MM06: Agrivoltaic Systems

Measure category

Cropland management: agronomy

Overview

Agrivoltaics is the practice of integrating solar photovoltaic (PV) cells with agricultural land (Dinesh & Pearce, 2016). Cells can be mounted in rows at ground level, though a more integrated approach is to mount the cells on stilts, allowing crops to be grown directly beneath. Stilts are made high enough (5—7m) that normal field operations can take place beneath, and cells are spaced such that shading does not preclude crop growth (Dinesh & Pearce, 2016; Valle et al., 2017; Amaducci et al., 2018). Solar-generated electricity has much lower embedded emissions than grid electricity in the United Kingdom (Gerbinet et al., 2014; DEFRA/DECC, 2018), so emissions from electricity are offset by the solar cells. Crop production below the cells decreases with lower light availability, though this can be mitigated to some extent via system design (Valle et al., 2017).

Mitigation summary

*Effect on GHG categories**	*Rating*	*Notes*
Enteric CH_4		
Manure CH_4		
Manure N_2O		
Soil N_2O: residue N		
Soil N_2O: applied N		
Soil N_2O: grazing		
Energy CO_2: fieldwork		
Energy CO_2: other		
CO_2 liming and urea		
CO_2 sequestration below ground		
CO_2 sequestration above ground		
Pre-farm emissions		
Post-farm emissions		
Substitution of higher C products	-	*Solar-generated electricity substitutes higher-emission grid electricity.*
Production increases by more than the emissions		
Confidence in mitigation effect	*High*	
*Cost-effectiveness***	*Low-Moderate*	*Highly dependent on location*
Confidence in cost-effectiveness	*Moderate*	

**   ”-“ GHG reduction, “+”: GHG increase, “ ”: no significant effect*

*** low: =< £0/tCO_2e, moderate: £0/tCO_2e< >SCC, high: >SCC*

Related measures and potential interaction

Measure	Impact on other measures
4. Agroforestry	Measure will likely preclude implementation of agroforestry systems, since both measures compete with crops for light.
3. Optimisation of pH	Improving pH on grassland will increase grass yields; this measure decreases yields on grassland.
26—38. All livestock measures	The measure as assessed here is implemented on livestock grazing land and results in loss of production on this land, changing stocking densities/requirements.

Inclusion in other marginal abatement cost curves

UK 2008	UK 2010	UK 2015	Ireland 2012	France 2013	France 2019
No	No	No	No	No	?

What does the measure entail?

Agrivoltaics is the practice of integrating electricity generating solar arrays into agricultural systems. These arrays are comprised of photovoltaic (PV) cells which covert solar radiation to electric current.

In typical agricultural land (arable or grazing land) PV cells may be either stilt-mounted or ground-mounted (Dinesh & Pearce, 2016). The former allows livestock, personnel and agricultural machinery to move freely beneath the arrays; this allows flexibility in spacing and density. The latter does not, and hence can be assumed to preclude agricultural production in the area of installation. Dinesh & Pearce (2016) assessed two types of stilt-mounted system at various spacings, and and one type of ground-level system arranged in rows between crops; the stilt-mounted systems take up negligible ground area, but cast shade over the cropping system, while the ground-level system displaces planted area, but casts no shade over crops. Outside of arable or grassland, solar PVs may be integrated into agricultural systems above greenhouses, or on the roofs of barns (Xue, 2017; SAC, 2018).

Abatement potential

Once solar PV cells are constructed and installed, the electricity generated can largely be considered carbon neutral (Gerbinet et al., 2014). Most life cycle analysis (LCA) studies scale the emissions cost of solar PV construction/installation over the lifetime of the solar cell, yielding results scaled per kWh or equivalent unit. This can be used to calculate the difference in emissions intensity between typical grid electricity and solar-generated electricity (Table #AV.1).

Table 1. LCA-derived GHG impacts for solar PV-generated electricity, and estimated abatement vs. UK grid electricity (sources from Gerbinet et al., 2014).

Source	GHG impact of generated electricity (g CO_2-eq kWh^{-1})	GHG abatement vs. UK grid electricity (g CO_2-eq kWh^{-1}) [1]
Pacca et al. (2007)	34—72	211—249
Stoppato (2008)	50—80	203—233
Perez et al. (2012)	10	273

Jungbluth et al. (2005)	100—136	143—183
Desideri et al. (2012)	9	274
Graebig et al. (2010)	63	220
Desideri et al. (2013)	45	238

[1] Abatement vs. UK grid calculated based on an emission factor of 283 g CO_2-eq kWh^{-1} (DEFRA/DECC, 2018).

