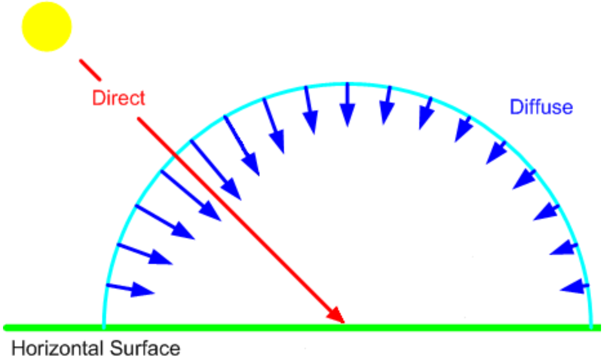


Figure 8: Isotropic diffuse irradiation compared to direct irradiation at a point on earth. Adapted from 'Modelling Solar Devices' by Brighton Webs Ltd., Available at `http://www.brighton-webs.co.uk/energy/modelling_solar_panels.aspx`.

The diffuse irradiation is based on how much of the hemisphere, in which a panel is situated, the panel is facing. A panel facing upwards will be able to receive the entire available diffuse irradiation while a panel at 90° to the horizontal will only be able to receive half of the available diffuse irradiation [Perez et al., 1990].

Many models exist to calculate the clear-sky direct and diffuse irradiation at a particular point on the earth throughout the year [Gueymard, 2003]. These models consider the path length of solar radiation through the atmosphere; the transmittance of various particles in the atmosphere including Ozone, water and aerosols as well as the albedo effect for reflected radiation [Bird and Hulstrom, 1981]. Measured data for direct and diffuse irradiation, used by many modelling programs for PV arrays, allows for the existence and extent of cloud cover to be considered. Increased irradiation increases PV panel output, through an increased rate of photon absorption into the semiconductor, but also leads to increased panel temperature. Increased temperature reduces the panel output; this is a result of the open circuit voltage being a strong negative function of temperature [Amaratunga and Hiralal, 2013].

Method

The current installation was modelled using the solar array modelling software PV*SOL. This is the same software used at CUED to model their solar array in advance of installation (see Case Study 2). The benefit of PV*SOL is the advanced shading and irradiation modelling that takes place, alongside the capability to assess the effect of the placement and choice of inverters for overall system efficiency.

A 3D model of the building was produced in PV*SOL with the use of building drawings (Appendix A). As the drawings were not sufficiently detailed, a site visit was required to measure rooftop obstacles and shading from nearby trees. The subsequent model allowed an in-depth shading distribution and a prediction of input from the designed solar array. Different mounting inclinations could then be tested to find the optimum inclination (to the horizontal) and orientation (clockwise from North) for the solar array. Due to the time-intensive nature of PV*SOL, a mathematical model was adapted from "A Simplified Clear Sky model for Direct and Diffuse Insolation on Horizontal Surfaces" [Bird and Hulstrom, 1981] and the gathered information was combined with irradiation data from a Cambridge weather station, operated by the company Atomwide. This allowed the optimum inclination and orientation to be calculated for verification in PV*SOL. Various panel types were also considered for the best use of available space, alongside the optimal angle information.

Results

Sainsbury Laboratory Roofscape

The SL roof has a total area of $\sim$3690m^2 and useful area of $\sim$1939m^2 due to rooftop obstacles, such as roof lights, air handling units and vents (see Appendix A for detailed drawing). Once modelled, including the largest nearby trees (1 deciduous and 1 coniferous which give varying transparency throughout the year), the shading distribution over the roof can be calculated by PV*SOL (figure 9). Regions of the roof with an annual shading reduction below 5% are considered unshaded, giving an unshaded roof area of 960m^2.

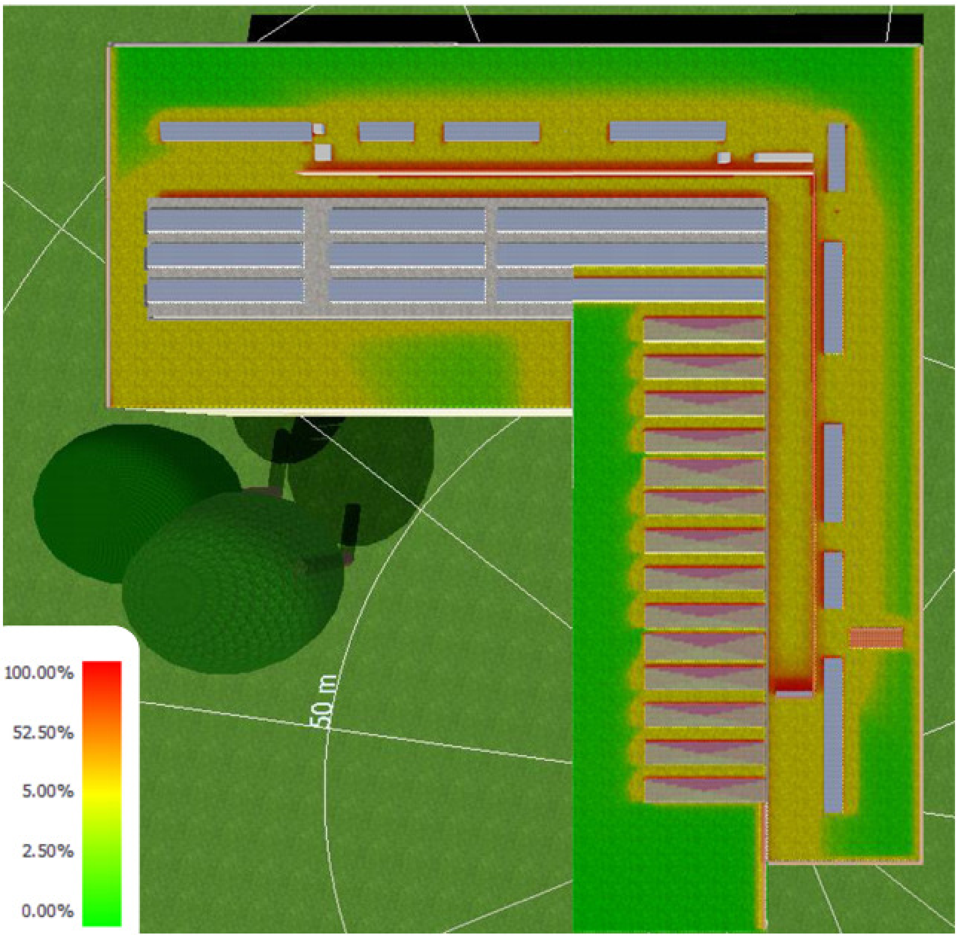


Figure 9: Annual
shading distribution over the SL roof (% shading corresponds to a % irradiation reduction compared to the unshaded condition). Grey or tiled orange areas are not available for panel installation.

PV modules

There are 728 modules on the SL roof, covering 1070m^2 of roof space and utilising 55% of the useful area on the roof (figure 10). The panels cover 11% more of the available space than is unshaded; some panels are subjected to a yield loss due to shading up to 36.4% (figure 11). The modules are inclined at 5° to the horizontal and were predicted to produce 119,000kWh by the M&E contractor in 2010. This prediction is within 4% of the PV*SOL predicted value, found post-construction, and 5% of the annual production in 2013 (figure 12).

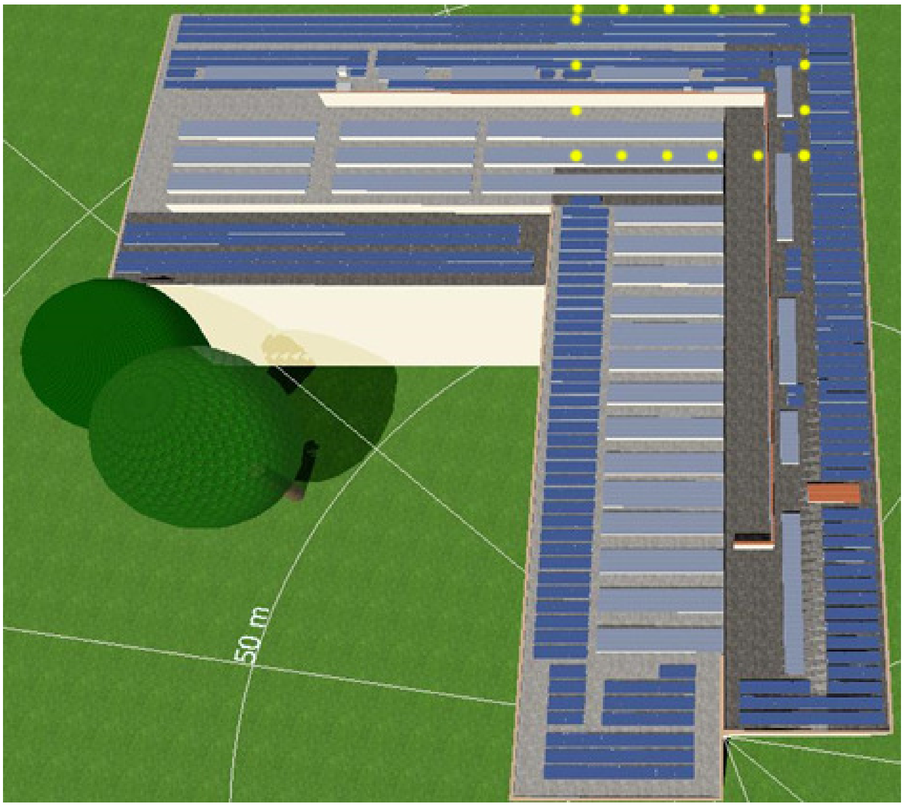


Figure 10: Panel layout,
modelled in PV*SOL, as installed on the SL roof (dark blue corresponds to panels, varying shades of grey to the roof and the yellow dash-bounded square to the section considered in figure 11).

