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Solar panels or green roofs?

Evaluating the effectiveness of financially subsidising rooftop measures to abate carbon emissions by 2050 in Bristol, UK

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Abstract

A considerable reduction in CO_2 emissions is necessary for the UK to reach net zero targets by 2050. Solar roofs and green roofs offer two key measures to abate carbon emissions using existing city rooftops, but direct comparisons between these two alternatives remain relatively underexplored. This study evaluates and compares the potential outcome of providing direct financial incentives for either alternative in the city of Bristol, UK. Three key research performance objectives are compared for green roofs and solar PV systems using the latest remote sensing data and regional figures. These involve calculating the total CO_2 abatement potential by the year 2050, the net financial cost-benefit outcomes per annum, and the cost-effectiveness per tonne of abated CO_2.

For the city of Bristol, this study finds solar PV systems to be over five times more cost-effective than green roofs per tonne of abated CO_2, with the potential to abate over 60 times more CO_2 than green roofs by the year 2050, totalling 9.7 million tonnes. However, green roofs are highlighted as a more financially affordable alternative per annum, delivering numerous environmental and social benefits which solar PV systems cannot provide, and many that cannot easily be monetised. The findings of this study also demonstrate the impact of considering a wider scope of private, public, and global benefits on the net annual value of each alternative, revealing net annual savings from subsidising green roofs when considering the social benefits of reducing global carbon emissions. The significant impact of feature uptake success on total abated emissions by the year 2050 is also highlighted. The information provided in this study will aid Bristol City Council in assessing all available uses of state funding to achieve national net zero targets, as well as its own more ambitious net zero target for 2030.

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1. Introduction

In 2019, the UK pledged to reach "net zero" carbon emissions by the year 2050 (HMG, 2019), while the city of Bristol pledged an even more ambitious target to reach this goal by the year 2030. Net zero refers to when the total greenhouse gas emissions emitted by the UK are equal to, or less than those removed by the country (Pye *et al.*, 2017). These can be removed either via reducing current emissions or by removing emissions from the atmosphere via natural sinks or greenhouse gas removal technologies. Across the globe, 58% of our capacity to abate (avoid) greenhouse gas emissions stems from city buildings (Colenbrander *et al.*, 2019). With more than 80% of building stock set to be constructed by 2025 (Castleton *et al.*, 2010), retrofitting existing buildings represents an important pathway to reaching net zero goals. In addition to retrofitting buildings with improved insulation and more energy efficient appliances (Gouldson and Millward-Hopkins, 2015), green roofs and solar PV systems offer two key low carbon measures for retrofitting existing building rooftops. A green roof is defined as roof with living vegetation on the surface and can exist in "extensive" or "intensive" forms (Castleton *et al.*, 2010). An extensive green roof usually holds lower-growing sedums and grasses and has a shallow depth, while intensive green roofs usually exceed a depth of one foot, and often hold more substantial vegetation such as trees and crops (Cavanaugh, 2008). Green roofs have been around since the Roman Empire (Peck, 2002) and have been shown to offer a variety of benefits. These benefits include sequestering (absorbing) greenhouse gases (such as carbon dioxide, CO_2)(Blackhurst, Hendrickson and Matthews, 2010), insulating building rooftops and saving heating energy emissions (Niachou *et al.*, 2001), improving local biodiversity (Elmqvist *et al.*, 2015), absorbing rainwater run-off, and improving mental health (Abolhabib, Sharifi and Dehaghani, 2020). Solar Photovoltaic (PV) systems, or "solar panels", are a more recent invention consisting of integrated photovoltaic (PV) cells which harness solar energy and convert it into electrical energy (Macintosh and Wilkinson, 2011). By installing these solar PV systems to generate electricity on city rooftops, the carbon dioxide emissions that would have otherwise been released via fossil fuel energy sources can be avoided.

As rooftops account for around a quarter of the average city's surface area (Besir and Cuce, 2018), retrofitting these spaces with green roofing or solar PV systems represent two important potential pathways to abate CO_2 emissions and achieve net zero targets. However, there are numerous barriers to both of these low carbon measures, such as building structural capacity and public awareness, with financial barriers constituting a major barrier to uptake (Castleton *et al.*, 2010; Mahdiyar *et al.*, 2020). The provision of financial subsidies to incentivise solar PV system and green roof uptake offers one way to overcome financial barriers, with successful case studies existing from Australia to America (Carter and Fowler, 2008; Macintosh and Wilkinson, 2011).

Current literature has explored the environmental and economic effectiveness of green roofs and solar PV systems independently in regions and climates across the globe (Kato, Murata and Sakuta, 1998; Clark, Adriaens and Talbot, 2008; Laleman, Albrecht and Dewulf, 2011; Claus and Rousseau, 2012). In addition, recent studies have made use of the latest advances in remote sensing to identify the rooftop area suitable for retrofit at the city scale (Santos, Tenedório and Gonçalves, 2016; Silva, Flores-Colen and Antunes, 2017). Despite advocating the potential of both green roofs and solar PV systems to mitigate global climate change, only one study has directly compared the two, focusing on the environmental life cycle benefits of both in a cold Canadian climate (Cubi *et al.*, 2016). The city-scale emissions abatement potential, financial cost-benefit ratio, and cost-effectiveness of each alternative for abating emissions are yet to be directly compared. With ambitious net zero targets and a recently calculated total city rooftop area suitable for retrofit with extensive green roofing or solar PV systems (Constantine, 2019), the city of Bristol makes an excellent case study for directly comparing both alternatives in a temperate region. Bristol does not yet have its own strategy for incentivising green roofing or solar PV system uptake across the city, and in fact, no financial incentives are currently offered in the UK for green roofing at all (Carter and Fowler, 2008).

The objectives of this study aim to provide a direct comparison of providing financial subsidies to incentivise the uptake of either green roofs or solar PV systems in Bristol, UK, in relation to three key questions:

- Subsidising which alternative has the potential to abate the greatest quantity of CO_2 equivalent emissions (CO_2-e) at the city scale by 2050?
- Considering the economic equivalent of all major costs and benefits, which alternative offers the best financial outcome per m2 implemented?
- Subsidising which alternative will provide the most cost-effective abatement of CO_2 equivalent emissions per tonne (tCO_2-e)?

This study focuses on extensive green roofs due to their lighter weight, making them easier to implement without encountering issues with building structural capacity. By taking into account the influence of different uptake success scenarios towards the year 2050, and the different scopes of feature impacts (private, state, and global), this study hopes to provide a useful comparison between the two alternatives over a variety of scenarios. The information presented in this study aims to bridge the literature gap of directly comparing the economic and environmental potential of green roofing and solar PV systems in a temperate climate. By using the latest regional data and remote sensing information for the city of Bristol, this information will prove useful for Bristol City Council in identifying the best possible use of available rooftop area and fiscal resources to achieve national and city net zero targets, with a predominant focus on the national 2050 target.

This study finds solar PV systems to be over 5.6 times more cost-effective than extensive green roofing at abating CO_2 emissions, with the potential to abate over 9.7 million tonnes of CO_2-e by 2050 following a realistic successful scenario. While green roofs offer an inferior emissions abatement potential, they offer a more financially affordable option to implement, with a superior financial cost-benefit ratio, and a variety of environmental and social benefits that solar PV systems cannot deliver. Considering the current climate emergency and net zero targets, solar PV systems are advocated as the most efficient use of rooftop space in Bristol to achieve these crucial targets. The variation in outcomes for different study scenarios highlights the importance of carefully considering uptake rate and impact range within evaluations. The influence of sociodemographic factors, city financial capacity, and combined green-solar roofs on comparative outcomes are highlighted as useful avenues for future research.

2. Overview of current literature

2.1. Environmental sustainability of urban transport systems

Model outcomes in the latest IPCC report stated that, to limit global temperature rise to 1.5°C, global efforts must be made to reach net zero CO_2 emissions by approximately 2050 (IPCC, 2018). Despite the inherent error in modelling future climate scenarios, the IPCC claimed a high level of confidence in these projections, highlighting the urgency of action required to effectively limit the impacts of climate change globally. Following a recent study by Regen in 2019, it was concluded that the city of Bristol's efforts were currently insufficient to match national targets to become carbon neutral by the year 2050, and Bristol's own more ambitious targets to do so by 2030, implying that further policy action was required. That same year, Colenbrander *et al.* (2019) highlighted residential and commercial buildings as a key sector for cities to further reduce their emissions, estimating that 58% of the actionable ability to abate global carbon emissions lies within this sector, such as improving energy efficiency. For the case of Bristol, previous work in 2015 by Gouldson & Millward-Hopkins had already advocated the importance of low carbon measures to curb emissions, such as installing solar PV systems and improving home energy efficiency, claiming these types of measures could cut the city's carbon emissions 18.3% below 2005 levels as soon as 2025. Furthermore, Millward-Hopkins *et al.* reiterated the case for solar PV in 2018, concluding PV systems to be an excellent and cost-effective avenue to avoid CO_2 emissions that would otherwise be emitted as a by-product of burning non fossil fuels for the same purpose. Alternatively, a variety of literature has proposed green, “living”, roofs as an effective way to abate CO_2 emissions, either by directly sequestering CO_2 into vegetation and substrate matter (Blackhurst, Hendrickson and Matthews, 2010; Whittinghill *et al.*, 2014), or by insulating the buildings they are constructed on, thereby reducing energy consumption and related emissions (Niachou *et al.*, 2001; Saiz *et al.*, 2006; Carter and Keeler, 2008; Castleton *et al.*, 2010; Claus and Rousseau, 2012). Furthermore, a variety of additional cobenefits to green roof installations have been identified in academic literature, including: biodiversity improvements (Pearce and Walters, 2012; Elmqvist *et al.*, 2015; Partridge and Clark, 2018; Langemeyer *et al.*, 2020), stormwater absorption (Shafique, Kim and Kyung-Ho, 2018), building soundproofing, air quality improvements, improved roof life length, increased public wellbeing (Abolhabib, Sharifi and Dehaghani, 2020), and even claims of increased concentration levels within offices (Lee *et al.*, 2015)

