Increased Water Availability and Flood Risk Due to Reduced Evaporation at Lime Down

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Summary

1. Solar installations are designed to capture solar energy in the form of electricity, and remove it from site for use elsewhere. Solar energy also drives evaporation of water from land surfaces. In solar sites, there will therefore be less energy available to evaporate water, and evaporation will be reduced. This will result in an increase in soil moisture in solar sites, and the effective production of water, which can be a benefit in dry areas, and increase flood risk in wet areas. In dry areas, the additional water is the basis for *agrivoltaism*, the co-location of agriculture and solar energy production for mutual benefit. Studies on agrivoltaic sites have confirmed the increase in soil moisture which occurs due to solar installations. This report suggests a method of calculating the excess water due to reduction of evaporation, applies it to the Lime Down Solar Farm and considers whether it will increase flood risk.

2. At Lime Down, the additional water generated from evaporation restriction, calculated using fairly conservative assumptions, amounts to about 233,000 cubic metres per annum. This will increase soil wetness and increase the flow of rivers and streams both on- and off site. Off-site the proportional increase in flows will be small, but needs to be considered in the context of the cumulative effects of other solar developments which feed into the same rivers. In the small watercourses on site, the proportional effects will be larger. Both need to be considered in flood risk assessments. The increased soil moisture will increase flood risk by increasing the area of saturated ground close to the panels, and extend the time during which the ground is saturated. In the Autumn the catchments will become more flood-sensitive at an earlier date in time for the Autumn storm season, and the flood-sensitive period will be prolonged in Spring. The additional water needs to be considered in the flood risk assessments and mitigation strategies, and provides another reason for not consenting the Lime Down Solar Farm in such a flood-sensitive area.

Author

3. I am an Emeritus Professor of Geography and Environmental Science at the University of Reading. I have been involved in hydrological research since 1977, first as an environmental scientist in the electrical generation industry working on the effects of acid rain on freshwaters, and after I returned to academic life in 1999, working on modelling and monitoring freshwaters, and hydrology and climate change. I am a co-author of the standard paper on climate change and the water environment in England and Wales, and co-led the modelling work packages of two large EU-funded projects, EUROLIMPACS and REFRESH, which investigated the predicted effects of climate change on waters across Europe. My publications on hydrological topics have been referenced more than 1000 times. I live adjacent to the Lime Down area. The evidence I have produced is based upon my professional expertise, and is my true and professional opinion.

Introduction

4. The replacement of agricultural crops or natural vegetation with solar panels can have a number of profound hydrological effects, which have not been widely studied in the UK. Most solar farms around the world are located in sunny environments where the climate is much drier than the UK, often arid or semi-arid. Though research and experience in dry areas is still relevant, the relative importance of the various hydrological mechanisms are likely to change in wetter areas. In this report I will briefly review the evidence that solar farms can make the ground wetter, and describe some mechanisms which may account for this. I will attempt to quantify the effects for the Lime Down Solar Farm, and assess the potential implications for flooding on- and off-site.

Effects of Solar Farms on Soil Wetness

5. There is ample evidence that solar panel installations on soil and vegetation surfaces cause an increase in wetness. Increased soil moisture and water availability is the main benefit supporting the practice of *agrivoltaism* – co-location of solar panels and agriculture for mutual benefit (e.g. [1]). Agrivoltaic systems are becoming widespread around the world, but not in the UK, where the additional water is less likely to be a benefit, and the other main advantage – shading of crops from intense sunlight – is not applicable. In a meta-analysis of 42 studies round the world, Chen et al. [2] noted an average 300% increase in soil moisture in fields with solar panels, though with wide variability. Reviews of agrivoltaic systems (e.g. [1] quote large numbers of papers in which soil moisture increases in the agrivoltaic scheme. Some studies of pure solar farms show the same thing. In the UK, Armstrong et al. [3] made a year's micrometeorological study of a solar farm near Swindon. The data in this paper are hard to evaluate because they are presented as smoothed by a statistical model, but essentially soil moisture was higher than in the open field, both under the panels and in the gaps between the panels, for the first 9 months of the year, and the same everywhere for the remaining 3 months. The results of such studies will of course depend on the weather in the year in question. Adeh et al., [4] working in an area of Oregon, USA, with a Mediterranean climate, followed the time course of soil moisture in a solar farm from saturated conditions in early spring to dry summer conditions. Soil moisture under the panels remained high whereas areas partially shaded by panels were a little drier and control areas away from the influence of the solar farm dried quickly. Redistribution of water complicates these studies: for instance, Wu et al. [5] in a study in China found that moisture content increased by 60% under the middle of the panels but by 114% under the bottom edge. In a dry site in Colorado, USA, Choi et al. [6] found a statistically significant increase in soil moisture under panels, most pronounced under the lower edge. Bajehbaj et al. [7] working in Pennsylvania, USA, found higher soil moisture under driplines, but lower under panels compared to outside. Yavari et al 2022 [8] review these and other studies in which soil moisture under panels increases. As well as the academic literature, photographs of solar panels in the UK standing in pools of water are commonplace (see e.g. the expert report from Stop Lime Down's Soil and Agriculture consultant). Though moderated by site conditions, is seems clear that solar farms in general increase soil moisture.