Dinesh & Pearce (2016) assume row spacings of 6.4m for a 'half density' stilt-mounted system, and 3.2m for a 'full density' stilt-mounted system. The ground-level system is mounted at 6m spacings, and all panels have 1m width. In this configuration, these systems would provide between 1562—3125 m^2 ha^{-1} of PV surface area. Assuming 13% panel efficiency (Dinesh & Pearce, 2016), and solar irradiation of around 867 kWh m^2 $year^{-1}$ (based on a median value from Fig. 1), a half-density stilt-mounted system could be expected to produce around 176 MWh annually. Based on a mean of the abatement rates reported in Table 1, this could represent an abatement of 40.8 tonnes CO_2-eq ha^{-1}.

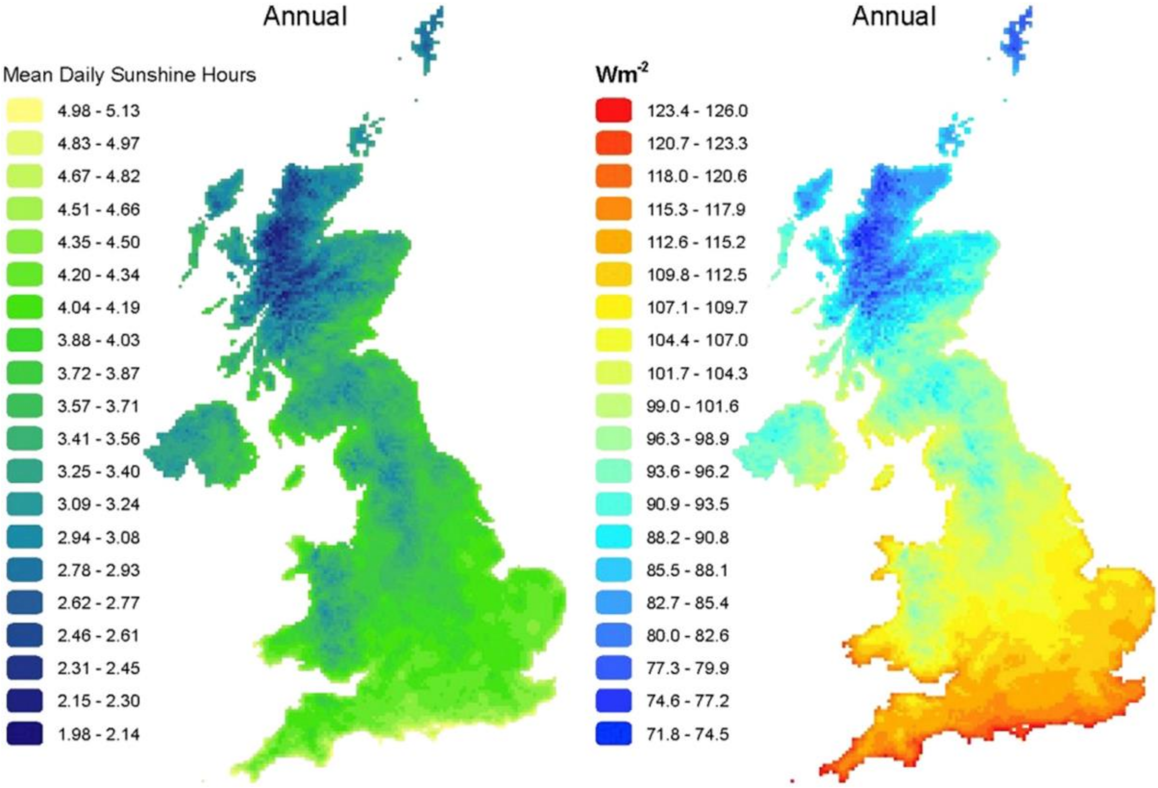

Fig.1. Mean daily sunshine hours and solar irradiance (in W m^2) for the United Kingdom (source: Burnett et al., 2014).