2.2. Uptake barriers and enablers

Despite offering key opportunities to help achieve global emissions targets, multiple barriers have been identified in current literature which limit the uptake of both green roofs and solar PV systems. For green roofs, the most prominent of these barriers include: building structural capacity (Castleton *et al.*, 2010), roof slope (Santos, Tenedório and Gonçalves, 2016; Silva, Flores-Colen and Antunes, 2017), awareness (Wilkinson and Reed, 2009) and financial cost (Mahdiyar *et al.*, 2020). Following two studies to identify the most prominent barriers to green roofs this year by Abolhabib, Sharifi and Dehaghani, and also by Mahdiyar, both found financial investment requirements to be the largest current barrier restricting uptake. Similar barriers have also been identified limiting the uptake of solar PV systems, including public awareness and suitable local infrastructure, with the significant installation costs of solar installations considered the major uptake barrier (Margolis and Zuboy, 2006; Ansari *et al.*, 2013; Palm, 2018). In relation to this major financial barrier limiting both green roof and solar PV system uptake, numerous policy mechanisms have been evaluated and discussed in literature to overcome such a barrier. For green roofs, these mechanisms include indirectly incentivising uptake by offering reductions in building water management fees (Claus and Rousseau, 2012), or in the case of solar PV systems, offering Feed-in Tariffs (FITs) which supplement the value of solar energy in comparison to non-renewable energy sources (Chapman, McLellan and Tezuka, 2016; Pyrgou, Kylili and Fokaides, 2016). Within the range of financial incentive options for promoting both green roof and solar PV system uptake, a frequently implemented and evaluated mechanism involves providing a direct one-off subsidy payment to incentivise uptake. In 2019, Burszta-Adamiak and Fiałkiewicz considered the effectiveness of a variety of different green roof incentives enacted in European cities, concluding that the best outcomes for promoting green roofs in these cities have stemmed from the inclusion of a direct subsidy advancing investment returns to within 5-10 years of installation. In 2012, Claus and Rousseau proved these subsidies to be highly necessary and socially desirable for convincing private green roof uptake in Belgium. Carter and Fowler (2008) also highlighted the success of previous subsidy schemes implemented in cities including Berlin and Toronto, as well as similar grant-based schemes offered in Chicago and the state of Columbia. However, they also noted that, despite their potential to overcome the financial barriers to green roof installation, direct subsidies require the implementing authority to have a high financial capacity. In parallel with Cater and Folwer's findings highlighting the financial requirements of providing direct subsidies, Mullen, Lamsal and Colson (2013) argued that simple information sharing and technical consultation services hold a superior cost-benefit ratio in comparison to financial subsidies, after evaluating the effectiveness of previous mechanisms implemented in Atlanta. However, it should be noted that Mullen, Lamsal and Colson's analysis was solely focused on instrumental cost-effectiveness, and that information sharing and consultation services fail to address the previously highlighted major financial barriers to uptake, against which subsidies remain a key enabling instrument. Moving from green roofs to solar PV systems, a similar case exists for direct subsidies. Hsu (2012) advocated the superior long-term cost-effectiveness of direct subsidies over Feed In Tariffs (FITs), and an evaluation of previous subsidy schemes in U.S. states by Hagerman, Jaramillo and Morgan

(2016) claimed the necessity of these direct subsidies for ensuring the financial viability of solar PV systems against alterative home energy sources. In agreement, the significant effects of solar PV subsidies boosting uptake have been highlighted by case study evaluations in Sweden (Mundaca and Samahita, 2020), Poland (Kaya, Klepacka and Florkowski, 2019), California (Hughes and Podolefsky, 2015), and Australia (Macintosh and Wilkinson, 2011).

2.3. Solar PV and green roof performance

Considering the aforementioned literature highlighting the potential for green roofs and solar PV systems to abate CO_2 emissions, and the potential effectiveness of directly subsidising their uptake, a natural comparison follows: subsidising which alternative offers the most cost-effective use of roof space for abating emissions? Since the turn of the century, several studies have been conducted evaluating the enumerate costs and benefits of green roofs, claiming their potential to provide a positive return on environmental and economic investments over time: (Banting *et al.*, 2005; Clark, Adriaens and Talbot, 2008; Blackhurst, Hendrickson and Matthews, 2010; Tomalty, Komorowski and Doiron, 2010; Porsche and Köhler, 2013). In 2012, Claus and Rosseau conducted a cost-benefit analysis of constructing a single extensive green roof in Belgium, considering numerous public and private costs and benefits. This analysis involved monetising the impacts of green roofs on improving air quality, reduction in stormwater management costs, abating emissions, and costs of installation, maintenance, and the subsidy itself, claiming that financially incentivising green roof production provides a net positive return on state investments in a best-case success scenario, but not in a worst-case success scenario, with roof life span being the dominant factor in this outcome. Similar results were found following an evaluation of a green roof in Rotterdam, but this study did not include financial incentives, and net returns on investments were received much later (Arcadis, 2008). A similar case exists for solar PV systems, with considerable literature claiming their potential to provide net economic and environmental benefits over time (Kato, Murata and Sakuta, 1998; Black, 2004; Laleman, Albrecht and Dewulf, 2011; Gerbinet, Belboom and Léonard, 2014).

Despite the numerous studies evaluating the costs and benefits of green roofs and solar PV systems, their competitiveness against each other remains relatively unexplored. In 2016, Cubi *et al.* directly compared the environmental impacts of extensive green roofs, white-painted roofs, and solar PV system alternatives, finding the environmental benefits of solar PV systems to be between 10 and 30 times greater than those of the alternatives. However, this study only considered environmental impacts such as air quality, stormwater retention, and energy savings, and did not take financial costs and benefits into account to derive a cost per abated tonne for each, such as considering the high cost of solar PV installations. In contrast, Macintosh and Wilkinson (2011) analysed the cost per tonne of abated CO_2 equivalent emissions following the Australian Government's Photovoltaic Rebate Program (PVRP), which subsidised the uptake of residential solar PV systems. Despite claiming a six-fold increase in solar PV uptake, an extremely low cost-effectiveness was claimed, at AU$238-282 per tonne of abated CO_2-e. This was largely due to the high installation costs of solar PV systems. Furthermore, the analysis by Cubi *et al.* was conducted considering a cold (Canadian) climate, where factors such as solar intensity, precipitation, and temperature will influence the competitiveness of each different alternative to abate emissions. While Cubi *et al.* claimed white-painted roofs to hold the least environmental benefits in comparison to green roofs and solar PV systems, Sproul *et al.* (2014) claimed otherwise after evaluating alternatives in the U.S., claiming white-painted roofs to be three times more effective than green roofs at cooling the globe, but green roofs as the best choice for tackling local environmental effects. This highlights the importance of analysing alternative emissions abatement options in situ, whilst holistically considering all the intrinsic costs and benefits to each. With current advances in remote sensing technology, this is now much easier to achieve. Several studies have now made use of available remote sensing data to determine the total rooftop area of suitable for green roof retrofit, in cities including Lisbon, Portugal (Santos, Tenedório and Gonçalves, 2016), Braunschweig, Germany (Grunwald, Heusinger and Weber, 2017), and Thessaloniki, Northern Greece (Mallinis *et al.*, 2014; Karteris *et al.*, 2016). For the case of Thessaloniki, Northern Greece, Mallinis *et al.* (2014) used remote sensing techniques to calculate the available rooftop area equally suitable for both green roofing and solar photovoltaic (PV) retrofit. Karteris (2016) went even further, using high resolution satellite imagery to extrapolate green roof emissions savings per m2 over the entire city's suitable rooftop area. Karteris *et al.* claimed a potential abatement of over 75,000 tonnes of CO_2 emissions per annum following city-scale green roof retrofitting, but did not consider equivalent solar PV system impacts, nor the economic costs and benefits of each. Instead, Karteris *et al.* underlined financial incentives as a key area for further research.

2.4. Application to Bristol

The city of Bristol, UK, was awarded "Green Capital" status in 2015, reflecting its commitment to maintaining high environmental standards. The same year, Gouldson & Millward-Hopkins (2015) evaluated the performance of a range of low carbon instruments with the potential to reduce Bristol's future emissions. Gouldson & Millward-Hopkins considered domestic solar PV installations within their study and concluded a cost-effectiveness of £505 per abated tonne of CO_2. However, this analysis did not consider the cost-effectiveness of incentivising green roof uptake, nor the impact of providing financial subsidies on cost-effectiveness. More recently, in 2019, Constantine successfully used remote sensing techniques to determine the area of rooftop suitable for either extensive green roofing or solar PV system retrofitting across Bristol, considering factors such as solar potential, building ownership, listed status, and roof slope within this analysis. Structural capacity was not considered in this analysis due to the low-weight nature of the extensive green roofs considered, in comparison to intensive green roofs which often require structural alterations prior to retrofitting (Castleton *et al.*, 2010). Bristol City Council also published an open dataset in 2019, presenting values of solar energy potential and suitability for individual rooftops across Bristol, as well as respective potential annual emissions abatement (Bristol City Council, 2019). Using the latest data estimating the total retrofittable rooftop area within a city and literature estimating regional-specific impacts of both green roofs and solar PV systems per m2, it is now possible to estimate the potential city-scale emissions abatement and the cost-effectiveness of these schemes more accurately than ever. The GIS data provided by Constantine in 2019 is yet to be utilised to provide an emissions abatement estimate for the city of Bristol, considering either green roof or solar PV system retrofitting. In addition to this, the latest literature and regional studies are yet to be utilised to conduct a holistic cost-benefit analysis of green roofs in Bristol and compare these to solar PV system alternatives. Furthermore, these emissions and cost-benefit outputs can then be combined to derive and compare the net cost per abated tonne of CO_2 for each alternative. These comparisons are yet to characterised for the city of Bristol and will prove necessary for informing future council decisions on achieving net zero city targets.

3. Methods

Estimates for the total rooftop area suitable for extensive green roofing or solar PV system retrofit used in the following calculations were based upon previous estimates by Constantine in 2019 for the city of Bristol (Figure 1), who took into account limiting factors such as roof slope and solar radiation. This value was then taken at 90% to account for the possibility of any rooftop objects, such as air conditioning units and skylights, highlighted by Wong and Lau (2013) to potentially restrict the area available for retrofit.