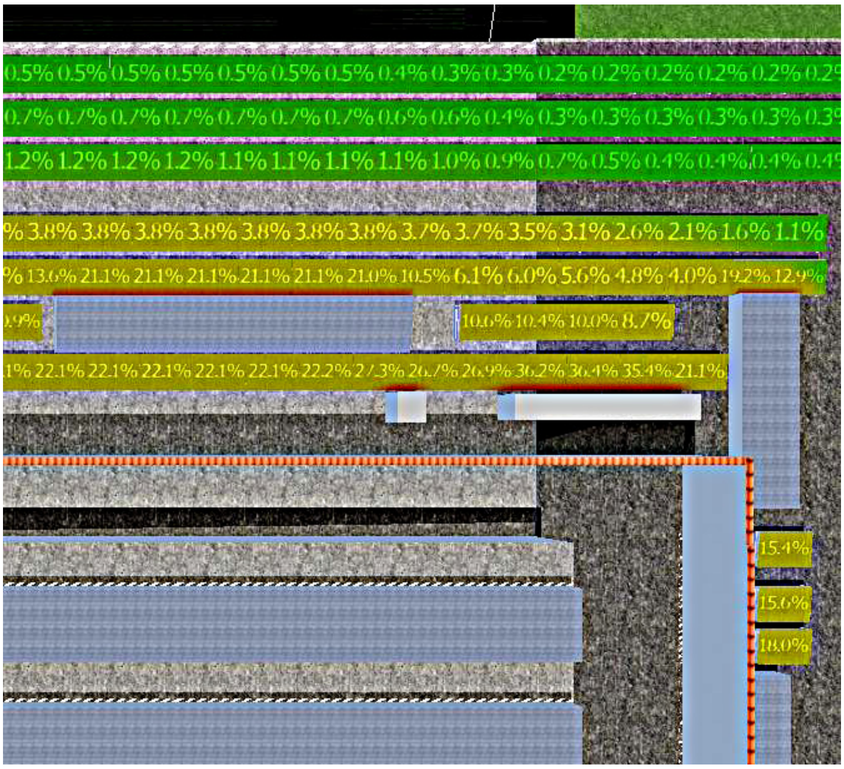


Figure 11: Per-panel yield loss of a section of
PV panels installed on the SL roof (location of section shown in figure 10) as modelled in PV*SOL.

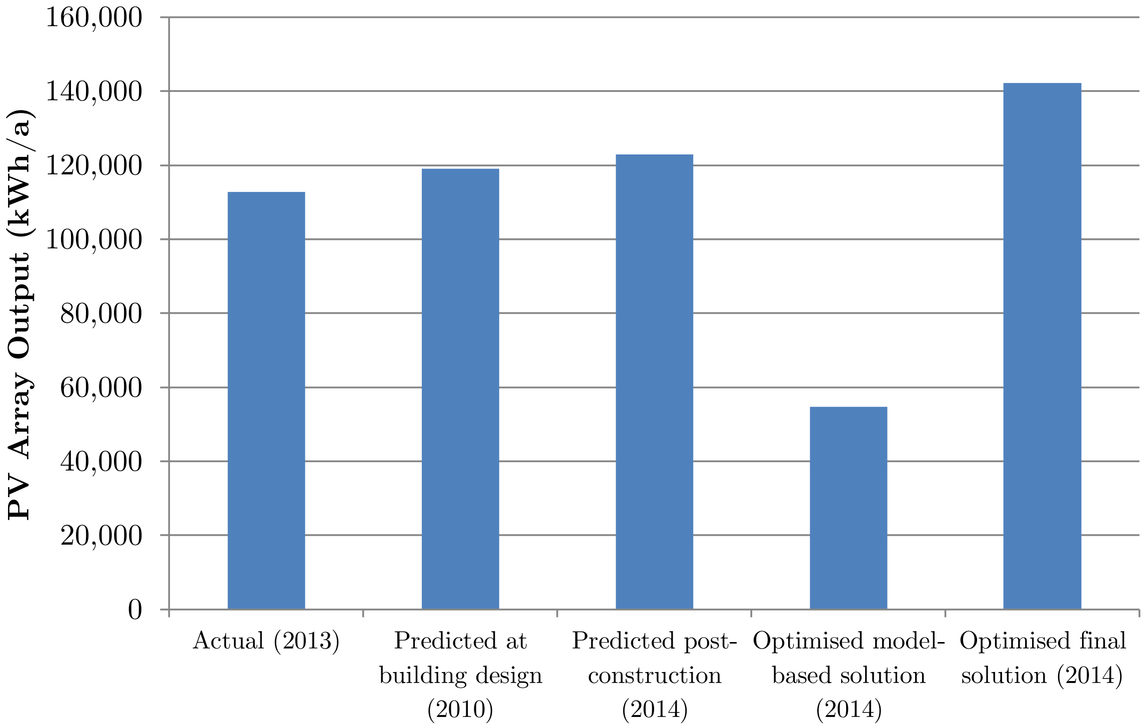


Figure 12: Comparison between various predictions of array output on the SL roof to the actual output in 2013.

Module inclination

The inclination of the entire array was varied between 0° and 90°in PV*SOL, utilising the same available space on the roof and the same inverter layout (figure 13). 5° inclination in the considered environment is the optimum angle for the panels, with panels inclined at 25° having a 13% lower output. The 5° array suffers a 14% yield loss due to shading while the 25° array suffers a 31% yield loss, due to additional shading between panels which are set close together in order to fit the required number on the roof. In an unshaded environment, PV*SOL predicts that a 40° inclination could provide the largest output at 158,729kWh, 30% greater than the predicted output of the installed array.

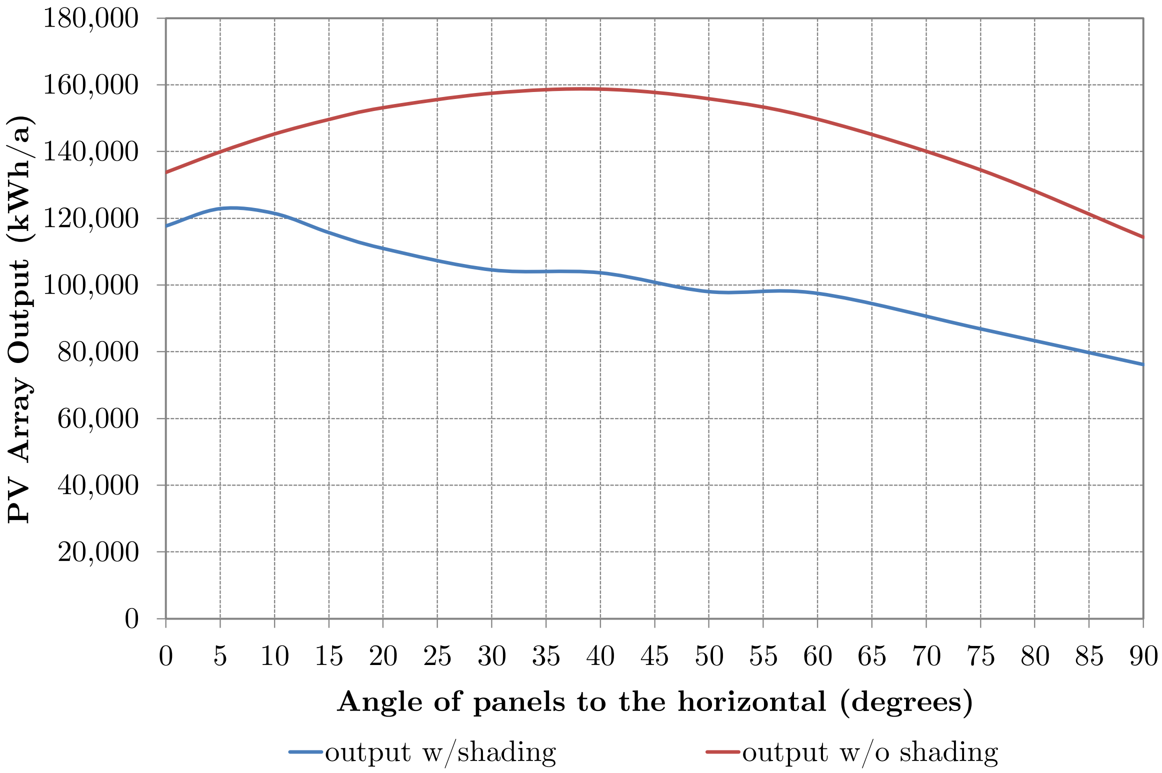


Figure 13: predicted actual and unshaded annual output for the SL PV array over a range of module inclination.

Simplified model

The SL roof is at an azimuth of 174°, with the panels orientated at the same angle. In order to analyse whether orientating the panels at a different angle to the roof would be beneficial, a simplified model was created as set out in the theory (section 3.1). The simplified model suggests that 40° inclination and 180° orientation is ideal and would provide 314,580kWh over a year (figure 14). At 5° inclination and 175° orientation, as for the SL array, it predicts an output of 267,050kWh. This value is larger than the unshaded result from PV*SOL due to the lack of considered cloud cover. Measured irradiation data includes the effect of cloud cover on the value of G_h, which is utilised in the actual model.

Actual Data model

Using the Atomwide G_h data for Cambridge, averaged over 2007-2013, the output compared to the simplified model is far more variable (figure 15). In order to translate this measured data into incident irradiation onto any orientation and inclination of panel, the result of relative importance of diffuse and direct irradiation at any point in time is taken from the clear-sky model and used to separate diffuse and direct irradiation from the measured data (figure 16).The resulting optimised inclination and orientation for the SL array is thus calculated to be 50° and 200°, respectively (figure 17).