Mechanism of Moisture Generation: Reduced Evaporation

6. The major reason behind the increase in soil wetness in solar farms is likely to be reduced evaporation. Evaporation from land surfaces is driven by solar energy. The whole purpose of a solar farm is to capture this energy and move it offsite in the form of electricity, for use elsewhere. There will therefore be less solar energy available on site for evaporating water. To illustrate the potential magnitude of this effect, if the Applicant's estimate of the energy output from the scheme of 438,000 MWh yr^{-1} from ES Ch 7 [APP-059] paragraph 7.10.73 is accepted, then the site will lose the ability to evaporate 642,984 cubic metres of water per year (see Appendix 1 for calculation). For comparison, rainfall on the 878 ha of solar PV areas (ES, Ch3 [APP-055] Paragraph 3.2.8) will supply 7,436,000 cubic metres annually (Appendix 1). This calculation shows that the export of energy is likely to be significant in reducing evaporation and cannot be neglected.

7. Evaporation in catchment areas is sometimes referred to as evapotranspiration to recognise that much of it takes place through uptake of water by plant roots and evaporation from leaves (transpiration). Evapotranspiration is driven by solar energy, but can be restricted by water availability. Evapotranspiration with an adequate supply of water is known as Potential Evapotranspiration (PET), and can be calculated relatively easily (see Paragraph 10 below). Evapotranspiration when water supply is restricted is known as Actual Evapotranspiration (AET). A few papers report direct measurements of AET under solar panels compared to the outside. Marrou et al. [9,10] measured both PET and AET reductions under panels in an irrigated agrivoltaics scheme in Montpelier, France (43°N). For a lettuce crop, AET was reduced by 29% under full panel cover, 25% with half the panel density. As expected, PET was reduced a little more, by 38% and 31% respectively. For a cucumber crop, the reduction was somewhat less, 19% and 14% for AET, 27% and 19% for PET. A study in Greece [11] calculated a reduction in PET under solar panels of about 466 mm, though the baseline was not stated. Annual rainfall in this area is about 630 mm, so the reduction in AET would be much less than 466 mm due to lack of water availability. The increase in water percolation due to panel construction was calculated to be between 38 and 82 mm yr^{-1} – a benefit in this dry area.

8. Latent heat fluxes approximate to AET and have been measured in a number of studies. Jiang et al. [12] measured a 47% decrease in latent heat flux under panels in an arid area of China. Chang et al. [13] modelled a widespread decrease in latent heat fluxes over northern China due to solar panel installation. They state that the decrease in evaporation and thus increased water availability will bring benefits to this largely dry region. It can be seen that what data there are support the theoretical prediction that solar panels will reduce evaporation, but there are few data from wet areas. Reductions in evaporation would be expected to be greater in wet areas, as water is available most of the time, and more incoming solar radiation would be expected to be dissipated as latent heat than in dry areas, rather than warming surfaces.