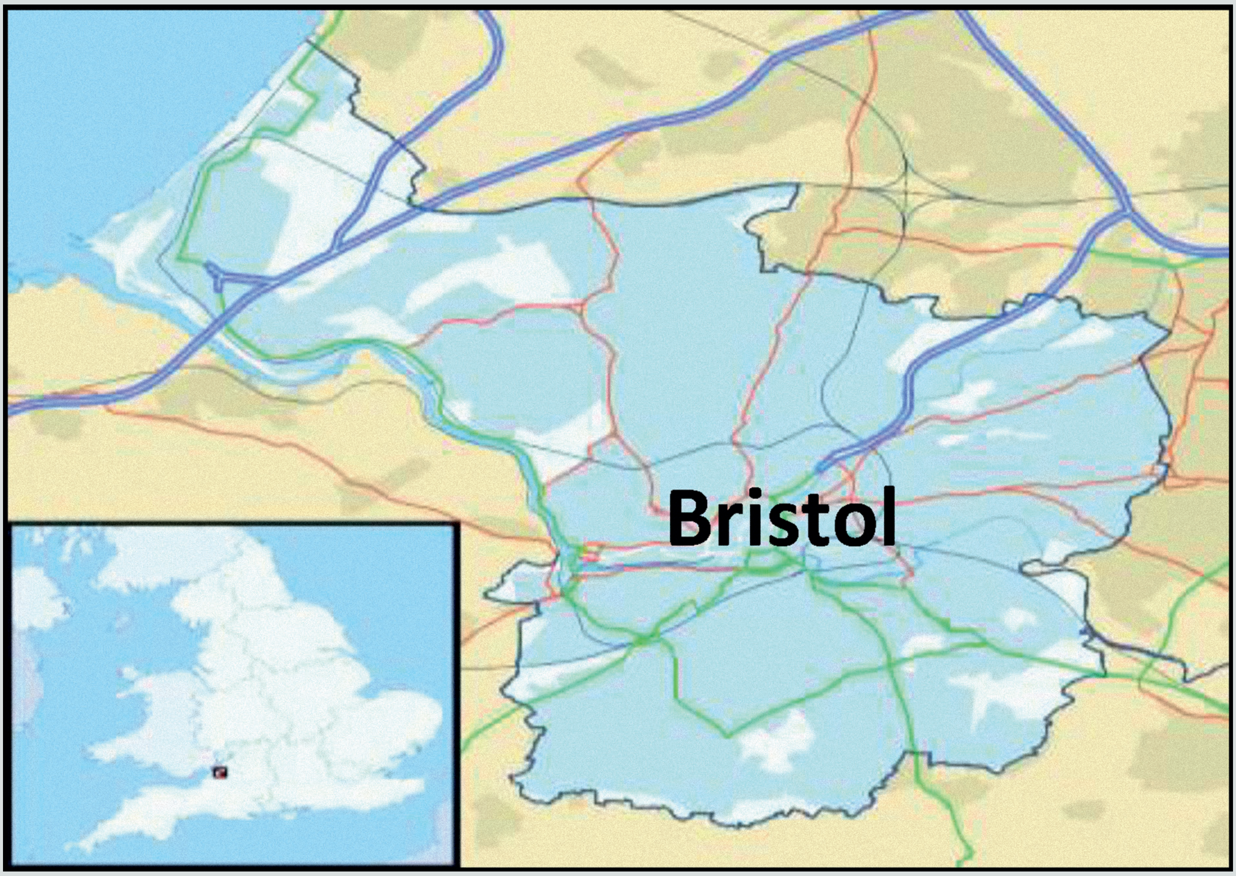

Figure 1: The geographical location and administrative boarder of Bristol, UK, (adapted from Nilfanion, 2010).

3.1. Emissions calculations

Potential carbon dioxide reductions by the year 2050 were calculated for both green roof and solar PV subsidy schemes in Bristol. For green roofs, this involved calculating the potential direct carbon dioxide absorption by green roof vegetation, as well as the reduced building heating energy consumption (and resultant emissions reductions) resulting from green roof insulation effects. For solar PV systems, calculations of abated emissions solely involved the potential to produce solar energy, thereby avoiding the carbon dioxide emissions that would have otherwise been produced via fossil fuel energy sources, such as natural gas.

To calculate the total area of Bristol rooftop that would be suitable for both green roof and solar PV system retrofit, estimates by Constantine 2019 were utilised. This area was adjusted to 90% of its original value to account for the presence of any rooftop objects such as ventilation units and air conditioning units, then used to extrapolate the emission reduction calculations per m2 up to the city scale. Following this, the city scale potential emissions reductions were extended towards the year 2050 and adjusted for three different scenarios, representing three different levels of uptake over the next 30 years:

Scenario A: 100% success – A theoretical maximum success scenario representing what could be achieved by 2050 if all potential roofs were currently retrofitted.

Scenario B: 75% success - A realistic high success scenario, representing a moderate uptake rate and strong subsidy success towards 2050..

Scenario C: 50% success - A realistic medium success scenario, representing a slower uptake rate and lower subsidy success towards 2050.

Potential Green Roof Emissions Abatement

Direct Emissions Absorption

For green roofs, to calculate the potential absorbed emissions by both substrate and vegetation by 2050, an absorption value of 0.375kg of carbon dioxide per m2 per annum for an extensive green roof was adopted from (Getter *et al.*, 2009). This was then multiplied by the area of Bristol roofing suitable for retrofit that was previously adjusted from Constantine (2019) to give the total annual carbon dioxide absorption potential for the city. This figure was then multiplied for the next 30 years, and adjusted for uptake scenarios A, B, and C.

Building Insulation Effects

To calculate the potential CO_2-e abatement that would result from the insulating effects of green roofing on Bristol buildings, the emissions that would have otherwise been produced via fossil fuel heating energy sources were calculated. The average Bristol building heating energy consumption was assumed to be

10,926 kWh per annum, based upon estimates by Regen (2019) (“using EPC data”), who calculated heating energy consumption for buildings in Bristol with different Energy Performance Certificates (EPCs). An average EPC rating of ‘D’ was selected to model the buildings in this study, being the 2020 national average EPC rating for both domestic and non-domestic dwellings (MHCLG, 2019). Claus and Rousseau (2012) estimated that the insulating effects of a green roof will reduce building heating energy consumption by 1.5% on average, by taking an average of estimates from two past European studies (Niachou *et al.*, 2001; Saiz *et al.*, 2006). This study adopts this average heating energy saving value of 1.5%, equating to average savings of 163.89 kWh per building per annum for the case of for Bristol. To convert annual energy savings per dwelling into city-scale impacts, this value was then was multiplied by the 129,676 dwellings that were previously identified to be suitable for roof retrofit in Constantine’s (2019) study of Bristol. The potential energy savings across Bristol per annum were then extrapolated up to the year 2050 for uptake scenarios A, B, and C. It should be noted that actual heating energy savings will vary between cities and dwelling due to a variety of factors which cannot realistically be accounted for in this study, including: building size, regional climate, future climates, and green roof characteristics. Alternatively, the average annual energy saving per m2 of green roofing in Bristol was calculated by dividing the estimated annual heating energy saving across the city by the (adjusted) rooftop area suitable for retrofit from Constantine (2019), giving a saving of 2.427 kWh per m2 per annum (for use in later cost-benefit calculations).

To calculate the equivalent emissions savings due to improved home energy efficiency following a green roof installation, energy saving estimates in Bristol per m2 of green roofing and for all 2050 uptake scenarios were converted to equivalent carbon dioxide emissions savings using the BEIS 2020 carbon intensity value for natural gas, at 0.18387kg CO_2-e per kWh of energy use (BEIS, 2020a). Natural gas was assumed as the source of dwelling heating energy in these calculations since it accounts for over 90% of heating energy provision within Bristol, according to Regen (2019). As a small proportion of Bristol’s heating energy will be supplied via alternative energy sources such as small-scale renewables, and the proportion of Bristol’s energy from fossil fuel sources will likely be replaced by low carbon and renewable sources towards 2050 (decarbonisation) (Colenbrander *et al.*, 2019), these abated emissions calculations will likely constitute an upper bound of estimates. This process calculated the 1.5% reduction in dwelling heating energy use resulting from green roof insulation to save an average of 0.446kg of CO_2-e per m2 per annum, for input in later cost-benefit calculations.

Potential solar PV emissions abatement

By producing and utilising zero carbon solar energy within buildings, the emissions otherwise associated with energy obtained via fossil fuel sources can be avoided (Gouldson and Millward-Hopkins, 2015). Estimates for the potential emissions savings from a solar PV system subsidy scheme in Bristol were based on initial figures from the Bristol City Council Solar Suitability open dataset (BCC, 2019). This dataset identifies all individual Bristol rooftops suitable for solar PV system retrofit, as well as their potential annual energy production and resultant abated emissions. The aggregate potential abated emissions within this dataset per annum was divided by the total potential solar PV system area encompassed within this dataset to obtain the average potential abated emissions per m2 of Bristol solar PV system per annum (49.256kg CO_2). This value was then multiplied by the total (adjusted) rooftop area suitable for retrofit identified by Constantine (2019) to determine the potential annual emissions savings for the city comparable to green roofing, and extrapolated up to the year 2050 for uptake scenarios A, B, and C. All emissions values were rounded to three decimal places.

3.2. Cost calculations

The costs analysed in this evaluation of a green roof and solar PV subsidy scheme in Bristol include the private and state level costs of: initial feature installation, feature maintenance, the subsidy itself, and any administration costs that would be incurred when providing a subsidy. All costs were calculated at a value per m2 per annum, except for installation and subsidy costs which was considered as a one-off sum. These one-off sums were divided by the 30 year period to obtain an annual equivalent cost for use in cost-benefit calculations.

Installation costs

Initial feature installation costs for green roofing were obtained by averaging previous installation estimates from Li and Yeung (2014), Mahdiyar *et al.* (2016) and Claus and Rousseau (2012). Estimates for solar PV system installation costs per m2 were based on current government figures for the average cost of solar PV system installation per kWh (BEIS, 2020b), at £1,704 per KW installed. To calculate this cost at a m2 value relative to Bristol, it was first multiplied by the average potential solar PV system KW capacity for Bristol rooftops (7.331KW) according to Bristol City Council data (BCC, 2019), giving the average installation cost per solar PV system installed in Bristol. This value was then divided by the average area of a single potential solar PV installation in Bristol, obtained from the same BCC dataset (51.316 m2), providing an average installation cost per m2. To avoid double-counting in cost-benefit calculations, state subsidy values were subtracted from installation costs in combined calculations. As the cost of solar PV system installations are falling over time, although at a reducing rate, the estimates for installation costs used in this study will likely form an upper bound, depending on future advances in this field over the next 30 years.

Maintenance costs

The maintenance costs for a green roof in Bristol per m2 per annum were calculated by averaging estimates presented by Claus and Rousseau (2012) and Li and Yeung (2014). For solar PV systems, a maintenance cost of 5% of each feature installation cost (previously calculated) was adopted from Hsu (2012). This value was converted into to a value per m2 per annum using the average solar PV system area according to the Bristol City Council Solar Suitability open dataset (BCC, 2019), and divided by the 30-year study length to obtain an annual equivalent cost. As extensive green roofs are currently estimated to last for up to 50 years (Shafique *et al.*, 2020), and solar PV systems are able to last beyond 30 years (Grant and Hicks, 2020), replacement costs were not included in this analysis.