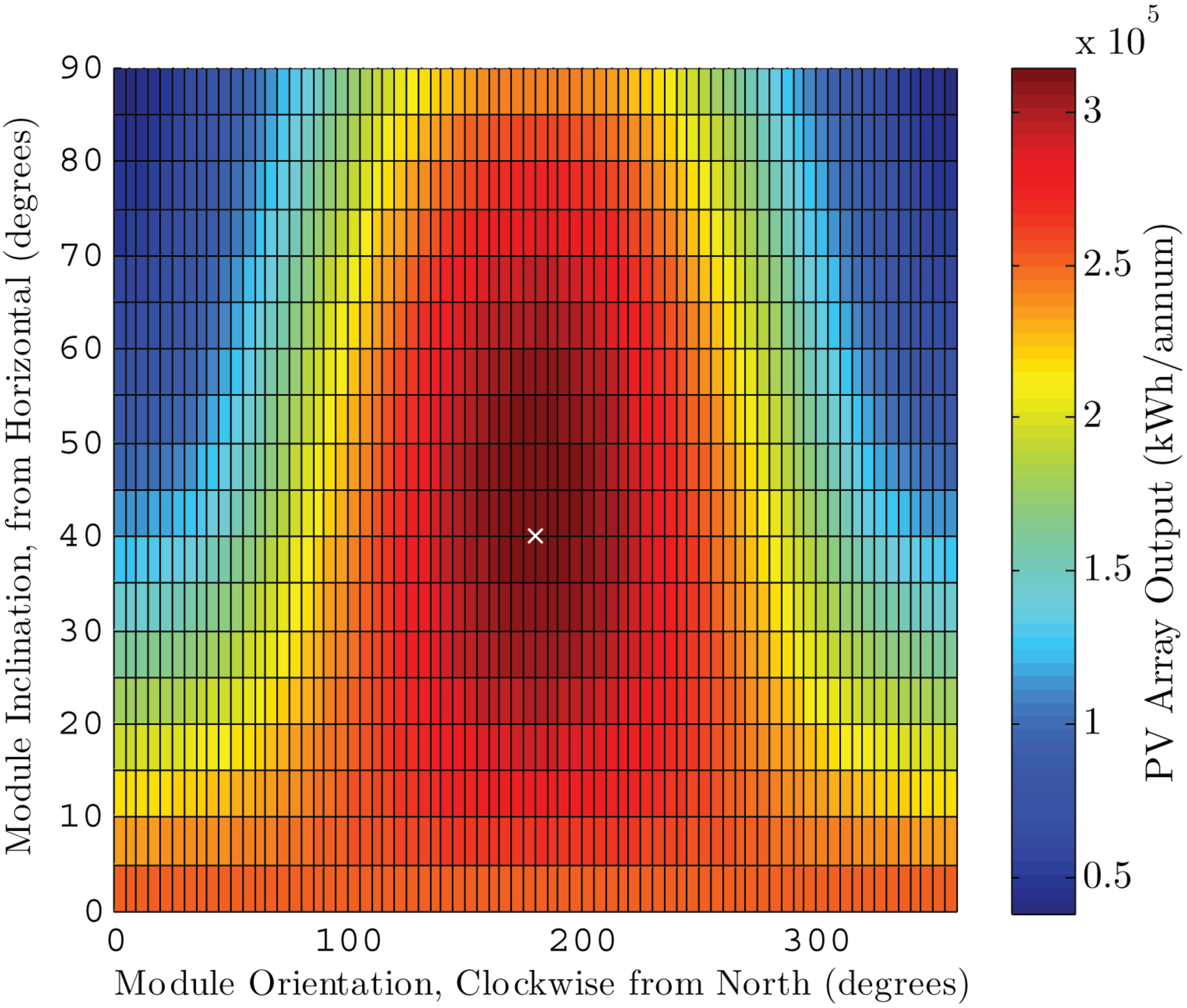


Figure 14: Variation of simplified SL PV array output with module inclination and orientation (white cross indicates point of maximum output).

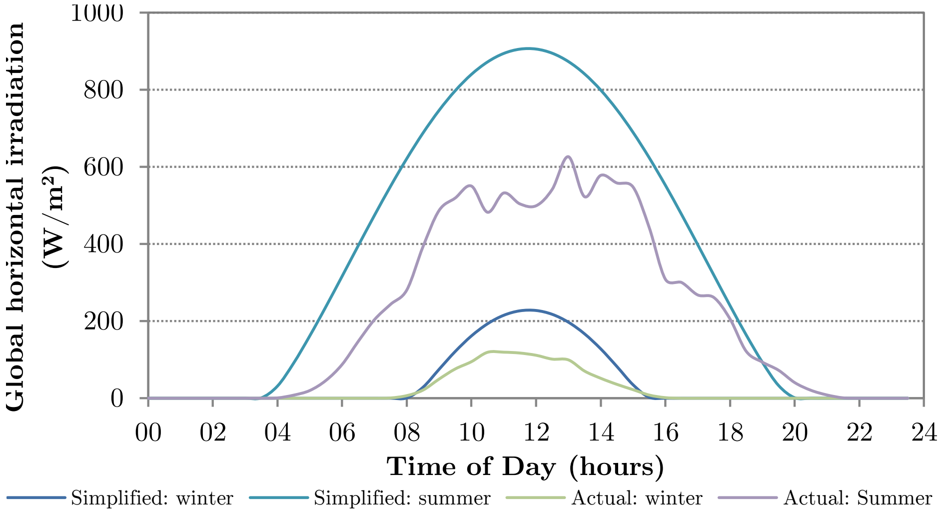


Figure 15: Comparison of measured to modelled G_h throughout one day in summer and winter.

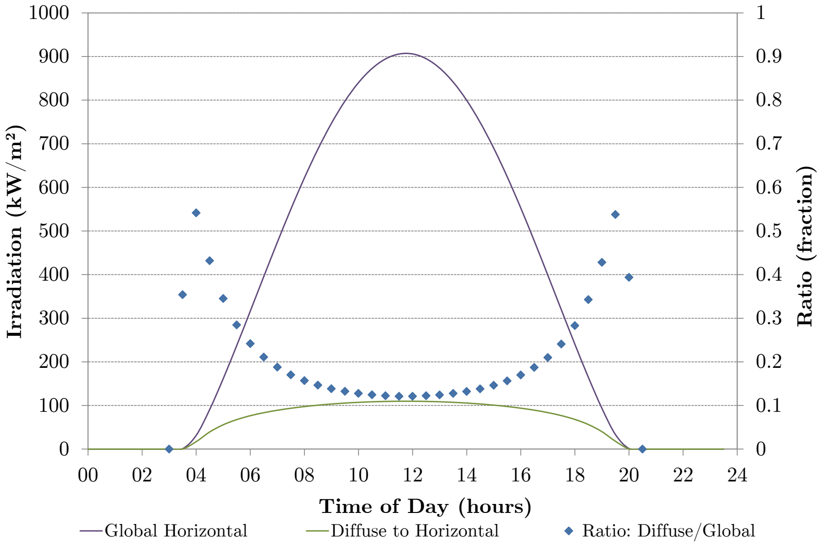


Figure 16: Variation in contribution of G_h from I_{diff} throughout a summer day.

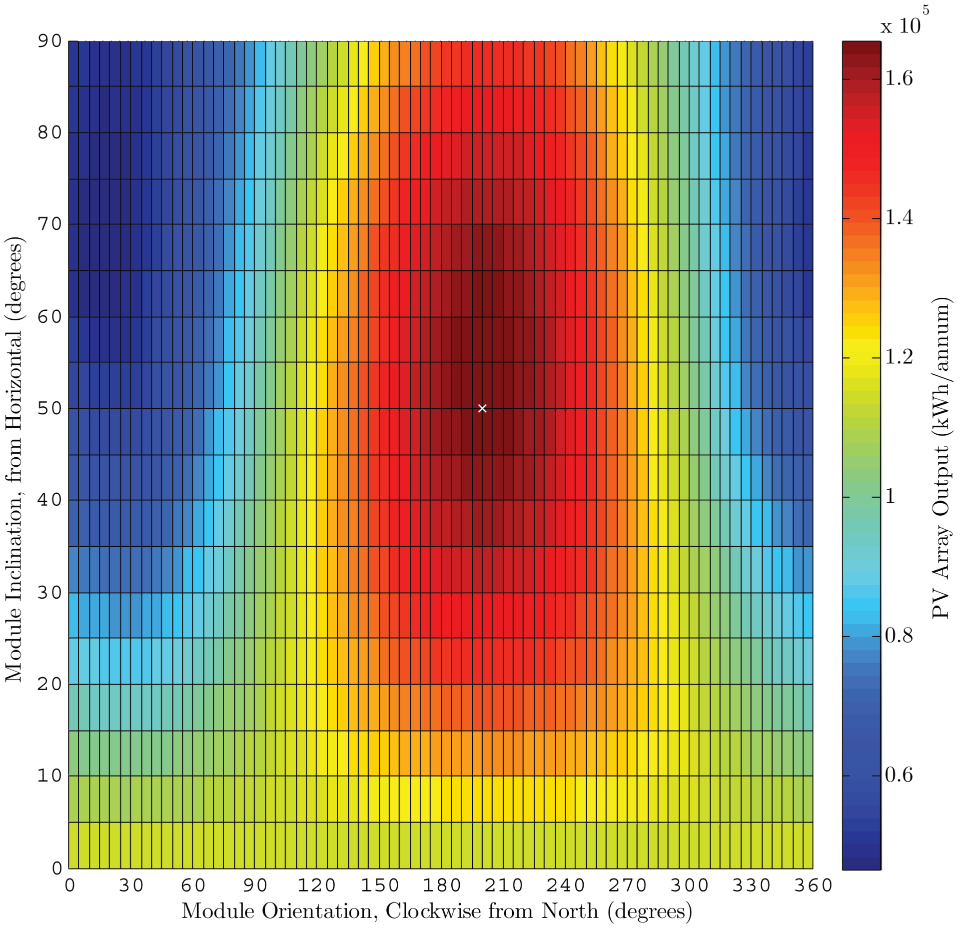
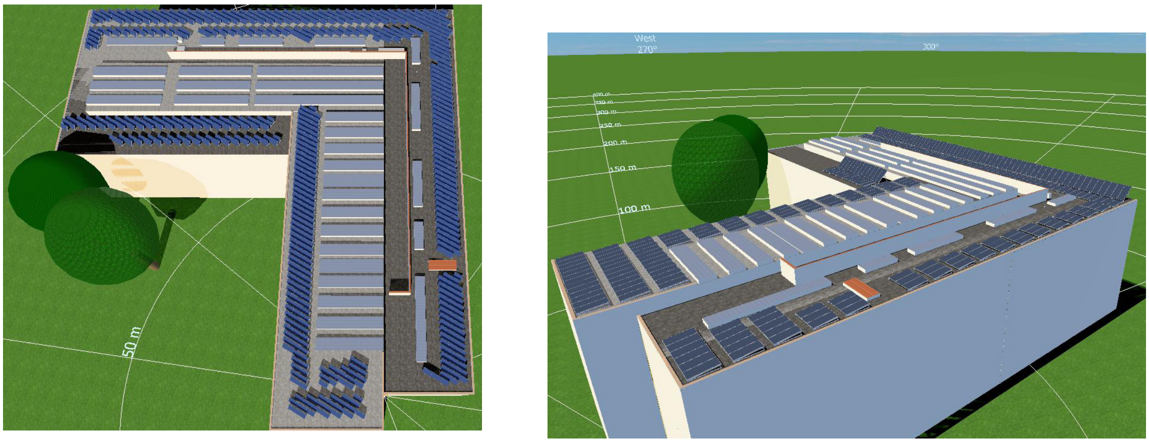


Figure 17: Variation of SL PV
array output with module inclination and orientation as calculated using a combination of measured data and a simplified model for irradiation (white cross indicates point of maximum output).