#AV.7. Implementation costs

The cost of solar cell implementation stems from the purchase, installation and maintenance cost of the solar panels and accompanying infrastructure. Solar cells are typically priced according to power rating (in kW), with an output rating of 1 kW representing a surface area of approximately 7—8 m^2. Cost per kW of solar PVs varies with economies of scale, with prices ranging from £1,153—1,840 kW^{-1} depending on system size (Department for Business Energy & Industrial Strategy, 2018b). Linking this cost to electrical generation, SAC (2018) estimate an installed cost of £45,000 for a 40 MWh $year^{-1}$ system (covering approximately 250 m^2). Most LCA and CBA studies assume negligible maintenance costs. It is challenging to determine costs for agrivoltaic-specific solar panels, given the relative novelty of such systems as a concept; however, Scognamiglio (2016) points out that ground-mounted panels are the current least-cost implementation for solar PVs, and hence agrivoltaic systems are unlikely to be more expensive to implement than more typical roof-mounted PVs.

Benefits of agrivoltaic systems stem from electricity generated. In the United Kingdom, solar-generated electricity fed back into the national grid is paid on the basis of a feed-in tariff (FIT) scheme, introduced in 2010 (SAC, 2018). Under the FIT, the owner of the PV array has priority use of generated electricity, and any excess is purchased by the national grid at the export tariff (ET) rate. The export rate is typically much lower than the cost of purchased electricity; this effectively means that the lower the electricity consumption of a given enterprise, the lower the return per kWh of solar-generated power. Regardless of the end user of the electricity, the owner of the solar PV arrays is also currently paid a generation tariff (GT) for each kWh of electricity generated. The current (2018) ET is 5.03 p kWh^{-1} and current GT is 4.25 p kWh^{-1} (SAC, 2018).

The market for electricity is highly regulated, and it is challenging to accurately represent the price value of solar-generated vs. grid electricity. This is further compounded by a) environmental and seasonal effects on electricity demand, and b) the difficulty in efficiently storing generated electricity. Solar PV output cannot be adjusted over small timescales to meet local demand, so the value of solar-generated electricity is highly variable, while 'on-demand' grid power is valued more highly. The feed-in tariff (FIT) in part is designed to address this challenge, with the ET representing the market value of the generated electricity, and the GT designed to internalise the value of emissions offset.

Assumptions used in MAC

The following assumptions were used in the calculation of the marginal abatement cost for agrivoltaics:

1. PV cells are installed in a stilt-mounted system at half-density, according to the spacings defined by (Dinesh & Pearce, 2016). This results in a PV surface area of 1,562.5 m^2 ha^{-1}.
2. Agrivoltaic systems will be implemented on grassland, as low-value land in comparison to arable systems. Grass production under the system will be 51% of sole yield (Dinesh & Pearce, 2016).
3. Installation costs per kW are between £1,131 and £1,175 (Department for Business Energy & Industrial Strategy, 2018b).
4. PV cell lifetime is between 20 and 30 years (Sherwani et al., 2010). Installation cost is annualised using a discount rate of 3.5%.
5. Solar generation is based on daily sunshine hours, with a UK-specific range from Burnett et al. (2014), and solar panel efficiency, with an agrivoltaic-specific range from Dinesh & Pearce (2016).
6. Solar-generated electricity is assigned an emission factor corresponding to the range of literature values reported by Gerbinet et al. (2014).
7. Grid electricity is be assigned an emission factor according to the most recent GHG Conversion Factors for Company Reporting (DEFRA/DECC, 2018)
8. Value of solar-generated electricity is assumed to be equal to the value of the solar ET (5.03 p kWh^{-1}) (SAC, 2018). This value is used to calculate the MAC. In addition, private benefits, including the GT subsidy (which internalises the mitigation benefit of solar electricity generation) are used to calculate a private benefit estimate which is separate from the MAC calculation.
9. Value of grid electricity is assumed to be 13.85 ± 0.49 p kWh^{-1}.

A Monte Carlo simulation (sample = 10^5, Mersenne seed = 2605) was conducted to assess the effect of the ranges and uncertainties defined above on the marginal abatement cost. Uncertainties are reported ± 1 std. dev. unless otherwise specified.

Costs for implementation of the system were approximately £257,000 ha^{-1}. This annualised to £15,753 ± 1,178 ha^{-1} $year^{-1}$, with the majority of the uncertainty stemming from variability in estimates of the system lifetime (20—30 years). Costs stemming from lost grass production were comparatively small at £275 ± 25 ha^{-1} $year^{-1}$. The system generated electricity at 266 ± 45 MWh ha^{-1} $year^{-1}$, valued at 13,365 ± 2,268 £ ha^{-1} $year^{-1}$.