Subsidy cost

Subsidy values for incentivising green roof and solar PV system retrofitting in Bristol were based upon an average of previously successful subsidy schemes in other cities. For green roofing, these were based upon subsidies offered in similar European cities, the values of which reflected 50% of green roof installation costs (Carter and Fowler, 2008; Claus and Rousseau, 2012). The subsidy value for solar PV systems was also chosen at 50% of installation costs (which are considerably higher for solar PV systems), reflecting the average of previous subsidies successfully implemented in Melbourne, Australia (Macintosh and Wilkinson, 2011). Although “Feed-In Tariffs” (FITs) are also often used to incentivise solar energy production (by increasing the value of solar energy per kWh), this study focuses on one-off subsidy payments that will counter the barrier of initial retrofit costs. These costs were divided by the 30-year study period to obtain an annual equivalent cost.

Subsidy administration costs

To calculate the administration costs that would accompany a subsidy scheme in Bristol promoting green roofs or solar PV systems, an administrative cost was assumed at 0.2% of the subsidy in question, adopting the value assumed by Claus and Rousseau in 2012.

3.3. Benefit calculations

To calculate the administration costs that would accompany a subsidy scheme in Bristol promoting green roofs or solar PV systems, an administrative cost was assumed at 0.2% of the subsidy in question, adopting the value assumed by Claus and Rousseau in 2012.

Reduced social cost from carbon dioxide emissions

The direct and indirect impacts of carbon dioxide on human lives are far reaching, tied to the impacts of climate change. In this study, an average social cost of carbon dioxide emissions per tonne of $77 was adopted from Poelhekke (2019) and converted to pounds sterling using the average exchange rate for the year (HMRC, 2019), equalling £0.060 per kg of CO_2. Poelhekke’s original estimate in 2019 was based upon a meta-analysis of previous estimates and includes the anticipated impacts to generations over the next 50 years. The converted value from Poelhekke (2019) was then multiplied by the previously calculated emissions reductions per m2 per annum for both green roofs and solar PV systems in Bristol to obtain an equivalent monetary benefit value of avoided costs following green roof and solar PV system installation.

Air quality

Green roofs have been shown to absorb hazardous pollutants in the atmosphere, including nitrogen oxides, which can otherwise lead to harmful respiratory impacts (Chen *et al.*, 2007; Sun *et al.*, 2017). To calculate the economic equivalent benefit of green roofing absorbing this harmful pollutant, a value of 0.0124 euros per m2 of green roofing per annum was adopted from the value used by Clark, Adriaens and Talbot (2008), and Claus and Rousseau (2012), converted to 2020 pounds sterling using an average inflation rate of 2% per annum and the HMRC 2019/20 yearly average exchange rate of 0.8717 (HMRC, 2019). The impacts of green roofs on other harmful pollutants such as ozone, heavy metals and volatile organic compounds were not included in this study due to insufficient data.

Water management

Green roofs have been shown to absorb an average of 50% of the precipitation that they receive whilst leading to significant delays in urban run-off (Fioretti *et al.*, 2010; Carpenter and Kaluvakolanu, 2011; Hashemi, Mahmud and Ashraf, 2015). On the city scale, these reductions in run-off can translate to significant cost reductions for managing rainwater and flood risk in urban drainage systems. To quantify this benefit, a financial valuation of the reduced loading on drainage systems was adopted from estimates by Claus and Rousseau in 2012, at 0.1 Euros per m2 of green roofing per annum. This figure was converted to 2020 pounds sterling using an average inflation rate of 2% per annum and the HMRC 2019/20 yearly average exchange rate of 0.8717 (HMRC, 2019), before use in cost-benefit calculations. As the long-term reduction in flood risk and flood damage for the city of Bristol could not be monetised in this study due to insufficient data, the financial benefits of reduced urban run-off will likely constitute a lower bound. Although green roofs have also been shown to filter harmful elements from water that pass through them (Hashemi, Mahmud and Ashraf, 2015), this water must still be processed prior to consumption and therefore any monetary benefits of improved water quality were not included in this study.

Energy cost savings

To calculate the resultant heating energy cost savings in Bristol due to green roof insulation effects and solar PV energy production, the previously obtained values for reductions in natural gas consumption per m2 per annum (2.427 kWh and 90.710 kWh) were multiplied by the current national average price for natural gas per kWh, at £0.045 (BEIS, 2020c). The average solar energy production per m2 per annum had been previously obtained using the Bristol City Council Solar Suitability open dataset (BCC, 2019). Both these estimates will be accompanied by an element of inherent uncertainty due to unpredictable changes in future energy supply and the price of natural gas over the next 30 years.

All costs and benefits per m2 per annum were categorised by scale of impact, with ‘private’ effects impacting building residents, ‘state’ effects impacting the public and local authority of Bristol, and the ‘global’ social impacts associated with climate change due to increased carbon dioxide levels. To calculate net cost-benefit outcomes per m2 per annum, the monetary benefit estimates were subtracted from the combined annual cost estimates for each alternative, at different scoping levels of state, global, and private impacts. To calculate the cost per abated tonne of CO_2-e (cost-effectiveness), the net public cost-benefit outcome per m2 per annum was divided by the respective abated tonnes of carbon per m2 per annum. All monetary cost and benefit values were rounded to two decimal places. The green roof benefits of biodiversity, ecosystem services, visual amenity, property value (which is a benefit also associated with solar PV systems), individual wellbeing, and reductions in urban heat and noise were not included in this study due to unmonetizable effects, negligible impacts, or insufficient available data. The resultant cost-benefit outcome for green roofing will therefore likely constitute a negative lower bound.

4. Results

4.1. Potential city-wide emissions abatement by 2050

By directly absorbing carbon emissions and increasing building energy efficiency through insulation effects, green roofs display the ability to abate a significant quantity of emissions by 2050, up to over 160,000 tonnes of CO_2 equivalent (tCO_2-e) following a realistic high success scenario (Table 1, figure 2, scenario B). However, this is dwarfed by the potential abatement from an equivalent solar PV subsidy scheme over the same period and area of Bristol rooftop, potentially abating over 9.7 million tCO_2-e, over 60 times greater than the potential of green roofing in the same scenario. Between a realistic high uptake and medium uptake success scenario, the potential abated emissions from green roofs are shown to vary by 54,000 tCO_2-e, whereas for an alternative solar PV system scheme, this may account for differences in abatement potential of over 3.2 million tCO_2-e (Table 1, figure 2).

Table 1: The quantity of potential abated emissions by the year 2050 for green roof and solar PV system subsidy schemes, tonnes CO_2 equivalent (CO_2-e). Uptake scenarios A, B and C denote a theoretical maximum success scenario, realistic high uptake success scenario, and reali22 stic medium uptake success scenario, respectively.

		Abated Emissions (tonnes CO_2-e)		
Subsidy scheme	**Installation effect**	**Scenario A**	**Scenario B**	**Scenario C**
Green roof	Absorbed Emissions	98,516	73,887	49,258
	Building Insulation	117,231	87,924	58,616
	Combined effects	**215,748**	**161,811**	**107,874**
Solar roof	Zero carbon energy	**12,940,044**	**9,705,033**	**6,470,022**

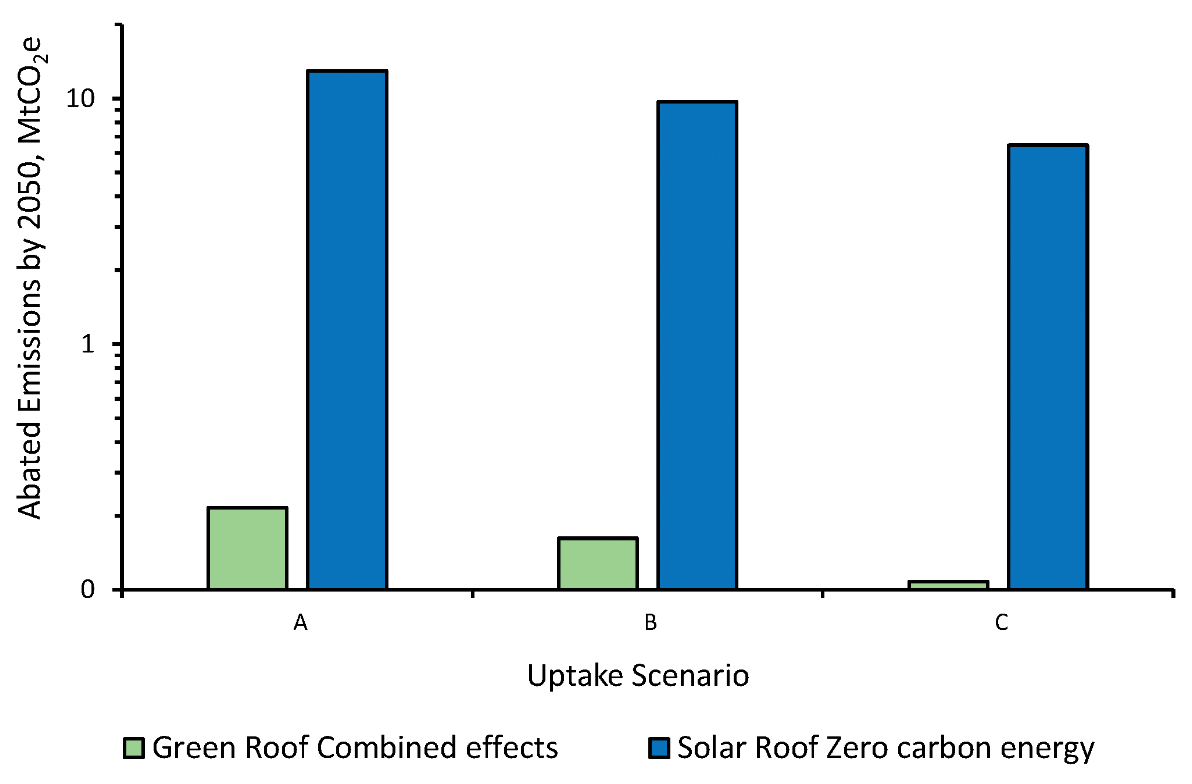

Figure 2: A visual representation of the quantity of total potential abated emissions by the year 2050 for a green roof and solar PV subsidy scheme in Bristol, in million tonnes (megatonnes) of CO_2 equivalent ($MtCO_2$-e). Uptake scenarios A, B and C denote a theoretical maximum success scenario, realistic high uptake success scenario, and realistic medium uptake success scenario, respectively.