An array designed to match this inclination and orientation was designed in PV*SOL (figure 18a) with the same number of panels installed to provide a comparison of output. The resulting array produced 54,774kWh/annum - 44% lower than the annual output from the PV*SOL installed case (optimised model-based solution seen in figure 12).

Finally, in order to obtain a maximum value of output based on the roof size and shading conditions, an array was designed using more efficient, large panels at varying inclinations across the roof (figure 18b). The chosen panels are the same as used on the CUED roof (see Case Study 2) as they were specifically chosen for efficiency at the design stage. When modelled in PV*SOL the updated model produced an output of 142,300kWh/annum (optimised final solution seen in figure 12).



(a) Array orientated and inclined as per maximum given in figure 17.

(b) New array optimised for reduced shading loss.

Figure 18: Visualisation of the optimised PV arrays from PV*SOL 3D rendering.

Discussion

In the case of the SL, design of the renewable installation was perceived to stray from maximum potential output due to the architectural requirement for building appearance, leading to the solar panels being set at a sub-optimal inclination. The initially proposed angle of 25° could have provided a 10% greater output from the PV array than the final installed 5°, if no shading was considered. However, due to the shading distribution over the roofscape of the building (figure 9) the highest output for the array was found to be ~6° (figure 13); 25° panels would only provide 87% of the 122,900kWh provided at 5°. Therefore, the installed angle of the panels was, unknowingly, the installation optimum angle. This result is only possible to see through the application of a full annual shading analysis, which is not required for the installation of an array.

When considering a clear-sky, unshaded, case for a PV installation, a 40° inclination and 180° orientation is optimal for a solar panel in Cambridge (figure 14). The maximum output inclination agrees with the maximum unshaded case calculated by PV*SOL (figure 13) but the lack of cloud cover consideration puts the maximum output well above the PV*SOL maximum output. The cloud cover effect can be reasonably accounted for using the data provided by the Cambridge City Atomwide weather station which shows a great deal of output lost compared to the clear-sky case, particularly in the summer (figure 15). Splitting the contribution of global horizontal irradiation to that from diffuse and that from direct irradiation is particularly important when considering different orientations of panels, whereby the panels may no longer be facing the direct sunlight at peak irradiation. The model predicts a lower contribution to G_h from I_{diff} at midday and highest at dawn and dusk (figure 16); this result lends to the notion that south facing panels will produce a greater output than East or West facing as they benefit from the high levels of direct irradiation around the middle of the day without losing out greatly from not facing directly at the sun at dawn or dusk.

When using this data in conjunction with the Atomwide data, the maximum output occurs at a 50° inclination and 200° orientation (figure 17). The greater inclination for maximum output shows a greater contribution to the PV output from summer irradiation, likely caused by the effect of greater cloud cover in the winter, caused by inclement weather. The more westerly orientation could be attributed to lower levels of cloud cover in the latter half of the day, but when considering the skew in output in figure 15 and the location of the weather station (in an urban environment) it could be due to the effect of nearby trees to the East of the station and the lack of them to the West. For a more accurate measure of solar conditions, a weather station would need to be situated in an unobstructed environment with the use of an upward and downward facing sensor - the former for G_h and the latter to analyse the exact I_{diff} contribution.

An array design that conforms with the updated model for array peak output provides an output which is 44% of the output found for the installed case and is 55% of the output found for the same inclination (50°) but in line with the roof orientation (172°) using PV*SOL. This low output shows that the orientation of 200° is not optimum and casts doubt once again on the validity of the Atomwide data, as well as the correlation between I_{diff} and G_h found from the simplified model.

By utilising a higher efficiency panel and a combination of 5° and 45° inclined panels - for minimum shade loss and maximum use of direct sunlight, respectively - an array design was produced in PV*SOL with an output 16% higher than that predicted for the installed array. Even when optimising for maximum output for the installed array, the maximum output from the useful roofspace is only two percentage points higher than that for the MR 10% emissions reduction target. Optimising the PV array to meet theoretically higher targets is thus not possible for the SL. It should be noted that the chosen 'optimum' PV array may, in fact, not be the optimum and was based on information available at the time of conducting the study.

The SL is a typical scientific research building with an emissions intensity per area equal to $238\text{kgCO}_2/\text{m}^2$, similar to the emissions intensity of the University Chemistry, Pathology and Biochemistry department buildings [UoC, 2010] while having a larger useful roof area. As such, a combination of renewable sources would be required if a more stringent target were imposed at the design stage of new developments or for commissioned buildings.

This case study has shown the need for more detailed analysis of renewable installation designs to ensure that a particular design is optimised for the given situation. For greater levels of research into PV arrays on the Estate, there is a need for more reliable irradiation data for Cambridge; such data can be used to aid design of future arrays as well to analyse on-going array performance. Finally, for emissions intensive buildings, including scientific research facilities, there is a need for a range of renewable sources if the use of such sources is set to offset more than current requirements.

3.2 Ground Source Heat Pumps

The installed GSHPs, whether to meet MR targets or otherwise, have mostly failed (red highlighted buildings in figure 4). Only the Battcock building (BC) has a fully functioning heat pump which is working at a promising winter seasonal performance factor (SPF) of 3.98. The SPF is a ratio of heating energy to the building water supply to electrical energy into the heat pump; as CO_2 emissions are incurred by the electrical input coming from the electricity grid, a net emissions saving occurs for any SPF above 2.2.

The reason for failure varies. At KI and ARB it is due to the requirement for heat pump maintenance, perhaps as a result of a faulty component. At HF and AE the failure was found to be a result of poor control systems or incorrect initial installation. The exact cause of failure of the heat pumps is largely unknown as the faults are rarely acted upon by the EM Maintenance Department due to their low urgency - if the GSHP fails, gas boilers will continue heating the building to the set temperature, so there is no loss of occupant comfort. Further discussion on the effect of these failures can be found in section 4 (Social Effectiveness), but the lack of knowledge on their reason for malfunctioning led to GSHPs not being suitable as case studies.

4 Social Effectiveness

4.1 Operation and Maintenance

Operation and maintenance (O&M) procedure can affect the functioning of renewable installations. Incorrect O&M measures taken by University staff has led to equipment malfunctions and lengthy lead times for repair - thus, understanding O&M procedure, or lack thereof, is required. Currently, only buildings with PV arrays are making any contribution to the CO_2 emissions offset on the Estate, albeit small. GSHP installations suffer from a lack of knowledge from building maintenance managers as to system operation. None of the maintenance managers interviewed for this study understood the system beyond the need to report malfunctions, evident from a red light on a dashboard in the service room.

The need to act on a fault is not considered as urgent from the point of view of the EM Maintenance Department due to comfort levels remaining undisturbed by the functioning, or otherwise, of an installed GSHP - gas boilers are able to cope with the entire load of a building, without the need for GSHP contribution. Some GSHPs have been left with a fault for over a year - the KI GSHP has signalled a fault due to low pressure in the piping system since approximately June 2013 while the AE GSHP has been switched to zero running hours by the control system, without any faults being signalled. When visiting the AE, the maintenance manager was unaware of its status and had only interacted with it when a PhD report included it in its studies [Garber, 2011]. When action is taken to rectify malfunctions, the EM Maintenance Department will usually contract a refrigeration company to undertake the work, due to the use of a refrigeration cycle in GSHPs. This means that understanding of the whole GSHP system, including the ground ethylene glycol loop, building water loop and heat exchangers, is lost; this may lead to continued malfunctioning.

The effect of this lack of operational knowledge combined with delayed maintenance leads to negative connotations with regards to the installation of GSHPs on the Estate, particularly from building facilities/maintenance managers and the Maintenance Department. With the need for a combination of sources to offset a reasonable proportion of CO_2 emissions, GSHPs would ideally be part of all new developments - but this may not transpire if negative views based on current installations are included at the design stage. Building designers, consultants and M&E contractors are generally unaware of the functioning or otherwise of installations post-commissioning, so are unlikely to be prejudiced based on the Estate's experience, but GSHPs being removed from consideration by the University due to current poor performance is becoming more prevalent.

PV arrays also suffer from not being integral to the comfort of the building, but are inherently more reliable than GSHPs due to being a simpler system. However, as seen for the

SL case (figure 6 on page 15), malfunctions do occur. The Estate solar installations do not usually have the same green/red light approach to fault monitoring as the GSHPs so it is not as simple a task for building facilities managers to be made aware of faults without actively visiting each inverter (of which there are 7 on the SL roof) to check fault history. This added requirement may lead to negligence in terms of array upkeep. Rooftop PV arrays are also installed to standards such that they are self-cleaning, it is recommended that a 10° inclination is the minimum for panels to allow for self-cleaning [BRE, 2006]. In the case of the SL, where the installers chose 5° to be the minimum inclination, there was evidence of dirt build-up around the lower edge of each panel (figure 19) which may lead to a lower array output.

Figure 19: Dirt build up on lower edge of three PV panels (left) and close-up on one PV panel (right) situated on the SL roof.

4.2 Logging and Displaying Data

Logging of renewable sources currently takes place by various methods. If the installation is to benefit from the FIT (for PV) or RHI (for GSHP), its output is logged manually on a monthly basis from a meter placed at the connection from the inverter with the building/grid supply. The University then undertakes fine-grain monitoring of all Estate buildings, via the TREND BMS, for all gas and electricity consumption/production. The BMS allows control systems for heating/cooling and lighting to be set-up and maintained as well as for troubleshooting malfunctioning systems. This data is not logged beyond 1000 data points per meter, unless specifically targeted for saving; it has an unsatisfactory user interface, the inability to obtain data being recorded for analysis and is restricted to only a select number of University staff. The SystemsLink database is more accessible than the TREND BMS, providing monthly - sometimes half-hourly - data for all Estate buildings but it does not allow for easy comparison between buildings and does not have any GSHP data.

Due to the unsatisfactory methods by which GSHP and PV performance across the Estate is monitored and displayed, a more transparent method of logging and displaying production data from installations is necessary to ensure that malfunctioning devices can be easily and quickly recognised, their reason for malfunctioning can potentially be deduced and their contribution to University CO_2 emission reductions can be quantified for viewing by EM staff as well as interested University members.

In order to assess the viability of greater data logging and display, the following case study considers the logging of data from a PV array at RC for viewing by College members.

Case Study 4: Robinson College

Logging data

RC is not part of the University BMS, as such PV array output data is only currently logged monthly for the FIT requirement. In order to access live data from the array, the inverter must be used (more information on the use of inverters for PV arrays can be found in section CS2.1). Among other values, the output voltage, current and power of a PV array is logged by the inverter. This data is stored on the inverter for a limited period of time and can be sent, by various methods, for remote logging beyond the period held by the inverter.