The per-hectare abatement rate was calculated at 61 ± 11.96 tonnes CO_2-eq ha^{-1} $year^{-1}$. The cost of implementation was £2,664 ± 2,556 ha^{-1}. Marginal abatement cost was 52 ± 53 £ tonne CO_2-eq^{-1} (Fig.2).

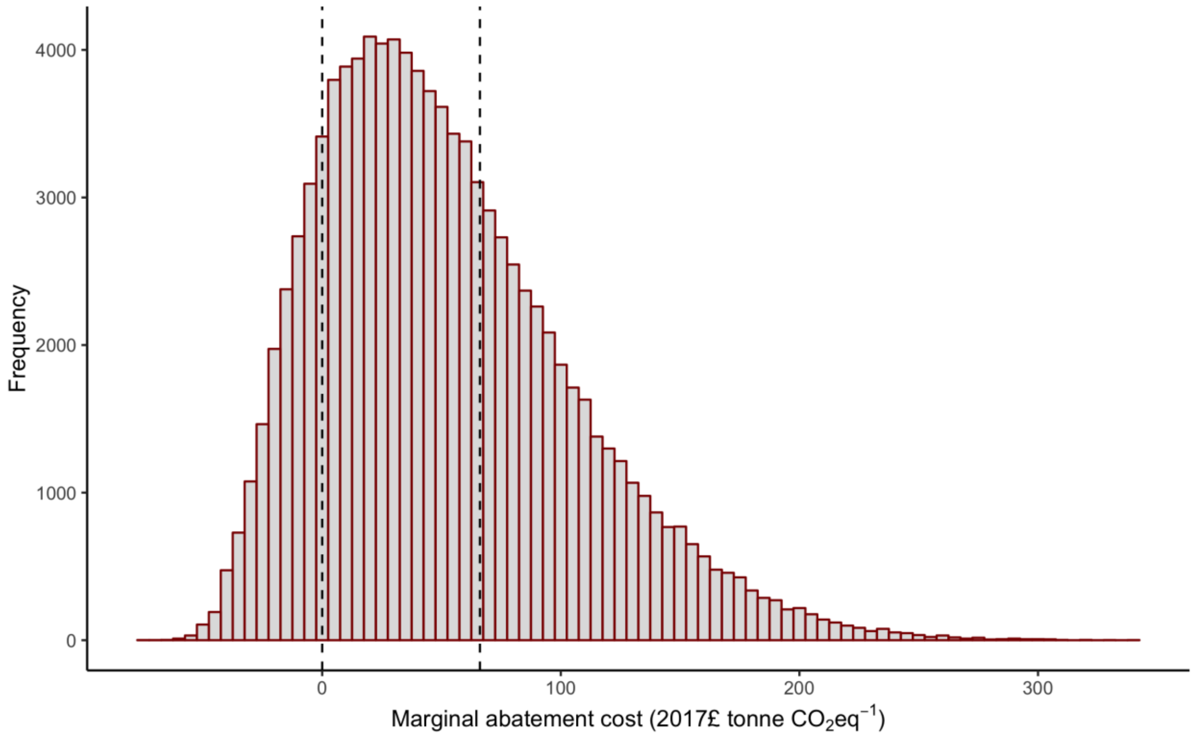

Fig.2. Marginal abatement cost for agrivoltaic systems in UK grassland. Costs are in 2017 pounds sterling. Vertical dashed lines indicate costs of £0 and £66.10 (the SCC; Department for Business Energy & Industrial Strategy, 2018a).

When privately realised annualised costs were compared (including offset of grid electricity use, and the generation tariff of 4.25 p kWh^{-1}), 14.3% of implementations resulted in a privately realised net benefit of less that £0 ha^{-1}; i.e. the annualised cost of the solar PV investment over the assumed lifetime of the cells (20—30 years) was greater than the benefits of the generated electricity. The remainder of simulations (85.7%) saw net private profit; the average privately realised annual revenue was 152% of annualised costs. These values are highly dependent on both the market cost of electricity and the current tariffs (export and generation).

Approximately 16% of modelled abatement was realised at negative cost; 66% of abatement was available at costs of <SCC (£66.10). The available sunshine hours (modelled based on Burnett et al., 2014) was a key influencing factor on the marginal abatement cost, since it impacted both the net benefits and GHG abatement potential of the system (Fig.3).