4.2. Net financial value and cost per abated tonne of CO_2-e

An annualised cost-benefit analysis of a green roof and solar PV system subsidy scheme revealed significant cobeneifts following green roof installation, along with considerably lower private installation costs and resultant state subsidy requirements, over eight times cheaper than solar PV system alternatives (Table 2). When considering cost-effectiveness, despite a solar PV subsidy scheme only bringing the benefits of renewable energy production (and the resultant avoided emissions) whilst costing the state over 10 times more per m2 per annum than green roofing, its cost per tonne of abated CO_2 equivalent is over 5 times cheaper than green roofing (Table 3, scope 1). Alternatively, when including the global scale reductions in the social impacts of carbon emissions, a green roof subsidy scheme returned a net positive investment, at a value of £0.11 (Table 2, Scope 2), equalling £114 per tCO_2-e (Table 3, scope 2), while solar PV systems remained negative. For the building tenant, the private monetary savings from solar energy production were over 37 times greater than the savings from green roof heating efficiency improvements, at £4.08 and £0.11 per m2 per annum, respectively. When private, state, and global costs and benefits were considered, the cost per abated tCO_2-e did not improve for either alternative, and revealed the least cost-effective green roof outcome, costing 46 times more than a solar PV subsidy scheme per abated tCO_2-e (Table 3, scope 3).

Table 2: A cost-benefit analysis of the value of green roofing and solar PV subsidy scheme alternatives for the case of Bristol, per m2 installed per annum. Values are displayed in pounds sterling per m2 per annum, unless otherwise stated as one-off. Scopes 1, 2, and 3 refer to the consideration of a different range of costs and benefits: only state, state and global, and state, global, and private, respectively. A "(+)" denotes the occurrence of an overall net economic gain.

			Cost, £	
Effect	**Scope**	**Subsidy Scheme**	**Green Roof**	**Solar PV**
Cost	Private	Installation (One-Off)	30	243.43
	Private	Maintenance	1	0.41
	State	Subsidy (One-Off)	15	121.72
	State	Administration (One-Off)	0.03	0.24
Benefit	Private	Energy Cost Savings	0.11	4.08
	State	Improved Local Air Quality	0.02	n/a
	State	Reduced Surface Run-Off	0.10	n/a
	Global	Avoided Social Costs of Emissions	0.49	2.96
Net		Scope 1	0.38	4.07
		Scope 2	(+) 0.11	1.11
		Scope 3	1.31	1.72

Table 3: The net cost-effectiveness (per tonne of abated CO_2 equivalent) for green roofing and solar PV subsidy scheme alternatives in the case of Bristol, per m2 installed per annum. Values are displayed in pounds sterling. Scopes 1, 2, and 3 refer to the consideration of a different range of costs and benefits: only state, state and global, and state, global, and private, respectively. A "(+)" denotes the occurrence of an overall net economic gain.

	Net Cost per tCO_2-e, £	
Considered Effects	**Green Roof**	**Solar PV**
Scope 1	462.85	82.63
Scope 2	(+) 133.98	22.54
Scope 3	1,595.62	34.92

5. Discussion

In light of national commitments to become carbon neutral by the year 2050, and Bristol council's ambition to do so by 2030, the findings of this study are discussed in relation to achieving these targets, with a focus on national commitments.

5.1. Potential city-wide emissions abatement by 2050

Considering the potential for a solar PV system subsidy scheme to abate over 60 times as many tonnes of CO_2-e than a green roof subsidy scheme by 2050 (table 1, Figure 2), its superiority for helping Bristol and the UK to reach their respective net zero targets is clear. This suggests that replacing fossil fuel energy consumption with "zero-carbon" solar energy is a far more effective measure than the combined carbon sequestration and home insulation effects of green roofing. In comparison to Cubi *et al.* (2016), who claimed the environmental benefits of solar PV systems were 10 - 30 times greater than those of green roofs, this study suggests that the difference for the case of Bristol may be more than double Cubi *et al.*'s original estimates in Canada. In 2016, Bristol's annual carbon emissions were estimated to be around 1,724 kt CO_2-e (Regen, 2019). If Bristol's emissions were to retain this annual rate between 2020 and 2050, they would amount to a cumulative 51,720 kt CO_2-e. Comparing this latter figure to the potential 9,705 kt of abated CO_2-e that a solar PV subsidy scheme can deliver over the same 30-year period (Table 1, scenario B), the apparent potential contribution of a solar PV subsidy scheme to national net zero targets is substantial, at 19% of total city emissions within the next 30 years. It should also be noted that, as this study only considers the 61% of Bristol rooftops that can support either solar PV systems or green roofs (adapted from Constantine, 2019), the estimated contribution of solar to city and national net zero emissions targets will constitute an underestimate, as solar panels can be fitted onto rooftops of greater slope than green roofs. In comparison to solar PV systems, the estimated 162 kt of abated CO_2-e that a green roof subsidy scheme would deliver in same scenario period (Table 1, scenario B) amounts to less than 0.01% of total city emissions over this period.

The range of results in this study highlights the influence of assuming different levels of uptake success on 2050 abatement potential. With a greater overall abatement potential for solar PV systems, the impact of uptake success on total 2050 carbon abatement is heightened, with a difference of over 3.2 million tonnes CO_2-e between a low and high realistic uptake success scenario (Table 1, figure 2, uptake scenarios B and C). The significantly higher savings for the case of a theoretical instantaneous uptake scenario for both alternatives demonstrates the environmental benefits of implementing low carbon measures as soon as actionably possible to maximise mitigative effects.

5.2. Net financial value

In contrast to the superiority of solar PV systems for abating emissions, subsidising green roofs offers a greater annualised net financial cost-benefit outcome at either private, state, or global levels. This is predominantly due to the financial costs of installation and subsidy provision for solar PV systems being over eight times the cost of green roofing (Table 2), rather than the disparity in financial benefits, where solar PV systems actually outweigh green roofing on all accounts. Although subsidising green roofing appeared to deliver a net financial gain when including the externality of reducing global CO_2 emissions (Table 2, scope 2), an immediate issue with this is that the benefits are rarely seen by the investor (Claus and Rousseau, 2012). This highlights the influence of internalising these externalities (Endres, 2010). Furthermore, should the costs of an imposed tax on carbon emissions (Poelhekke, 2019) be included in this analysis, its effects on the net worth of investment would likely lead to a similar increase in the net value of both features. Focusing on financial costs alone, as Carter and Fowler (2008) previously highlighted, not all implementing authorities will have the financial capacity to offer significant subsidy incentives. In the case of Bristol, despite green roof subsidies holding a far lower abatement potential by 2050 (Table 1), they constitute a far more affordable option for the local authority in terms of upfront costs (at one-eighth that of subsidising solar PV systems). However, as the upfront costs of solar PV systems are gradually decreasing over time (BEIS, 2020b), the financial cost-benefit estimates for solar PV systems will likely constitute a lower bound. When private costs and benefits are included in analysis (scope 3), a more negative outcome ensues due to the significant installation and maintenance costs which far outweigh any private energy cost savings. Considering the financial benefits from the energy-saving insulation effects of green roofs, Perini and Rosasco (2019) provided a similar estimate of average savings per m2 per annum, at £0.17 in comparison to the £0.11 calculated in this study. Differences in building use, heating energy source and climate are likely be the inherent causes of difference between these two study outcomes, with Perini and Rosasco basing their estimates on a typical office building in Genoa (Italy), while in this study averaged both commercial and domestic building energy use in Bristol.

The net negative cost-benefit outcomes of green roofs in this study (table 2, Scopes 1 and 3) agree with those of Carter and Keeler (2008) and Shin and Kim (2009), but contrast similar past studies by Herman (2003), and Porsche and Köhler (2013), who claimed a net positive annual return on investments between £0.48 to £1.61 per m2 per annum. This disparity is likely due to differences in a variety of factors including: assumed upfront costs, included costs and benefits, study climate, and roof life span. As stated by Blackhurst, Hendrickson and Matthews (2010), the effectiveness of green roofing for abating emissions may be limited to certain regions, where their potential to conserve urban temperatures and sequester emissions is greatest. Additionally, although many of these past studies assume a green roof life length of 50 years, this study is focused on evaluating pathways to national 2050 net zero targets, giving a shorter, 30-year analysis period. This shorter analysis period reduces the annual spread of upfront costs, increasing their liklihood of outweighing the annual financial benefits. This parrallels the findings of Claus and Rousseau (2012), who observed a net negative return of both private and public green roof investments when assuming a 25 year life span, but net positive returns when assuming a longer lifespan of 50 years. Shin and Kim (2015) and Carter and Keeler (2008) also noted a negative annual green roof cost-benefit ratio after assuming a life span shorter than 50 years, assuming 20 years and 40 years respectively. Although not within the scope of this study, this highlights the importance of considering feature life span when assessing the longer-term competetiveness of low carbon measures beyond national 2050 emissions targets.

For solar PV systems, the net negative cost-benefit outcome also contrasts previous studies claiming signnificant positive returns on investments (Black, 2004; Sedghisigarchi, 2009; Lacchini, Antoniolli and Rüther, 2017). Unlike green roofing, this disparity between studies cannot be due to differences in assumed life span, as solar PV systems are widely accepted to need replacing after around 30 years of use (Hughes and Podolefsky, 2015). These past studies claiming signnificant positive returns on solar investments predominantly focus on private investment returns from solar energy generation, whereas this study focuses on net state investments, only including private factors for a theoretical, total combined analysis (Table 2, scope 3). Even with the inclusion of private investment returns, the net negative outcomes observed in this study in comparison to previous studies likely relate to differences in assumed upront solar PV system costs and differences in geographical location, inclufencing solar potential and resultant net savings in Bristol. This is supported by the conclusions of the Californian study by Sedghisigarchi (2009), and Brazilian study by Lacchini, Antoniolli and Rüther (2017), who observed higher average values of solar insolation (radiation), and therefore greater resultant renewable energy production, in comparison to the average values obtained in this study using the Bristol City Council Solar Suitability open dataset (BCC, 2019). This reiterates the importance of weighing low carbon options in their intended climate when considering potential policy transfer.