In the case of RC, the inverters being used are SMA Solar Technology AG inverters, which can transmit output data via a wireless Bluetooth connection. In order to regularly access this transmission, a Raspberry Pi was installed with a logging script, adapted from open source script (available at https://code.google.com/p/sma-spot/). This data is saved onto the device every 5 minutes and simultaneously uploaded to a monitoring website (www.pvoutput.org). The website collects data from several thousand systems worldwide, displaying from live up to annual PV array energy production alongside building consumption (where available). Figure 20 displays the live output interface available on the website - it shows the instantaneous power generated throughout the day as well as the cumulative output for that day - while figure 21 displays the daily output and page layout in terms of accessing more or less fine-grained output data.

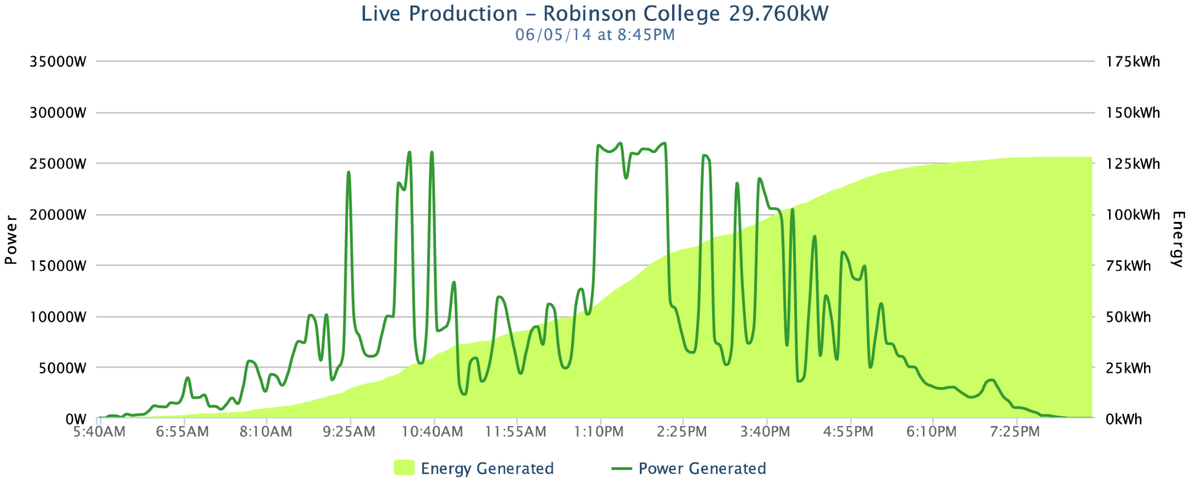
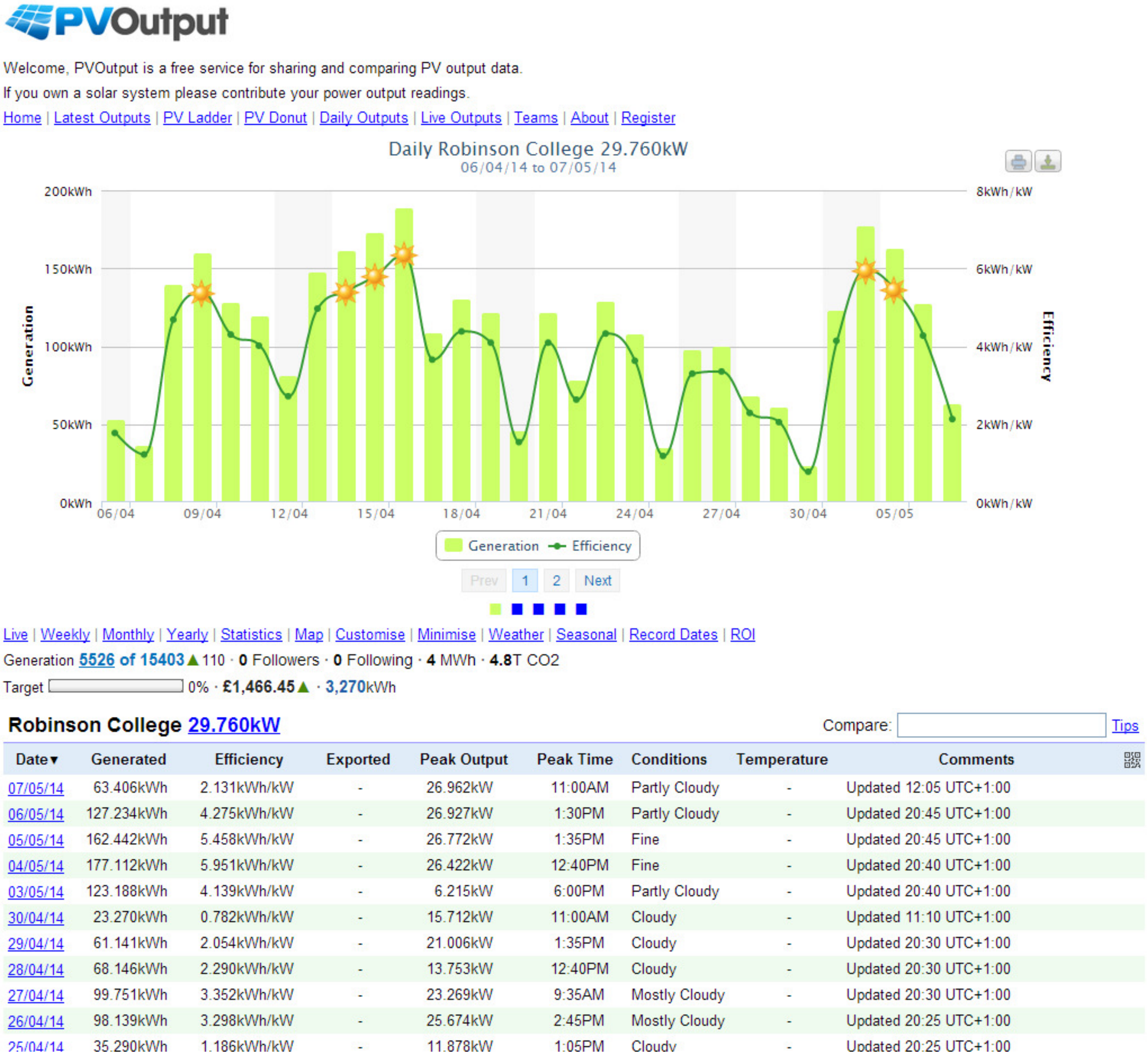


Figure 20: logging display of RC PV array, as seen on pvoutput.org.

With varying levels of data available through www.pvoutput.org and the capability to



Welcome, PVOutput is a free service for sharing and comparing PV output data.
If you own a solar system please contribute your power output readings.

Generation **5526 of 15403** ▲110 · **0** Followers · **0** Following · **4** MWh · **4.8**T CO2

Target ☐ 0% · **£1,466.45**▲ · **3,270**kWh

Robinson College 29.760kW

Date▾	Generated	Efficiency	Exported	Peak Output	Peak Time	Conditions	Temperature	Comments
07/05/14	63.406kWh	2.131kWh/kW	-	26.962kW	11:00AM	Partly Cloudy	-	Updated 12:05 UTC+1:00
06/05/14	127.234kWh	4.275kWh/kW	-	26.927kW	1:30PM	Partly Cloudy	-	Updated 20:45 UTC+1:00
05/05/14	162.442kWh	5.458kWh/kW	-	26.772kW	1:35PM	Fine	-	Updated 20:45 UTC+1:00
04/05/14	177.112kWh	5.951kWh/kW	-	26.422kW	12:40PM	Fine	-	Updated 20:40 UTC+1:00
03/05/14	123.188kWh	4.139kWh/kW	-	6.215kW	6:00PM	Partly Cloudy	-	Updated 20:40 UTC+1:00
30/04/14	23.270kWh	0.782kWh/kW	-	15.712kW	11:00AM	Cloudy	-	Updated 11:10 UTC+1:00
29/04/14	61.141kWh	2.054kWh/kW	-	21.006kW	1:35PM	Cloudy	-	Updated 20:30 UTC+1:00
28/04/14	68.146kWh	2.290kWh/kW	-	13.753kW	12:40PM	Cloudy	-	Updated 20:30 UTC+1:00
27/04/14	99.751kWh	3.352kWh/kW	-	23.269kW	9:35AM	Mostly Cloudy	-	Updated 20:30 UTC+1:00
26/04/14	98.139kWh	3.298kWh/kW	-	25.674kW	2:45PM	Mostly Cloudy	-	Updated 20:25 UTC+1:00
25/04/14	35.290kWh	1.186kWh/kW	-	11.878kW	1:05PM	Cloudy	-	Updated 20:25 UTC+1:00

Figure 21: Screenshot of main page for RC PV array on www.pvoutput.org.
Lack of output for 1/05 and 2/05 was due to logging device malfunction which was later rectified.

access and manipulate the raw data stored on the Raspberry Pi, it was necessary to understand the method by which members of the College would best receive the information for more widespread knowledge of the PV array contribution to emissions reductions.

College Survey

Method

In order to gain the aforementioned understanding of college engagement with the PV array, a questionnaire was produced in order to answer the following questions:

1. What level of awareness exists of renewable installations at the University and Robinson in particular?
2. How conscious are members of the College of their energy use whilst at the College?
3. Does knowledge of the renewable installations effect the way in which energy is used?
4. What is the favoured medium by which information of renewable sources can be displayed?
5. In what format should this information be conveyed?

The structure of the questionnaire can be found in Appendix B. The sample chosen was the entire College membershipand as such the questionnaire was distributed to 569 students (undergraduate or graduate), 105 staff members and 80 fellows via email lists. A total number of 150 questionnaires were completed, amounting to 20% of the available sample. The results acquired are intended to be indicative for future studies on a University scale.

Results

The primary results are given in the following figures.