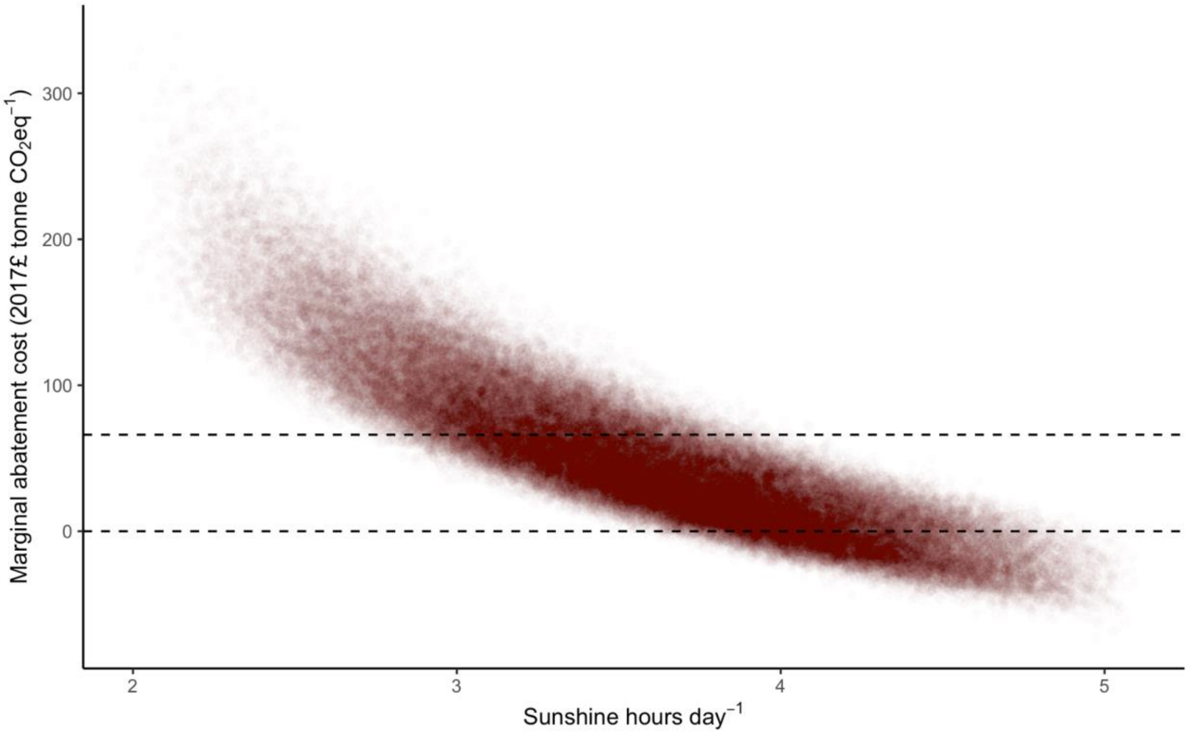

Fig.3. Scatter plot showing the impact of sunshine hours on the estimated marginal abatement cost of agrivoltaic systems. Horizontal dashed lines indicate costs of £0 and £66.10 (the SCC).

Fig.3 suggests that implementation of agrivoltaics in areas of the UK which see less that ~3.5 hours of sunshine per day over the course of a year is unlikely to be a cost effective mitigation strategy. Visual assessment using Fig.1 suggests that this rules out much of Scotland and parts of northern England. The cost of implementation is likely to be higher if systems are implemented in arable systems, since production loss will be greater; accordingly, this preliminary assessment suggests that pasture land in more central and southerly parts of England and Wales represents the ideal situation for implementation of this mitigation strategy.

No literature was found specifically documenting the state of current practice in UK agrivoltaic systems; the majority of literature relating to field trials of the technology related to systems in either continental Europe or the US. The observations relating to Figs. #AV.1 and #AV.3 suggest that uptake would only be possible on a small scale; without further insight, additional uptake of 0.1%, 1% and 10% of available area are assessed here; Eory et al. (2015) followed the same approach for agroforestry, a superficially similar measure. Based on a grassland (pasture only) area of 6,187,000 ha (Defra, 2018), Table 2 gives approximate abatement potential.