5.3. Cost per abated tonne of CO_2-e

When considering only state-level finances (scope 1), although subsidising green roofs require one tenth of the financial capacity of subsidising solar PV systems (Table 2), their ability to abate only one-sixtieth of the CO_2 emissions of solar PV systems (table 1) heavily influences their cost-effectiveness and subsequent attractiveness for implementation (Table 3). The superior cost per abated tCO_2-e of subsidising solar PV systems makes them 5.6 times more effective for reaching net zero emissions targets, stemming from the fact that their greater CO_2 abatement potential significantly outweighs their higher upfront costs, at a ratio far more attractive than for green roofing. In contrast, subsidising green roofs offers a far less effective, but more financially affordable option due to its cheaper installation costs and wider scope of social and environmental benefits.

This study's estimated cost of abating emissions by subsidising solar PV systems (£82.63 per tCO_2-e) corresponds well with estimates from previous Australian and U.S. studies which range between £56 and £160 per tCO_2-e (Macintosh and Wilkinson, 2011; Burtt and Dargusch, 2015; Hughes and Podolefsky, 2015). These studies were based on solar insolation data from different regions, and so minor disparities between cost-efficiency values are expected. In contrast the findings of this study significantly oppose those of Gouldson & Millward-Hopkins (2015), who claimed domestic solar PV installations in Bristol would cost over five times more per abated tCO_2-e than this study suggests. This may relate to Gouldson & Millward-Hopkins' inclusion of future national grid decarbonisation in their calculations (diminishing the future impact of residential solar), and the fact that solar PV system installation costs have significantly decreased over the last five years since their study (BEIS, 2020b). In addition, Gouldson & Millward-Hopkins were unable to use the Bristol City Council Solar Suitability open dataset, which was produced four years after their study (BCC), and may have further influenced their estimations of the potential for solar PV systems to abate emissions in Bristol. The low cost-effectiveness of green roofs observed in this study contrasts the findings of Blackhurst, Hendrickson and Matthews (2010), who also assessed green roofs over a 30-year period and claimed a far higher level of cost-effectiveness. This appears to be predominantly due to their inclusion of green roof city cooling effects (via evapotranspiration), which they claimed to collectively abate over 12 times the emissions abated via direct building insulation effects. Although less relevant to the temperate climate of the UK, Blackhurst highlighted the impact of green roofing on urban temperatures as a significant element for consideration in warmer city climates.

While the subsidisation of solar PV systems clearly offers a much more economical cost per abated tonne of CO_2, there are several green roofing benefits beyond emissions abatement that solar PV systems cannot deliver, such as air quality and rainwater run-off effects (Li and Yeung, 2014). In addition, there are numerous green roof benefits that were not included in this analysis due to unmonetizable impacts or data insufficiencies, such as improved mental wellbeing and biodiversity (Elmqvist *et al.*, 2015; Abolhabib, Sharifi and Dehaghani, 2020). Together, this suggests that the overall competitiveness of subsidising green roofing can be easily underestimated, and highlights the importance of carefully considering which private, state, or global impacts to include when evaluating the cost-effectiveness of low carbon measures. This is exemplified when considering the social benefit of reducing global CO_2 emissions in this study, which greatly improves the potential cost-effectiveness of both green roofing and solar PV system subsidy schemes, revealing net global savings for green roofing (Table 3, scope 2).

Reflecting on national net zero targets for 2050, solar PV systems offer a much more valuable instrument to help Bristol reach these targets (or its own more ambitious targets) in time, due to their higher annual rate of emissions abatement. Green roofs offer a more affordable, but less efficient option to abate emissions, with several other additional benefits to society and the environment that solar PV systems do not offer. Considering that solar PV systems can be retrofitted onto roofs with a greater slope than green roofing (Silva, Flores-Colen and Antunes, 2017), and the majority of roofs in Bristol are sloped, the applicability of solar PV system retrofitting across the city will exceed the area of roofing considered in this study (suitable for either alternative). In relation to this, when considering the limited number of flat roofs available in the city, and the unique benefits provided by green roofing, this may increase the weighting that should be given to green roofing in these circumstances.

More recent research has explored the effectiveness of deploying green roofs and solar PV systems on the same rooftop area, known as “biosolar”, with claims that solar PV systems enhance green roof performance by providing necessary shade, and green roofs cool solar PV systems to prevent overheating (Schindler *et al.*, 2016; Movahhed *et al.*, 2019). The combined effectiveness of these “biosolar” roofs therefore constitutes an interesting compromise between the two but would face similar issues in relation to financial capacity requirements and the complexity of offering subsidies for such instalments.

6. Conclusion

It is concluded that subsidising solar PV system retrofitting offers the most cost-effective way to abate emissions in the city of Bristol, with the potential to abate 60 times the carbon emissions that green roofs can by 2050. Despite the inferiority of green roofing for abating emissions, it constitutes a considerably more affordable low carbon instrument, especially when global-scale benefits are considered. In addition, many of the additional benefits offered by green roofs cannot easily be monetised, suggesting that the competitiveness of this low carbon measure is often underrepresented. For Bristol City Council, the implications of these findings suggest that solar PV systems constitute the most conducive use of available city roof space and state funding to aid the city in achieving net zero targets. Subsidising green roofs will contribute far less to net zero targets, but if state financial capacity is insufficient to subsidise solar PV systems, green roofing offers a more affordable option with a wider range of alternative social and environmental benefits, including wellbeing and biodiversity improvements. Considering the dominance of sloped roofs in Bristol, subsidising green roofing should not be overlooked as an option for scarcer flat roofs throughout the city, while predominantly aiming to subsidise solar PV system retrofitting in line with net zero targets. Although this study is concerned with the most effective use of available roof space, when considering state funding, it should be noted that the cost-effectiveness of green roofs and solar PV systems should be measured alongside other low carbon measures, such as home insulation and efficient domestic appliances (Gouldson and Millward-Hopkins, 2015; Gillingham and Stock, 2018), which may offer a higher level of cost-effectiveness for abating emissions.

The inherent limitations of this study should also be noted by readers. Firstly, due to the large number of factors influencing each estimate within this study, each with their own level of error, a considerable margin of inherent error will be present within the final study estimates of total abatement potential, cost-benefit ratio, and cost-effectiveness. Secondly, as a number of green roof benefits were not monetised in this study (such as wellbeing, biodiversity, and city cooling effects), and a number of time-related factors were not incorporated (such as decreasing solar technology costs), the calculations that follow will likely represent a lower bound of estimates. Thirdly, it should be noted that the findings of this study will have low transferability to other cities due to the influence of regional climate on solar suitability and building energy use factors, as well as differences in city size and available roof space.

Although time constraints did not allow for the consideration of sociodemographic factors within this study, their effect on the relative uptake of green roofing or solar PV subsidy schemes in Bristol would form a useful area of future research. This could be investigated via qualitative interviews followed by a thematic analysis. Further research for Bristol City Council considering the outcome of this study alongside other low carbon measures and the financial capability of the local authority over the next 30 years would provide a useful perspective on the best realistic course of action in relation to net zero targets. The combined competitiveness of aforementioned “biosolar” roofs and the difficulties surrounding their subsidisation and implementation also constitutes an interesting area of future research. In summation, it is hoped that the information provided in this study will aid Bristol city on its journey to becoming one of the first net zero cities worldwide.

References

- Abolhabib, M., Sharifi, F. and Dehaghani, A. R. (2020) ‘A hesitant fuzzy DANP for identifying and prioritizing effects and challenges of green roof on mental health in developing countries’, *Journal of Advanced Pharmacy Education & Research*, 10(1), pp. 125-136.
- Ansari, M. F., Kharb, R. K., Luthra, S., Shimmi, S. L. and Chatterji, S. (2013) ‘Analysis of barriers to implement solar power installations in India using interpretive structural modeling technique’, *Renewable and sustainable energy reviews*, 27, pp. 163-174.
- Arcadis. (2008). ‘*Groene daken Rotterdam – Maatschappelijke kosten-batenanalyse (Green roofs Rotterdam – social cost benefit analysis). Final report*’. Rotterdam: Arcadis (in Dutch).
- Banting, D., Doshi, H., Li, J., Missios, P., Au, A., Currie, B. A. and Verrati, M. (2005) ‘*Report on the environmental benefits and costs of green roof technology for the city of Toronto*’. Toronto: N.p.
- BCC. (2019) ‘*Solar potential. Bristol: Bristol City Council*’ (online dataset). Bristol: Bristol City Council. Available at: https://opendata.bristol.gov.uk/explore/dataset/solar-potential/information/ (accessed: 10/07/20).
- BEIS. (2020a) *‘UK government GHG conversion factors for company reporting*’ (online dataset). London: Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020 (accessed: 10/07/20).
- BEIS. (2020b) *‘Solar photovoltaic (PV) cost data’* (online dataset). London: Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/statistics/solar-pv-cost- data (accessed: 10/07/20).
- BEIS. (2020c) *‘Quarterly energy prices: June 2020*’ (online dataset). London: Department for Business, Energy & Industrial Strategy. Available at: https://www.gov.uk/government/statistics/quarterly- energy-prices-june-2020 (accessed: 10/07/20).
- Besir, A. B. and Cuce, E. (2018) ‘Green roofs and facades: a comprehensive review’, *Renewable and Sustainable Energy Reviews*, 82, pp. 915-939.
- Black, A. J. (2004) ‘Financial payback on California residential solar electric systems’, *Solar Energy*, 77(4), pp. 381-388.
- Blackhurst, M., Hendrickson, C. and Matthews, H. S. (2010) ‘Cost-effectiveness of green roofs’, *Journal of Architectural Engineering*, 16(4), pp. 136-143.

- Burszta-Adamiak, E. and Fiałkiewicz, W. (2019) ‘A review of green roof incentives as motivators for the expansion of green infrastructure in European cities’, *Scientific Review – Engineering and Environmental Sciences*, 28(4), pp. 641–652.

- Burtt, D. and Dargusch, P. (2015) ‘The cost-effectiveness of household photovoltaic systems in reducing greenhouse gas emissions in Australia: linking subsidies with emission reductions’, *Applied Energy*, 148, pp. 439-448.

- Carpenter, D. and Kaluvakolanu, P. (2011) ‘Effect of roof surface type on storm-water runoff from full-scale roofs in a temperate climate’, *Journal of Irrigation and Drainage Engineering*, 137(3), pp. 161- 169.

- Carter, T. and Fowler, L. (2008) ‘Establishing green roof infrastructure through environmental policy instruments’, *Environmental management*, 42(1), pp. 151-164.

- Carter, T. and Keeler, A. (2008) ‘Life-cycle cost–benefit analysis of extensive vegetated roof systems’, *Journal of environmental management*, 87(3), pp. 350-363.