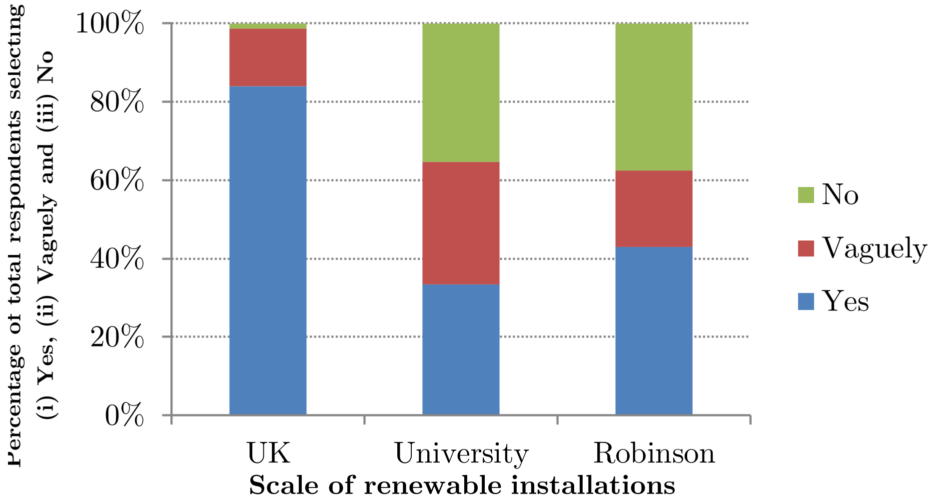


Figure 22: Percentage of respondents who are either (i) aware (ii) vaguely aware or (iii) unaware of renewable sources on a UK, University or College scale.

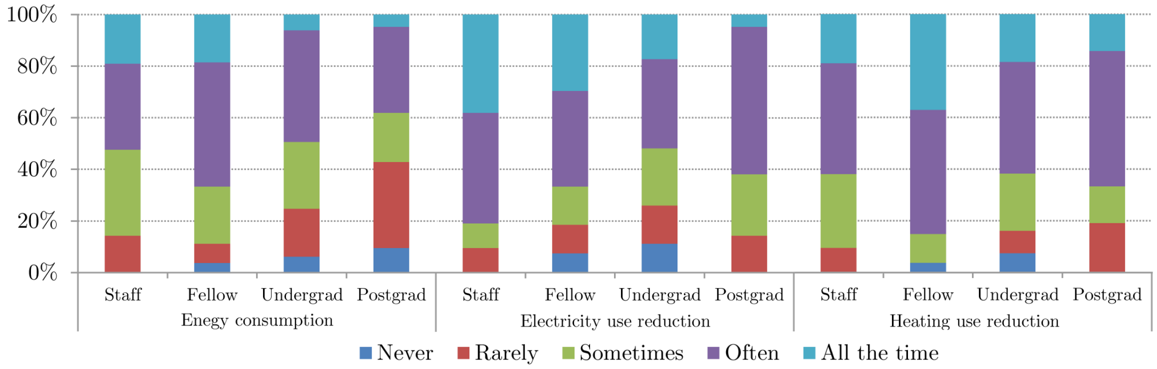


Figure 23: Questions posed: (i) “I am aware of my energy consumption whilst in the College”, (ii) “I actively try to reduce electricity waste whilst in the College”, (iii) “I actively try to reduce heat waste whilst in the College”. Responses split between main respondent groups.

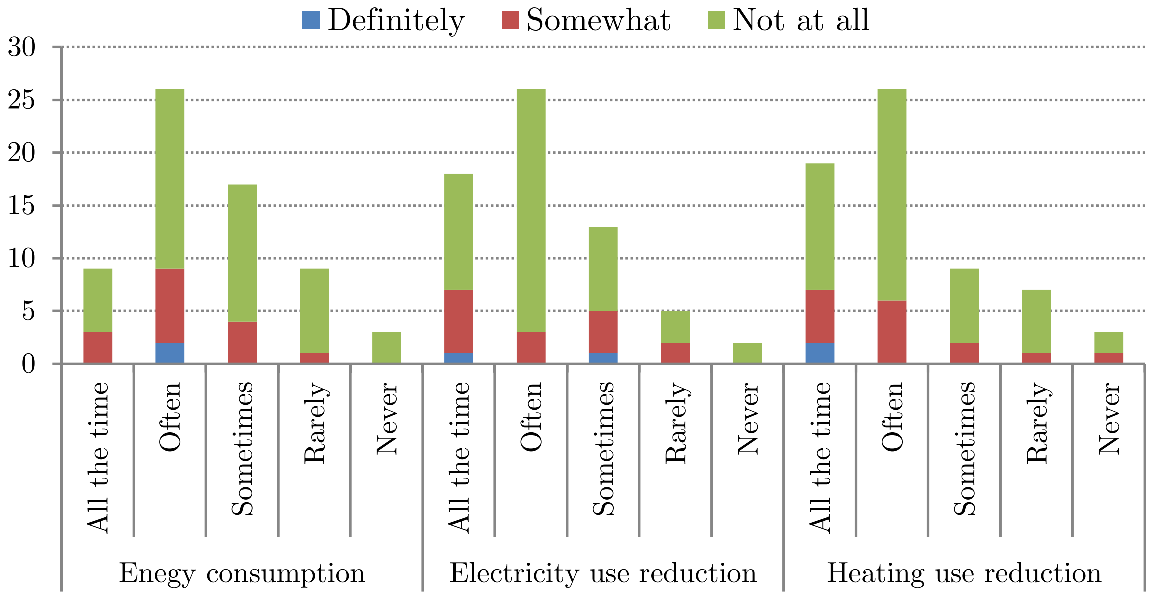


Figure 24: Comparison of answers as in figure 23 with responses divided by answers to the question “Has this knowledge changed the way in which you’ve considered your own energy consumption?” with reference to knowledge of the Robinson PV array.

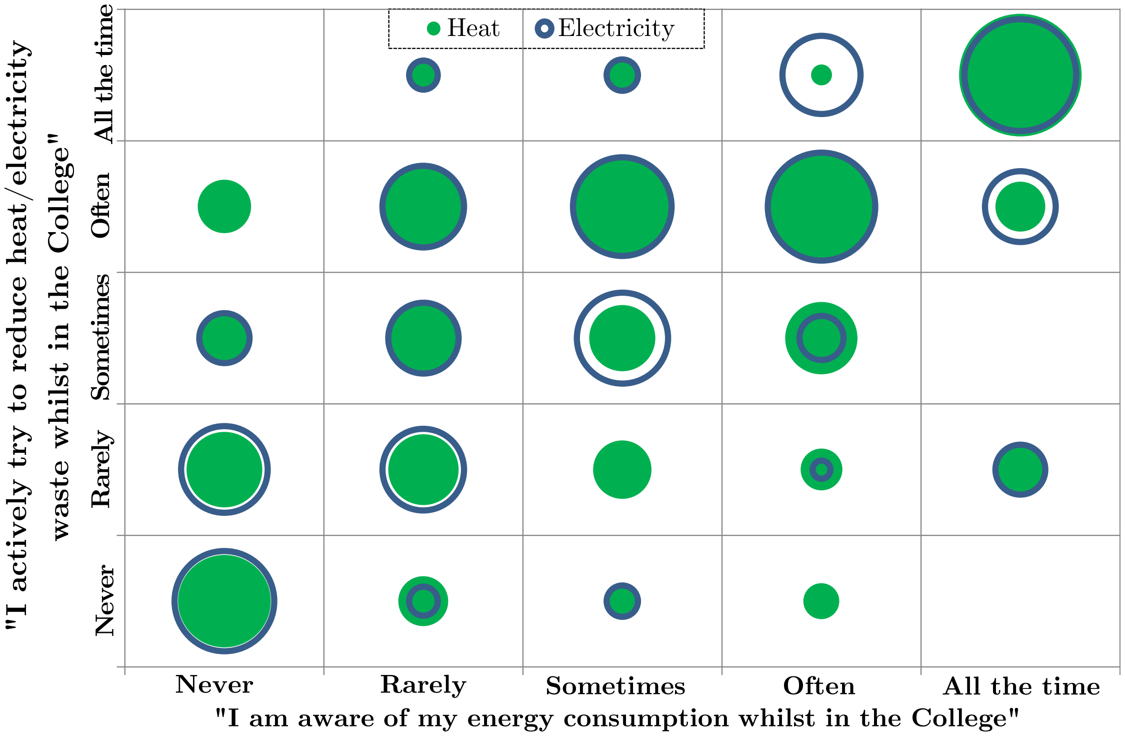


Figure 25: Comparison of level of awareness of respondents' energy consumption and their subsequent (i) electricity waste reduction and (ii) heat waste reduction. Area of bubbles corresponds to percentage of Y axis responses for a given X axis response.

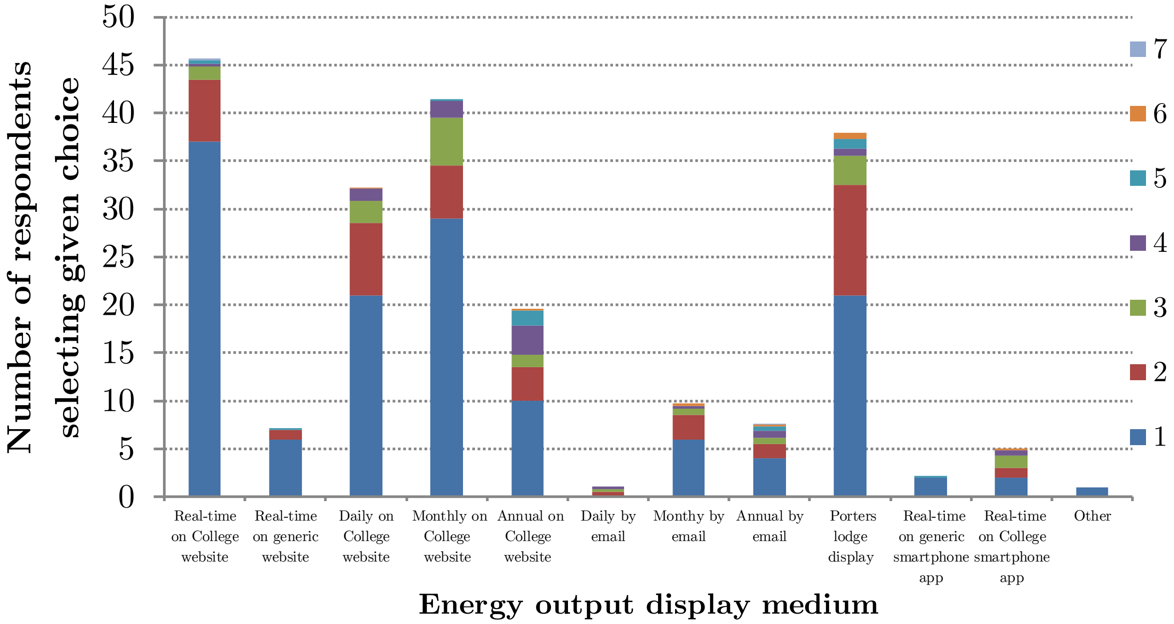


Figure 26: Question posed: "In what format would you like to receive information on what the panels are producing?". Given in order of preference (1-7) with each preference weighted as 1/(preference number).