9. Reduced evaporation provides an explanation for the observed increase in soil moisture in solar farms, but quantifying the amount of additional water due to reduced evaporation is a difficult problem. Ideally it would be based on micrometeorology of a solar installation, quantifying energy transformations and fluxes and their effect on evaporation. The data to evaluate this under UK conditions do not exist. However, it is possible to scope the magnitude of the problem by making a few assumptions. The method suggested is as follows:

a) Calculate average evaporation in the area. This gives evaporation in the absence of solar panels.

b) Reduce evaporation on the panel area by the efficiency of the panel expressed as a percentage. This allows for energy export as electricity by the panel. It assumes that evaporation is directly proportional to the energy input, and that the panel does not modify the energy flux in any other way.

c) Calculate the additional water produced in the catchment by the reduced evaporation.

d) Note that this calculation uses the actual panel area, not the area of ground occupied by panels. The number of panels at Lime Down is stated to be 598,260 in ES (Chapter 7 [APP-059], paragraph 7.10.11, each of an area of 3.12 m^2, generating a total panel area of 1,866,571 m^2).

10. The standard method for estimating evapotranspiration is the Penman-Monteith Model, developed by two British physicists, which exists in numerous variants. For instance, the UN Food and Agriculture Organisation adopted one of these as a standard method for scoping evapotranspiration in 1998 [14]. Essentially it calculates evapotranspiration from an adequately-watered, actively growing grass sward, and has proved to give reasonable results in a variety of environments throughout the world. The Penman-Monteith Model assumes an adequate supply of water at all times, and hence calculates PET. If water availability is limited, the amount of water evaporating will be reduced. This is the Actual Evapotranspiration (AET). AET is much more difficult to estimate than PET, and varies considerably between years and seasonally. In the UK, the average ratio AET to PET ranges from 1.0 in the wettest areas of the country in the mountains of the west (i.e. evaporation is rarely limited by water availability) to 0.78 in the driest areas of SE England [15]. These are high values by world standards. The high values mean that solar panels will have a larger effect on evaporation than in drier places, and also that the calculation is less uncertain. In the Lime Down area the AET/PET ratio is about 0.87 [15], Fig. 1.

11. Annual evaporation rates have been calculated using Penman-Monteith, up to the year 2015, for 671 British catchments by the CAMELS-GB Project [16]. This provides an independent estimate of evaporation calculated by experts in the field. The catchments include the Bristol Avon at Fosse Way upstream of Malmesbury, which is representative of Lime Down. I used the average PET calculated by CAMELS-GB for the Lime Down area for the years 2000 to 2015 as input to the calculation. AET was then calculated by multiplying by 0.87.

12. The calculation for Lime Down is:

Potential Evaporation	535.9 mm
Actual Evaporation	466.2 mm
Panel efficiency	23%
Evaporation reduction	107.2 mm
Panel Area, Lime Down	1,866,571 m^2
Additional Water generated	200,159 m^3.

13. The presence of the solar farm is thus calculated to generate an extra 200,000 cubic metres of water annually at Lime Down. This is likely to be an underestimate for two main reasons. 1) as well as losing energy to electrical power, solar panels absorb short-wave solar radiation and re-radiate it as long-wave radiation. To the extent that they are more efficient at this than the grass sward they replace, this will also result in a loss of energy for evaporation; and 2) evaporation also depends on energy advected in by the wind. This is allowed for in the Penman-Monteith calculation. Many studies show reduced windspeed in solar arrays. For instance, Armstrong et al. [3], working in a solar park near Swindon, UK, showed an 86% reduction in windspeed under the panels and a 63% reduction in the gaps between the panels. Adeh et al., [4] working in Oregon, USA, demonstrated a 37% reduction in windspeed in the gaps between the panels at 0.5 m above ground level, and a 24% reduction at 1.2m, both reductions being statistically significant. Reduced windspeed would be expected to reduce evaporation. Opposed to these two mechanisms, heat transfer from the panels by various routes may warm and dry the air over the underlying vegetation, and this will tend to increase evaporation compared to the situation without panels. It is not possible to calculate an upper bound for loss of evaporation potential without more investigation of these effects. If the panels completely eliminated evaporation, the additional water at Lime Down would be 870,000 m^3. This is very unlikely, but 500,000 m^3 might be a credible precautionary value.