- Castleton, H. F., Stovin, V., Beck, S. B. M. and Davison, J. B. (2010) ‘Green roofs; building energy savings and the potential for retrofit’, *Energy and buildings*, 42(10), pp. 1582-1591.

- Cavanaugh, L. M. (2008) ‘Redefining the green roof’, *Journal of architectural engineering*, 14(1), pp. 4- 6.

- Chapman, A. J., McLellan, B. and Tezuka, T. (2016) ‘Residential solar PV policy: an analysis of impacts, successes and failures in the Australian case’, *Renewable Energy*, 86, pp. 1265-1279.

- Chen, T.-M., Kuschner, W. G., Gokhale, J. and Shofer, S. (2007) ‘Outdoor air pollution: nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects’, *The American Journal of the Medical Sciences*, 333(4), pp. 249-256.

- Clark, C., Adriaens, P. and Talbot, F. B. (2008) ‘Green roof valuation: a probabilistic economic analysis of environmental benefits’, *Environmental science & technology*, 42(6), pp. 2155-2161.

- Claus, K. and Rousseau, S. (2012) ‘Public versus private incentives to invest in green roofs: a cost benefit analysis for Flanders’, *Urban forestry & urban greening*, 11(4), pp. 417-425.

- Colenbrander, S., Lazer, L., Haddaoui, C. and Godfrey, N. (2019) *Climate emergency, urban opportunity: how national governments can secure economic prosperity and avert climate catastrophe by transforming cities*. London, UK: World Resources Institute (WRI) Ross Centre for Sustainable Cities and C40 Cities Climate Leadership Group.

- Constantine, L. (2019) ‘*Green roofs: an investigation into the potential for green roof retrofit in Bristol, UK*’. (MSc dissertation) Bristol: University of Bristol.Cubi, E., Zibin, N. F., Thompson, S. J. and Bergerson, J. (2016) ‘Sustainability of rooftop technologies in cold climates: comparative life cycle assessment of white roofs, green roofs, and photovoltaic panels’, *Journal of Industrial Ecology*, 20(2), pp. 249-262.

- Elmqvist, T., Setälä, H., Handel, S. N., van der Ploeg, S., Aronson, J., Blignaut, J. N., Gómez-Baggethun, E., Nowak, D. J., Kronenberg, J. and de Groot, R. (2015) 'Benefits of restoring ecosystem services in urban areas', *Current Opinion in Environmental Sustainability*, 14, pp. 101-108.
- Endres, A. (2010) 'The internalization of externalities as a central theme of environmental policy', in *Environmental Economics: Theory and Policy*. 4 edn. Cambridge: Cambridge University Press, pp. 1- 31.
- Fioretti, R., Palla, A., Lanza, L. G. and Principi, P. (2010) 'Green roof energy and water related performance in the Mediterranean climate', *Building and environment*, 45(8), pp. 1890-1904.
- Gerbinet, S., Belboom, S. and Léonard, A. (2014) 'Life cycle analysis (LCA) of photovoltaic panels: a review', *Renewable and Sustainable Energy Reviews*, 38, pp. 747-753.
- Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M. and Andresen, J. A. (2009) 'Carbon sequestration potential of extensive green roofs', *Environmental science & technology*, 43(19), pp. 7564-7570.
- Gillingham, K. and Stock, J. H. (2018) 'The cost of reducing greenhouse gas emissions', *Journal of Economic Perspectives*, 32(4), pp. 53-72.
- Gouldson, A. and Millward-Hopkins, J. (2015) *The economics of low carbon cities: a mini-stern review for the city of Bristol*. Bristol: University of Bristol, C. I., Bristol.
- Grant, C. A. and Hicks, A. L. (2020) 'Effect of manufacturing and installation location on environmental impact payback time of solar power', *Clean Technologies and Environmental Policy*, 22(1), pp. 187- 196.
- Grunwald, L., Heusinger, J. and Weber, S. (2017) 'A GIS-based mapping methodology of urban green roof ecosystem services applied to a Central European city', *Urban Forestry & Urban Greening*, 22, pp. 54-63.
- Hagerman, S., Jaramillo, P. and Morgan, M. G. (2016) 'Is rooftop solar PV at socket parity without subsidies?', *Energy Policy*, 89, pp. 84-94.
- Hashemi, S. S. G., Mahmud, H. B. and Ashraf, M. A. (2015) 'Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: a review', *Renewable and Sustainable Energy Reviews*, 52, pp. 669-679.
- Herman, R. (2003) 'Green roofs in Germany: yesterday, today and tomorrow', *The first North American green roof infrastructure conference, awards and trade show: greening rooftops for sustainable communities*. Chicago, IL, United States, 29-30 May 2003.
- HMG. (2019) '*The Climate Change Act 2008 (2050 target amendment) order 2019*'. London: HMG. Available at: https://www.legislation.gov.uk/ukdsi/2019/9780111187654 (accessed 10/09/20).

- HMRC. (2019) '*Guidance - average for the year to 31 December 2019'* (online dataset). London: HM Revenue & Customs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877346/Average-for-the-year-to-December-2019.csv/preview (accessed: 10/07/20).
- Hsu, C.-W. (2012) 'Using a system dynamics model to assess the effects of capital subsidies and feed- in tariffs on solar PV installations', *Applied energy*, 100, pp. 205-217.
- Hughes, J. E. and Podolefsky, M. (2015) 'Getting green with solar subsidies: evidence from the California solar initiative', *Journal of the Association of Environmental and Resource Economists*, 2(2), pp. 235-275.
- IPCC. (2018). *Summary for policymakers. In:Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors,
- J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge: Cambridge University Press.
- Jo, J. H., Golden, J. S. and Shin, S. W. (2009) 'Incorporating built environment factors into climate change mitigation strategies for Seoul, South Korea: a sustainable urban systems framework', *Habitat International*, 33(3), pp. 267-275.
- Karteris, M., Theodoridou, I., Mallinis, G., Tsiros, E. and Karteris, A. (2016) 'Towards a green sustainable strategy for Mediterranean cities: assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data', *Renewable and Sustainable Energy Reviews*, 58, pp. 510-525.
- Kato, K., Murata, A. and Sakuta, K. (1998) 'Energy pay-back time and life-cycle CO_2 emission of residential PV power system with silicon PV module', *Progress in Photovoltaics: Research and Applications*, 6(2), pp. 105-115.
- Kaya, O., Klepacka, A. M. and Florkowski, W. J. (2019) 'Achieving renewable energy, climate, and air quality policy goals: rural residential investment in solar panel', *Journal of environmental management*, 248, pp. 109309-109318.
- Lacchini, C., Antoniolli, A. F. and Rüther, R. (2017) 'The influence of different irradiation databases on the assessment of the return of capital invested in residential PV systems installed in different locations of the Brazilian territory', *Solar Energy*, 155, pp. 893-901.
- Laleman, R., Albrecht, J. and Dewulf, J. (2011) 'Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation', *Renewable and Sustainable Energy Reviews*, 15(1), pp. 267-281.

- Langemeyer, J., Wedgwood, D., McPhearson, T., Baró, F., Madsen, A. L. and Barton, D. N. (2020) 'Creating urban green infrastructure where it is needed: a spatial ecosystem service-based decision analysis of green roofs in Barcelona', *Science of the Total Environment*, 707, pp. 1-15.

- Lee, K. E., Williams, K. J. H., Sargent, L. D., Williams, N. S. G. and Johnson, K. A. (2015) '40-second green roof views sustain attention: the role of micro-breaks in attention restoration', *Journal of Environmental Psychology*, 42, pp. 182-189.

- Li, W. C. and Yeung, K. K. A. (2014) 'A comprehensive study of green roof performance from environmental perspective', *International Journal of Sustainable Built Environment*, 3(1), pp. 127-134. Macintosh, A. and Wilkinson, D. (2011) 'Searching for public benefits in solar subsidies: a case study on the Australian government's residential photovoltaic rebate program', *Energy Policy*, 39(6), pp. 3199-3209.

- Mahdiyar, A., Mohandes, S. R., Durdyev, S., Tabatabaee, S. and Ismail, S. (2020) 'Barriers to green roof installation: an integrated fuzzy-based MCDM approach', *Journal of Cleaner Production*, 269, p. 122365.

- Mahdiyar, A., Tabatabaee, S., Sadeghifam, A. N., Mohandes, S. R., Abdullah, A. and Meynagh, M. M. (2016) 'Probabilistic private cost-benefit analysis for green roof installation: a Monte Carlo simulation approach', *Urban Forestry & Urban Greening*, 20, pp. 317-327.

- Mallinis, G., Karteris, M., Theodoridou, I., Tsioukas, V. and Karteris, M. (2014) 'Development of a nationwide approach for large scale estimation of green roof retrofitting areas and roof-top solar energy potential using VHR natural colour orthoimagery and DSM data over Thessaloniki, Greece', *Remote sensing letters*, 5(6), pp. 548-557.

- Margolis, R. and Zuboy, J. (2006) *Nontechnical barriers to solar energy use: review of recent literature*. Golden, CO, United States: National Renewable Energy Laboratory.

- MHCLG. (2019) '*Energy performance of buildings certificates statistical release: Q1 2019: England and Wales'*. London: Ministry of Housing, Communities & Local Government.

- Millward-Hopkins, J., Gouldson, A., Scott, K., Barrett, J. and Sudmant, A. (2018) 'Uncovering blind spots in urban carbon management: the role of consumption-based carbon accounting in Bristol, UK', *Regional Environmental Change*, 17(5), pp. 1467-1478.

- Movahhed, Y., Safari, A., Motamedi, S. and Khoshkhoo, R. H. (2019) 'Simultaneous use of PV system and green roof: a techno-economic study on power generation and energy consumption', *Energy Procedia*, 159, pp. 478-483.

- Mullen, J. D., Lamsal, M. and Colson, G. (2013) 'Green roof adoption in Atlanta, Georgia: the effects of building characteristics and subsidies on net private, public, and social benefits', *Environmental science & technology*, 47(19), pp. 10824-10831.