Table 2. Potential abatement of agrivoltaics on given percentages of UK pasture land.

Additional uptake (% pasture land)	**Installed output capacity (GW)**	**Abatement potential (kt $year^{-1}$)**
0.1%	1.4	382
1%	14	3,816
10%	140	38,157

Ancillary effects

Installing agrivoltaic systems is very likely to reduce production in the areas in which it is implemented (Dinesh & Pearce, 2016). This may reduced by correct identification of appropriate areas, implementation configurations and crop/grassland systems, but will likely be unavoidable to a great extent. There is therefore potential for this measure to induce indirect emissions through induced land use change if implemented over a wide scale. Displaced grass production depends on uptake rate; approximately 3,030 ha-equivalent of grass production would be displaced by 0.1% uptake, 30,300 ha by 1% uptake and 303,000 ha by 10% uptake.

Potentially mitigating the effects of yield loss, mobile solar PV 'tracking' systems, whereby solar cells are mounted on moving arrays, have been implemented in an experimental site near Montpellier, France; these were shown to increase productivity from both solar cells and the understorey crop by contrast to static systems (Valle et al., 2017). The system can be controlled to optimise solar tracking for increased PV production or increased crop light availability, and thus is alterable to reflect season, climate, crop performance or weather conditions. However, panel surface area has been shown to be a determining factor in crop performance, regardless of panel mobility (Amaducci et al., 2018).

Identified implementation challenges and barriers

Installation of solar PVs in agrivoltaic systems represents a high capital expenditure which must be justified by the expected returns over a 20—30 year lifetime. Any uncertainty in the value of these returns will therefore be a large disincentive towards implementation of the measure. Much of the privately realised benefits in the present model are derived from centrally-regulated subsidies which may change over time, altering the economic viability of the system.

A central uncertainty in the current model is the amount of solar-generated power which is used by the farming system; Upton et al. (2013) found that an average dairy farm (in Ireland) consumed around 48 MWh of power annually (average farm size = 76 ha). The photovoltaic system assessed in the current model produced 181—350 MWh ha^{-1}, so one hectare of land under agrivoltaics far exceeds the demands of a system of the size assessed by Upton et al. (2013); with requirements for milking and milk storage, dairy farms are typically more energy intensive than beef or sheep, which have very low energy demand. The privately realised benefits of agrivoltaics, under the current tariff system, vary strongly with the amount of solar-generated electricity in use by the owner of the solar PVs; the returns diminish when the total MWh generated exceeds the requirements of the system. This may limit the economic incentive for the uptake of agrivoltaic systems beyond a certain size on farming systems; a change in the current legislative and economic framework for the solar electricity market could change this.

A European Union directive published in December 2018 (EU, 2018) requires that a fair market price be paid by member states for renewable electricity (including solar PV) generated by private individuals and fed into the national grid. The imminent departure of the UK from the EU may (though will not necessarily) remove this legal requirement, but in the meantime the UK government is legally obliged to design and implement a system which compensates solar PV feed-in at market price. Uncertainty surrounding Brexit may, in the short term, represent a barrier to uptake of agrivoltaics since it has considerable implications for their privately realised cost effectiveness.

The abatement rate of solar PV-generated electricity assessed in this study is 232 ± 22 g CO_2-eq kWh^{-1}. This rate is based on the difference between solar-generated electricity (Table.1) and the current emission factor estimated for UK grid electricity (DEFRA/DECC, 2018) of 283 g CO_2-eq kWh^{-1}. As the UK power sector decarbonises, the emission factor for grid electricity will decrease and the marginal abatement of solar generation will reduce accordingly.

Intermittency of generation and grid storage capacity may represent challenges as solar PV used increased on a national scale. Solar generation rates cannot be controlled in the same way as non-renewable sources, and the generated energy must be stored until required. Though also intermittent, wind generation via turbines may complement solar power through providing electricity generation at different times (e.g. at night or during winter). The cost of solar-generated electricity per MWh is deemed on par with wind generation (£50—70 MWh^{-1}; Committee on Climate Change, 2019). Both solar panels and wind turbines may present a visual impact to the area in which they are installed (e.g. Department for Communities and Local Government, 2013), though solar panels, being lower to the ground are typically less intrusive to the viewshed than turbines. There is also likely to be lower local noise pollution resulting from PV panel installation, since these have are no moving parts.

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Prepared by:	Alasdair Sykes, SRUC