14. Another contributor to evaporation is interception loss, which is evaporation of stored water before it reaches the ground. Interception loss is an important additional contributor to evaporation in countries like the UK with long periods of low to moderate rainfall. Vegetation surfaces store water from precipitation, making it more available for evaporation from advected energy. Solar panels will be much less effective in storing precipitation than vegetation as they are smooth, whereas vegetation is rough on a fine scale, leaves being typically covered in hairs and other small protuberances. The slope of solar panels also induces immediate runoff, leaving much less time for evaporation of the intercepted water to take place. Interception loss from solar panels is likely therefore to be much smaller than for vegetation, though it will not be zero. Replacing vegetation with solar panels is likely therefore to lead to a reduction in interception. There appear to be no quantitative measurements of interception loss by solar panels in the literature, and therefore no basis apart from the theoretical considerations above for estimating how large the reduction in interception loss might be. A reduction of 50-80% would seem to be a reasonable value for the UK. The CAMELS database provides an estimate of interception loss for a grass sward. For the Lime Down area in 2000 to 2015 this is 35 mm. Assuming conservatively that solar panels reduce interception loss by 50%, i.e. 17.5 mm, this leads to the generation of an additional 32,665 m^3 of water in the Lime Down catchment. The total additional water generated by reduction of evaporation by solar panels is thus 200,159+32,665 = 232,824 m^3.

15. There are a few papers which have measured actual evapotranspiration under solar panels compared to the outside which show that the above calculations are credible. Marrou et al. [9,10] measured both PET and AET reductions under panels in an irrigated agrivoltaics scheme in Montpelier, France (43°N). For a lettuce crop, AET was reduced by 29% under full panel

cover, 25% with half the panel density. As expected, PET was reduced a little more, by 38% and 31% respectively. For a cucumber crop, the reduction was somewhat less, 19% and 14% for AET, 27% and 19% for PET. A study in Greece [11] calculated a reduction in PET under solar panels of about 466 mm, though the baseline was not stated. Annual rainfall in this area is about 630 mm, so the reduction in AET would be much less than 466 mm due to lack of water availability. The increase in water percolation due to panel construction was calculated to be between 38 and 82 mm yr^{-1} – a benefit in this dry area. Latent heat fluxes approximate to AET and have been measured in a number of studies. Jiang et al. [12] measured a 47% decrease in latent heat flux under panels in an arid area of China. Chang et al. [13] modelled a widespread decrease in latent heat fluxes over northern China due to solar panel installation. They state that the decrease in evaporation and thus increased water availability will bring benefits to this largely dry region. The limited data from the scientific literature thus support the theoretical prediction that solar panels will reduce evaporation, but there are few data from wet areas. However, reductions in evaporation would be expected to be greater in wet areas, as water is available most of the time.

Implications

16. Once constructed, the Lime Down Solar Farm will effectively generate an additional 233,000 cubic metres of water annually in the Bristol Avon catchment. This needs to be taken into account in any Flood Risk Assessment. Though this is a large volume of water, the proportional increase in flow over the year on the main River Avon will not be large – about 0.22% at Great Somerford (see Appendix 1 for calculations). However, there are numerous other solar schemes in the catchment, built, under construction and planned, and the cumulative effect of these on this flood-prone river needs to be considered before Lime Down can be consented. It should be noted that the evaporation reduction mechanism only applies when panels are constructed over a water-storing surface such as soil or vegetation. Panels mounted over rapidly-draining surfaces such as rooftops, car parks etc will not make a significant difference to evaporation.

17. On smaller sub-catchments, the increased supply of water becomes more significant. On the Gauze Brook, which drains Area D of the scheme, the additional water adds 0.62% to the annual runoff. On the Norton Brook, which drains Area C and part of Area B, the increase is at least 2.6%. Both these streams have houses at risk on their banks. The small stream reaching the Avon on the west side of Norton would probably be similar to the Norton Brook. For the Sherston Avon in Malmesbury, draining Areas A, B and C, the increase is 0.44%. Though these figures may appear small, it must be questioned whether any increase is acceptable given the current prevalence of flooding.

18. Considering just the annual output of water is not adequate for assessing flooding, which occurs in extreme conditions. In its response to this point in Stop Lime Down's Relevant Representation, [PDA-009], SLD079, the Applicant states "Flood risk is determined by rainfall intensity, infiltration capacity and surface runoff generation during storm events, which occur over short timescales where evaporation rates are not the controlling factor, and any reduction in evaporation between rainfall events does not materially affect the capacity of