- Mundaca, L. and Samahita, M. (2020) ‘What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden’, *Energy Research & Social Science*, 60, pp. 101319-101323.
- Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A. and Mihalakakou, G. (2001) ‘Analysis of the green roof thermal properties and investigation of its energy performance’, *Energy and buildings*, 33(7), pp. 719-729.
- Nilfanion, P. (2010) ‘*Bristol UK location map*’. Available at: https://en.wikipedia.org/wiki/File:Bristol_UK_location_map.svg (accessed: 10/09/2020).
- Palm, J. (2018) ‘Household installation of solar panels: motives and barriers in a 10-year perspective’, *Energy Policy*, 113, pp. 1-8.
- Partridge, D. R. and Clark, J. A. (2018) ‘Urban green roofs provide habitat for migrating and breeding birds and their arthropod prey’, *PLoS One*, 13(8), pp. 1-23.
- Pearce, H. and Walters, C. L. (2012) ‘Do green roofs provide habitat for bats in urban areas?’, *Acta chiropterologica*, 14(2), pp. 469-478.
- Peck, S. W. (2002) ‘Green roofs: infrastructure for the 21st century’, *Clean Air Partnership and presented at the 1st Annual Urban Heat Island Summit, May*. Toronto. pp. 2-3.
- Poelhekke, S. (2019) ‘How expensive should CO_2 be? Fuel for the political debate on optimal climate policy’, *Heliyon*, 5(11), pp. 1-5.
- Porsche U, Köhler M. (2013) ‘Life cycle costs of green roofs: a comparison of Germany, USA, and Brazil’.
- *Proceedings of the World Climate and Energy Event, Rio de Janeiro,* Brazil, 1–5 December 2003.
- Pye, S., Li, F. G. N., Price, J. and Fais, B. (2017) ‘Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era’, *Nature Energy*, 2(3), pp. 1-7.
- Pyrgou, A., Kylili, A. and Fokaides, P. A. (2016) ‘The future of the Feed-in Tariff (FiT) scheme in Europe: the case of photovoltaics’, *Energy Policy*, 95, pp. 94-102.
- Regen. (2019). ‘*City of Bristol carbon neutrality*’. Bristol: Regen.
- Rosasco, P. and Perini, K. (2019) ‘Selection of (green) roof systems: a sustainability-based multi-criteria analysis’, *Buildings*, 9(5), pp. 134-151.
- Saiz, S., Kennedy, C., Bass, B. and Pressnail, K. (2006) ‘Comparative life cycle assessment of standard and green roofs’, *Environmental science & technology*, 40, pp. 4312-6.

- Santos, T., Tenedório, J. A. and Gonçalves, J. A. (2016) 'Quantifying the city's green area potential gain using remote sensing data', *Sustainability*, 8(12), pp. 1247-1263.
- Schindler, B., Blank, L., Levy, S., Kadas, G., Pearlmutter, D. and Blaustein, L. (2016) 'Integration of photovoltaic panels and green roofs: review and predictions of effects on electricity production and plant communities', *Israel Journal of Ecology and Evolution*, 62, pp. 68-73.
- Sedghisigarchi, K. (2009) Residential solar systems: Technology, net-metering, and financial payback', *2009 IEEE Electrical Power & Energy Conference*. Montreal, Canada, 22-23 Oct. 2009.
- Shafique, M., Azam, A., Rafiq, M., Ateeq, M. and Luo, X. (2020) 'An overview of life cycle assessment of green roofs', *Journal of Cleaner Production*, 250, pp. 119471-119484.
- Shafique, M., Kim, R. and Kyung-Ho, K. (2018) 'Green roof for stormwater management in a highly urbanized area: the case of Seoul, Korea', *Sustainability*, 10(3), pp. 584-599.
- Shin, E. and Kim, H. (2015) 'Analysing green roof effects in an urban environment: a case of Bangbae-dong, Seoul', *Journal of Asian Architecture and Building Engineering*, 14(2), pp. 315-322.
- Silva, C. M., Flores-Colen, I. and Antunes, M. (2017) 'Step-by-step approach to ranking green roof retrofit potential in urban areas: a case study of Lisbon, Portugal', *Urban Forestry & Urban Greening*, 25, pp. 120-129.
- Sproul, J., Wan, M. P., Mandel, B. H. and Rosenfeld, A. H. (2014) 'Economic comparison of white, green, and black flat roofs in the United States', *Energy and Buildings*, 71, pp. 20-27.
- Sun, J., Barnes, A. J., He, D., Wang, M. and Wang, J. (2017) 'Systematic review and meta-analysis of the association between ambient nitrogen dioxide and respiratory disease in China', *International Journal of Environmental Research and Public Health*, 14(6), pp. 646-662.
- Tomalty, R., Komorowski, B. and Doiron, D. (2010) *The monetary value of the soft benefits of green roofs - final report*. Montreal, QC, Canada: Smart Cities Research Services.
- Whittinghill, L. J., Rowe, D. B., Schutzki, R. and Cregg, B. M. (2014) 'Quantifying carbon sequestration of various green roof and ornamental landscape systems', *Landscape and Urban Planning*, 123, pp. 41-48.
- Wilkinson, S. J. and Reed, R. (2009) 'Green roof retrofit potential in the central business district', *Property Management*, 27(5), pp. 284–301.
- Wong, J. K. W. and Lau, L. S.-K. (2013) 'From the 'urban heat island' to the 'green island'? A preliminary investigation into the potential of retrofitting green roofs in Mongkok district of Hong Kong', *Habitat International*, 39, pp. 25-35.

Appendix

University of BRISTOL
SCHOOL OF GEOGRAPHICAL SCIENCES

PG Research Ethics Monitoring Form 2019-2020

Research by all academic and related Staff and Students in the School of Geographical Sciences is subject to the standards set out in the Code of Practice on Research Ethics.

It is a requirement that prior to the commencement of all funded and non-funded research that this form be completed and submitted to your dissertation advisor and the School's Research Ethics Committee (REC) (see Ethics Flow Chart). The Advisor and REC will be responsible for issuing certification that the research meets acceptable ethical standards and will, if necessary, require changes to the research methodology or reporting strategy.

A copy of the research proposal which details methods and reporting strategies must be attached. Submissions without a copy of the research proposal will not be considered.

The Ethics process seeks to establish from the form that researchers have (i) thought purposefully about potential ethical issues raised by their proposed research; and (ii) identified appropriate responses to those issues.

Use the Tab key to move between responses and remember to save regularly.

Name: *James Hepworth* Email address: *jh15274@bristol.ac.uk*

Title of research project: Solar Panels or Green Roofs? Evaluating the Effectiveness of Financially Subsidising Rooftop Measures to Abate Carbon Emissions by 2050 in Bristol, UK.

Source of funding if any? *None*

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1. Does your research involve human participants under the age of 18?

No

If YES, please provide further details

Click or tap here to enter text.

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2. Does your research involve human participants in vulnerable circumstances?

No

If YES, please provide further details

Click or tap here to enter text.

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3. Does your research involve ONLY the analysis of large, secondary and anonymised datasets?

No

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4. Do others hold copyright or other rights over the information you will use, or will they do so over information you collect?

Yes

If relevant, please provide further details of copyright etc. information

Ordnance Survey open dataset displaying the solar potential of Bristol rooftops: License information: Copyright : © Crown Copyright and database rights [2020] Ordnance Survey 100023406.
Licence requirements: No formal arrangement needed ("By using or accessing this data the INSPIRE End User is deemed to have accepted the Public Sector End User Licence - INSPIRE https://www.ordnancesurvey.co.uk/business-government/licensing-agreements/end-user-licence").

---

5. If asked, will you give your informants a
   a. written summary of your research aims and its uses?

   Yes

   b. verbal summary of your research aims and its uses?

   Yes

If NO to either 5a or 5b please provide further details
Click or tap here to enter text.

---

6. Does your research involve covert surveillance (for example, participant observation)?

No

If YES, please provide further details

Click or tap here to enter text.

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7. Does your research involve analysis of social media posts or images?

No

If YES, please provide further details

Click or tap here to enter text.

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8. Anonymising informants:
   a. Will your informants automatically be anonymised in your research?

   No

If NO, please provide further details

Although it is important to ensure that interviewees have the right to remain anonymous if they should wish, it would prove useful in my analysis to show the ward that Bristol residents live in, or the kinds of organisations interviewees work for. These details can be included without actually naming participants if they would prefer not to be named individually.

b. Will you explicitly give all your informants the right to remain anonymous?

Yes

If NO, please provide further details

Click or tap here to enter text.

c. Will data/information be encrypted/secured, and stored separately from identification material to maintain confidentiality?

Yes

If NO, please provide further details

Click or tap here to enter text.

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9. Will monitoring devices be used openly and only with the permission of informants?

Yes

If NO, please provide further details

Click or tap here to enter text.

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10. Will your informants be provided with a summary of your research findings?

Yes

If NO, please provide further details

Click or tap here to enter text.

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11. Will your research be available to informants and the general public without restrictions placed by sponsoring authorities?

Yes

If NO, please provide further details

Click or tap here to enter text.

---

12. Have you considered the implications of your research intervention on informants?

Yes

Please provide full details

Although anonymous, information provided by informants will influence research findings. These may possibly influence the Bristol City Council’s decisions on local policies for green roof uptake, should they take interest in this work in the future. Changes in local policy regarding or incentivising green roofs may thereby have resultant implications on informants, who may themselves have conflicting interests in this topic.

When providing information on an informant’s residential ward or sector of work (e.g. council, green infrastructure), I must be sure maintain their anonymity, and not include specific department/ infrastructure company details so that an individual's views cannot be linked back to them through my project. I must also be clear in my work that their views are personal perspectives, and not the views of their respective institutions.

My research may additionally influence informants by raising their concerns over climate change, greenhouse gasses, and the importance of environmental policy regarding green roofs and their benefits.

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13. Are there any other ethical issues arising from this research ?

No

If YES, please explain and include how they will be taken into consideration

Click or tap here to enter text.

Declaration

I have read the School's Code of Practice on Research Ethics and believe that my research complies fully with its precepts.

I will not deviate from the methodology or reporting strategy without further permission from my advisor and/or the School's Research Ethics Committee.

Student

Signed James Hepworth Date Click or tap to enter a date.

Advisor

Signed Date Click or tap to enter a date.

Progress tracker: (dates to be completed by advisor/ethics committee)

A	**Form submission to advisor**	28/05/2020	Choose date	Choose date	Choose date
B	**Clarification requested by advisor**	02/06/2020	Choose date	Choose date	Choose date
C	**Advisor stage passed**	22/06/2020	Choose date	Choose date	Choose date
D	**Clarification requested by ethics committee**	Choose date	Choose date	Choose date	Choose date
E	**Decision recorded by ethics committee**	26/06/2020	Choose date	Choose date	Choose date
F	**Email sent to student by ethics committee**	26/06/2020	Choose date	Choose date	Choose date