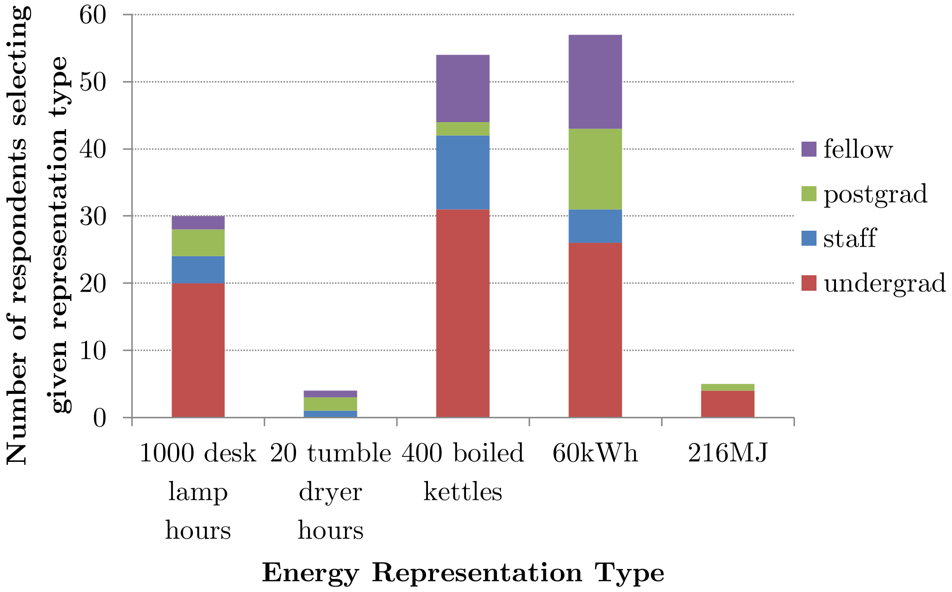


Figure 27: Question posed: “Energy production can be considered in several formats, which of the following is the most relateable representation of produced electricity for you?” split between main respondent groups.

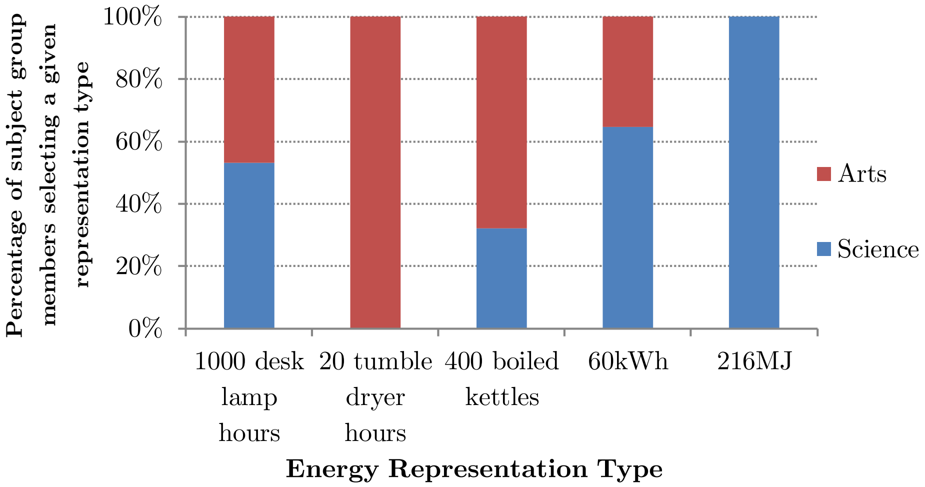


Figure 28: Representation of question posed in figure 27 in terms of preference of undergraduates and postgraduates studying either an arts or science subject. Science subjects given as: Mathematics, Engineering, Computer Science, Physical Natural Science, Biological Natural Science, Veterinary or conventional Medicine. Arts subjects include social sciences and are given as: Human, Social, and Political Science; Law; Languages (English, Modern and medieval, Classical); Music; Philosophy; Theology; Anthropology; History; Geography; Land Economy; Architecture; Economics.

Discussion and Evaluation

The results provide indicative answers to the posed questions set out in the method (page 33), each of which will be considered separately in this section.

What level of awareness exists of renewable installations at the University and Robinson in particular?

Figure 22 indicates that 35% of respondents were unaware of renewable installations on a University scale and 37% were unaware of them on a College scale. The concept of renewable installations is not unknown to the respondents as 85% of them were fully aware of UK scale renewable sources. This may indicate the lack of visibility of the University and College scale renewable sources, either in terms of being physically visible or a lack of publicity. The greater full awareness of renewable installations on a College scale may be a result of the disturbance to a number of College members due to the act of installing the panels, which are set above student accommodation as well as academic staff offices. Lack of full awareness of University scale renewable sources (32% fully aware) is a concern that will be discussed in greater detail as part of section 5 (Closing Discussion).

How conscious are members of the College of their energy use whilst at the College?

Student members of the college are the least aware of their energy consumption whilst in the College (figure 23) although they comprise the largest body of College members and, due to being in residence at the College, are likely to be the greatest users of energy on site. Fellows are most aware of their consumption which may be in part due to regular reports made to the fellowship by staff as to the College energy use, information which is not relayed to the student members. On the whole, a greater number of respondents try to reduce their energy waste than not - whether they're aware of their consumption or not.

There is a trend for greater knowledge of energy consumption leading to more attempts at reducing energy waste (figure 25) which could imply that a more fine-grain metering and display approach by the College would lead to a lower building energy consumption. At present the College has little beyond the main incomers for gas and electricity use to the main building (in which all the offices, catering and recreational rooms are situated as well as approximately half the College-owned accommodation) and so increasing knowledge of an individual's consumption is unlikely to be quantifiable without being in conjunction with a building retrofit. At University buildings the higher level of metering means that there is scope to increase an individual's knowledge of their energy use which may lead to lower energy waste, if the trend seen at a College level is similar in the departmental environment.

Does knowledge of the renewable installations effect the way in which energy is used?

Those who are aware of the PV array installed at RC tend to make a greater continual effort to reduce their energy waste even if they are not aware of their energy use all the time (figure 24). Only a small proportion of respondents considered their energy consumption differently as a result of being aware of the array. However, the survey was not set up in such a way to allow analysis of whether those who would know more about the array are likely or not to be more energy conscious individuals.

What is the favoured medium by which information of renewable sources can be displayed?

A real-time output on the College website is the preferred method for PV array display, followed by monthly output displayed in the same location and a display in the Porters' lodge (figure 26); the display is situated at the main entrance to the College, in which there is a 40 inch television visible to all those in the lodge. Emails, display on a smartphone app and use of a website other than the College website were not preferable options.

This information can be used by the College IT staff to ensure that the information is displayed in such a way as would be utilised by the College members. Assuming the preferences are similar at University departments then they are measures that can be rolled out for use on departmental intranet as well as department-wide displays; for instance, there are 5 television monitors within CUED, on which the information could be displayed.

In what format should this information be conveyed?

Representation of energy as kWh was overall preferred by respondents, particularly postgraduate students (figure 27). Representing the kWh unit in terms of boiled kettles scored almost as highly as kWh, with particular staff preference for this format. kWh is a non-SI unit used to represent utility electricity [CSE, 2014], which is perhaps why it has gained a greater preference than the SI unit of Joules. The purpose of separating the primary respondent groups can be realised here as the PV data can be communicated differently to different groups depending on their preference. It may be most useful to communicate kettles boiled to staff and kWh to postgraduates (and a combination for undergraduates and fellows due to the lower percentage difference between preference for the two formats). The responses show that different uses of energy, beyond the standard units, are more relateable. However, these formats come with the capability to be more confusing as, for instance, the energy used when boiling a kettle varies depending on the kettle type and quantity of water boiled. Also, the energy used when boiling a half filled kettle may not be half of that when boiling a filled kettle, due to fixed losses in the device. These types of inaccuracies could lead to a lowering of understanding of energy consumption and the results from the posed question may be better evaluated in terms of the line of questioning “to what level does a standard unit of energy, e.g. kWh, need to be better understood by the College members?”.

As might be expected, due to the use of energy units during the course of their studies, students of scientific subjects prefer kWh and MJ to students studying arts or social science subjects (figure 28). SI units conveyed in terms of number of kettles boiled or tumble dryer hours is better understood by students studying arts subjects while there is an almost even percentage of arts and science students who prefer desk lamp hours. This result may prompt the need to display renewable source production information in a different manner in different University departments (e.g. via in-house displays or on a local Intranet).

5 Closing Discussion

The three facets of renewable energy effectiveness on the Estate have been considered separately in sections 2,3 and 4. It is evident from the study that effectiveness in each facet is dependent on the others and this section will attempt to consolidate the discussion.

The current process of the University is to focus building on-site renewables on new developments, in order to comply with City Council regulation for emissions reductions in those new builds. The regulation has only been in place for 8 years, leading to renewable installations being built primarily in the past 4 years. These installations, for the most part, do not meet the required emissions offset they are designed for; in the case of PV installations this is due to building emissions being greater than predicted while GSHPs may be capable of supplying the required offset but are malfunctioning. Although not meeting the policy requirements, having policy set in place by the City Council has seen renewable sources installed where otherwise they may not.

As a result of their inability to reach building emissions offset targets and the low level of installations on the Estate, renewable energy offsets less than 1% of the University CO_2 emissions (figure 29). To provide more emissions offset on a University scale, a combination of sources on every viable building would be required, increasing the need for diverse maintenance knowledge from facilities/maintenance managers and a more positive attitude towards GSHPs. Both increased emissions offset and more appropriate maintenance knowledge requires the University to increase its commitment to on-site renewable sources. The University Carbon Management Plan only states that on-site renewable schemes will be a part of meeting the University CO_2 targets as a result of compliance with the MR. This discounts installations on new developments which go above offsetting 10% of predicted regulated emissions as well as discounting installations on current buildings. University policy would need to change such that new builds are required to meet as high an emissions offset target as is technically possible, using as many sources as feasible, alongside the introduction of installations at current sites at a higher rate than one installation (PV at CUED) over 3 years.