vegetated soils to infiltrate and attenuate rainfall during subsequent storms." The last phrase is highly contentious. I am not suggesting that reduced evaporation has a direct role during storm events. However, reduced evaporation will increase the area of saturated ground close to the panels, and also mean that saturation occurs earlier in the hydrological cycle. This will be particularly significant in the Autumn, as the catchments will become more flood-sensitive at an earlier date in time for the Autumn storm season. "Surface runoff generation during storm events" is strongly influenced by the amount of saturated ground. This is the "saturation excess" runoff generation mechanism in which water cannot penetrate the soil because it is already saturated with water, as opposed to the "infiltration excess" mechanism in which water cannot penetrate because the soil intrinsically has a low infiltration rate, like many of the soils at Lime Down. Saturation excess is the basis of modern understanding of runoff generation, as described in all hydrology textbooks (e.g. Ward and Robinson, 2000) [17] Ch 7.

Conclusion

19. The export of electrical energy from the solar farm, and the smaller interception loss from the panels, leads to reduced evaporation and an increase in the water content of the catchment containing the solar farm. This additional water will ultimately leave the solar farm, either in surface runoff or groundwater or both. It will therefore increase the amount of water off site, in the rivers draining the panel sites. The onus should be on the Applicant to demonstrate that this does not constitute an increased flood risk, contrary to the requirements of the Overarching Policy on Renewable Energy, EN-1. The same processes will occur in other solar farms in the same catchment, giving rise to a cumulative effect on the drainage waters which may in total increase the flood risk significantly, even if the individual contributions do not. This also needs to be assessed. The additional water will increase the area of saturated ground around the panels and tend to make it appear earlier in the Autumn and persist longer in Spring. The catchment will therefore be at risk of flooding for longer.

20. Covering a relatively high proportion of the area of small headwater catchments in a high flood risk district with outsize solar panels is unwise. The Applicant has failed to demonstrate that this will not cause an unacceptable flood risk both on- and off site. This is particularly true given the low permeability and sensitivity to compaction of the catchment soils as demonstrated in other reports. The Applicant's plans to mitigate the risks are mostly too vague to be credible. In my view, the additional water generated by the mechanisms discussed in this report will lead to an unacceptable flood risk and should contribute to the application being rejected.

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Appendix 1 – Calculations

1. Potential loss of Evaporation Capacity

Disclaimer: this calculation has been assisted by artificial intelligence (Claude.ai) and the output checked for "hallucinations".

Question – to find the volume of water evaporated by 1 MWh of energy. Assumed to evaporate in place at environmental temperatures (20°C).

1 MWh = 3,600,000,000 J (3.6 GJ)

- Energy available: 3,600,000,000 J
- Latent heat of water at 20°C: 2,453,000 J/kg
- Mass evaporated: 3,600,000,000 ÷ 2,453,000 ≈ 1,468 kg = 1.468 m^3
- Applicant's estimate of annual energy production 438,000 MWh yr^{-1} from ES Ch 7 [APP-059] paragraph 7.10.73.
- Therefore potential loss of evaporation capacity is 1.468 x 438,000 = 642,984m^3

2. Changes in River Flow

All hydrological data from Centre for Ecology and Hydrology National River Flow Archive https://nrfa.ceh.ac.uk/.

- On the Avon at Great Somerford, the annual water output is about 107,138,000 m^3. Increased water output is 232,824m^3, which is a 0.22% increase

On the Gauze Brook, the annual water output is about 9,151,700 m^3. The Gauze Brook drains Area D of the Scheme which includes 24.3% of the panel area, implying an increased water output of 56,576 m^3, which is a 0.62% increase.

For the Norton Brook, which is ungauged, the water flow can be assumed to be the same as the Gauze Brook scaled by their relative catchment areas. This will be an exaggeration of flow in the Norton Brook, because flow in the Gauze Brook is supplemented in the summer by a stream support borehole. Norton Brook catchment area is. 9.94 km^2 and the Gauze Brook 28.2 km^2. Annual output of the Norton Brook is thus 9,151,700 x 9.94/28.2 = 3,225,813 m^3. The Norton Brook drains Area C of the Scheme which includes 36.2% of the panel area, implying an increased water output of 84,282 m^3, which is a 2.6% increase.

On the Sherston Avon at Malmesbury, the annual water output is about 31,557,600 m^3. The Avon above Malmesbury drains Areas A, B and C of the Scheme which includes 59.9% of the panel area, implying an increased water output of 139,461 m^3, which is a 0.44% increase.