Another method to aid the development of on-site renewable sources, rather than maximising the University renewable source emissions offset, is to concentrate on utilising available space for research into innovative technology or processes. Not only is this in line with the ethos of the University, but would ensure that there is appropriate metering of the devices. Malfunctioning devices would be quickly spotted by researchers, leading to a feedback loop which is independent of the building facilities/maintenance manager, allowing them to concentrate on other aspects of the building for which they are correctly trained. This has been the approach taken by CUED during design of the PV array, but it has yet to be seen whether it will prove successful.

One concern with the latter method is the difficulty of integrating GSHPs into constructed buildings. Boring holes in order to place a vertical ground loop is expensive and requires

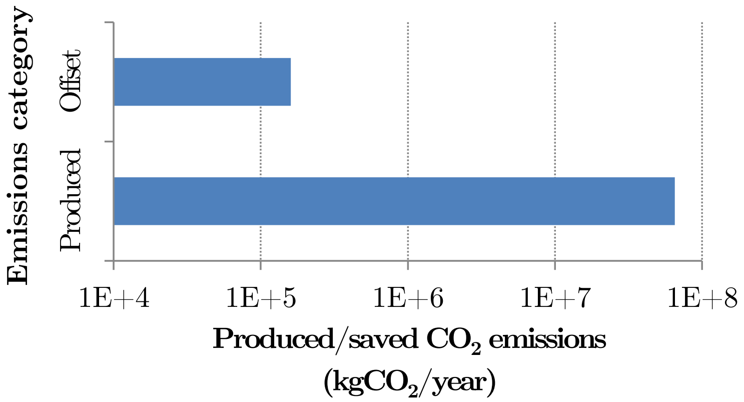


Figure 29: Comparison of 2013/14 annual emissions on the University Estate to emissions offset as a result of on-site renewable generation from PV arrays or GSHPs reductions (installations commissioned for less than one year have their output extrapolated based on current performance and predicted output).

space [GSHPA, 2007], which is difficult to acquire in central Cambridge. Hole boring would preferably take place at the construction phase to take advantage of holes being dug for piles, services etc.. GSHPs also work most effectively at lower temperature difference between the ground and the building water loop, contrary to the way in which gas-heated buildings operate. Older buildings are designed for gas boilers and thus a GSHP providing heated water at the same temperature would have a lower performance than preferable.

Finally, member awareness of the current progress of the University with respect to renewable installations is low. Improving awareness is unlikely to have an effect on energy use, but may make the University more accountable when an installation is shown to be malfunctioning. Surveying College members, showed there exists a lack of knowledge of standard units for measuring electrical energy. This leads to the question of how energy should be represented to University members, for their consumption of energy as well as production from on-site renewable sources.

6 Conclusions

The current process of installing on-site renewable sources in order to comply with City Council regulation (the Merton Rule) is insufficient for significantly offsetting building emissions on the University Estate. This is caused by inaccurate building emissions predictions leading to incorrectly sized installations, the compliance only specifying the need to offset regulated emissions and installations not performing to standard once in-situ.

If the University hopes to use on-site renewable sources to aid CO_2 emission reduction then it requires a different methodology to current practice. This involves changing the policy by which on-site renewable sources are installed, to augment the Merton Rule for new builds and incentivise further installations on current builds. Using PV arrays alone will not be sufficient to offset a substantial proportion of building emissions, particularly when considering scientific research facilities. For instance, The Sainsbury Laboratory can only feasibly increase its emissions offset by 20% from an optimised PV installation on its roof, leading to a maximum offset of 12% of building regulated emissions.

The use of ground source heat pumps alone or in conjunction with a PV installation would increase the emissions offset from on-site renewable sources. However, current experience on the Estate shows that they are prone to malfunction, for various reasons. Improved monitoring, maintenance and attitude towards ground source heat pumps is required for a successful heat pump portfolio on the Estate.

There is the possibility of using installations as test beds to aid research into future technologies or systems. This has occurred at the Engineering Department, thanks to a design independent of policy requirement but incentivised by University funding. Not only would this be in keeping with the University's mission but would also give the on-site installations a purpose beyond offsetting CO_2 emissions, which they are unable to do to a great degree.

There is currently no coherence within the University in terms of the on-site renewable sources. This is displayed in the lack of knowledge as to current operation of installations and their intended operation. Several sources of data were required to be collated to complete this study and would be required in future for any analysis of their performance. There is thus a need for a procedure by which data is acquired and dealt with by the staff of the University. This may help ensure that installations perform as designed and may increase knowledge and enthusiasm from University members for renewable source generation.

Energy use was not an implicit part of this study, but a survey of University members suggests that a greater attempt by the University at increasing awareness of individual energy use would increase endeavours to reduce energy waste.

7 Further Scope for Study

This report has discussed a preliminary study into the renewable energy sources installed on the University Estate. There is greater scope for study on the subject of the University's current and future on-site renewable sources, for which there was insufficient time or resources to complete as part of this report. The following avenues for further study are considered most relevant as a result of this report's conclusions.

University Policies

The University may benefit from an updated approach to on-site renewables, beyond that which has been set out in the Carbon Management Plan. This would involve putting in place policies to enact change - to realise a greater on-site renewable source presence for greater CO_2 emissions offset or researching innovative technologies.

GSHPs

This report has not considered GSHPs in great detail due to their current malfunctioning state. Study of the installations and implementation of more intelligent monitoring and control systems to reduce future malfunctioning may prove advantageous.

CUED PV Array

As the only on-site renewable installation with technology installed for the purpose of testing, it is recommended that it is utilised to assess the technology as well as to assess the capability of full-scale installations on the Estate to be used as test beds for research.

Data Display

A more rigorous approach to the subject matter covered in Case Study 4 would lead to a greater understanding of how to display production data from on-site renewable sources as well as displaying consumption data to University members. Consumption data display is likely to have a greater effect on energy use reduction on the Estate and as such may be considered a subject of greater importance for study.

References

G. A. J. Amaratunga and P. Hiralal. Factors which limit efficiency in p-n junction cells, 2013. unpublished.

Richard E Bird and Roland L Hulstrom. Simplified clear sky model for direct and diffuse insolation on horizontal surfaces. Technical report, Solar Energy Research Inst., Golden, CO (USA), 1981.

BRE - Building Research Establishment Ltd. Photovoltaics in Buildings Guide to the installation of PV systems, 2nd Edition, 2006.

Building Regulation Approved Document L2A. Conservation of fuel and power in new buildings other than dwellings, 2006.

Cambridge City Council. Cambridge Local Plan, 2006.

CSE - Centre for Sustainable Energy. How much electricity am I using?, 2014.

DECC - Department of Energy and Climate Change. Feed-in tariffs scheme: consultation on comprehensive review phase 1 tariffs for solar pv, 2011.

DECC - Department of Energy and Climate Change. Increasing the use of low-carbon technologies, 2014. URL `https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies`. [Accessed: 20 May 2014].

ECRP - University of Cambridge Energy and Carbon Reduction Program. Annual report, 2012.

Energy Saving Trust. Solar inverters, 2014. URL `http://www.energysavingtrust.org.uk/Generating-energy/Choosing-a-renewable-technology/Solar-panels-PV/Solar-inverters`. [Accessed: 20 May 2014].

Faber Maunsel. Low Carbon Energy Strategy: University of Cambridge., 2007.

Denis Garber. Implementation and Validation of Ground Source Heat Pump System Models in an Integrated Building and Ground Energy Simulation Environment. Master's thesis, University of Cambridge, United Kingdom, 2011.

Dino Green. Micro-inverters vs. string inverters which is better? *Renewable Green Energy Power*, 2013.

GSHPA - Ground Source Heat Pump Association. Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems, 2007.

Christian A. Gueymard. Direct solar transmittance and irradiance predictions with broadband models. Part I: detailed theoretical performance assessment. *Solar Energy*, 74(5):355–379, 2003.

HEFCE - Higher Education Funding Council for England. Carbon reduction target and strategy for higher education in England, 2010/01.

IPCC - Intergovernmental Panel on Climate Change. The Fourth Assessment Report, 2007.

M. Letcher, S. Smith, and E. Jones. A review of Merton Rule policies in four local planning authorities in Cambridgeshire., 2012. URL `https://www.scambs.gov.uk/sites/www.scambs.gov.uk/files/documents/Merton%20Rule%20Study%20(June%202012)_0.pdf`. [Accessed: 15 Jan 2014].

Mastervolt. FAQ Solar, 2014. URL `http://www.mastervoltsolar.com/solar/faq-solar/`. [Accessed: 21 May 2014].

Merton Council. The history of the Merton Rule, 2013. URL `http://www.merton.gov.uk/environment/planning/planningpolicy/mertonrule/the_history_of_the_merton_rule.htm`. [Accessed: 15 Jan 2014].

NREL - National Renewable Energy Laboratory. Passive Solar Design for the Home, 2001.

NREL - National Renewable Energy Laboratory. Glossary of Solar Radiation Resource Terms, 2014. URL `http://rredc.nrel.gov/solar/glossary/`. [Accessed: 20 May 2014].

R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 44(5):271–289, 1990.

Roderic Bunn. BSRIA response to the Commission of Enquiry into Achieving Best Value in the Procurement of Construction Work, 2011.

The Carbon Trust. Closing the Gap - Lessons learned on realising the potential of low carbon building design, 2012.

UoC - University of Cambridge. Univerisity of Cambridge Carbon Management plan, 2010.

UoC - University of Cambridge. The University's mission and core values, 2014. URL `http://www.cam.ac.uk/about-the-university/how-the-university-and-colleges-work/the-universitys-mission-and-core-values`. [Accessed: 20 May 2014].

Appendix A Sainsbury Laboratory Roof Plan Drawings

Appendix B Robinson College Survey

Appendix C Risk Assessment retrospective

The risk assessment submitted at the project outset stated that only computational and book work would take place in order to complete the project aims. For the most part this is true - site visits to a number of University departmental buildings were the only exception.

Site visits included visiting service rooms and in the case of the SL involved a roof visit. These tasks were undertaken alongside trained personnel and no safety equipment was required by the building safety officer due to using available thoroughfares throughout the visits.

In retrospect, the risk assessment would be completed after consultation with University building managers in order to ascertain the extent of the hazards that may be encountered during a visit, irrespective of whether those visits took place or not. It is also unlikely that visits were necessary in many cases due to the lack of maintenance knowledge available to the author.