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The Effects of Shelterbelts on Microclimate and on Passive Solar Gains

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Field measurements are reported of the effects of shelterbelts on wind speed and on ambient air temperature. The shelterbelts are of non-ideal form and are located in non-ideal surroundings in Milton Keynes (including in the Energy Park area before development). They typify the sort of belts often encountered in rural and urban settings in the U.K. and thus contrast with the sort of belts and barriers on which most earlier work has been performed. Even so, our data on wind speeds are surprisingly similar to earlier data. Our correlations of shelter versus ambient daytime temperature are significantly positive.

We also report a method of estimating the reduction in passive solar gains resulting from shading produced by shelter barriers.

1. INTRODUCTION

THIS PAPER summarizes two of a series of studies commissioned jointly by Milton Keynes Development Corporation (MKDC) and the Department of Energy in relation to the development of the Energy Park in the new city of Milton Keynes, U.K. The Energy Park [1] is an international demonstration project promoting all aspects of energy efficiency. It is located on a 120 hectare area near the city centre. It is a comprehensive project comprising over 100 000 square metres of offices and factories, over 1000 low energy houses, and local shops, schools, and parkland. The first buildings in the Energy Park were completed in August 1986.

Our studies stem from the MKDC plan to control wind in the Energy Park by means of shelterbelts. Britain is one of the most windy populated countries in the world, and though Milton Keynes is in one of its least windy regions this is offset by the somewhat exposed nature of much of the city and by the low rise, low density nature of the development [2]. As a consequence, Milton Keynes has proved windy for an urban environment. Therefore, MKDC have decided to investigate the use of shelterbelts, in the first instance with a view to application of the results in the Energy Park.

By the term shelterbelt, we mean a barrier consisting of vegetation. A shelter barrier can also be artificial and is then often called a wind break. In both cases, they can reduce the local wind speed. This in turn gives rise to reductions in:

(a) the force of the wind
(b) the wind enhanced ventilation rate of buildings
(c) convective cooling
(d) evaporation rates, and in evaporative cooling
(e) the rate of spread of outdoor air pollution
(f) the concentration of radon inside buildings.

Reduced windspeed can also give rise to a change in the local ambient temperature.

Shelter barriers also have effects *not* associated with their effect on wind speed:

(a) attenuation of sound
(b) aesthetic appeal
(c) partial blockage of the downhill drainage of cold air, with the subsequent formation of frost hollows
(d) change of wind direction
(e) alteration of the radiation environment, at solar and long wavelengths.

These various effects can be regarded as advantages or as disadvantages, depending on the circumstances. In the Energy Park the primary goals of leaving certain old hedging and of new shelter planting are to

(a) reduce wind speed and thereby reduce building energy consumption (particularly in the domestic sector) and also enhance outdoor thermal comfort
(b) control solar access, so that shade from the summer sun is provided without greatly reducing the passive solar gains in the winter.

Space heating in the U.K. domestic sector accounts for 64% of the energy consumed in this sector, or about 20% of the primary energy consumed in the U.K. Therefore installing shelter barriers in areas of domestic development, and elsewhere, could lead to significant energy savings.

A reduction in wind speed reduces building energy consumption in various ways [2, 3]. First, it reduces the ventilation rate. At high wind speeds, the ventilation rate is dominated by air infiltration arising from the air pressure gradients that winds establish across building

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elements, and can account for the order of a third of all heat losses from a conventional house. However, at low wind speeds the ventilation rate is dominated by the stack effect, which results from the temperature differences between the inside and the outside. For a conventional house the heat losses due to the stack effect for a temperature difference of 18 C are roughly comparable to those due to air infiltration at a wind speed of 4 m s^{-1}. Even in unsheltered housing estates in Milton Keynes the wind speed is less than 4 m s^{-1} for about 40% of the time [2] and so the stack effect is of some significance. Shelter has little effect on the stack effect and this somewhat reduces the beneficial influence of a shelter barrier.

Second, a reduction in wind speed reduces surface heat transmission because the air boundary layer around a building then becomes more substantial. However, except at windows, this is a rather small effect [4].

Third, a reduction in wind speed can change the local ambient temperature. During the day, the ground surface is heated by solar radiation and so is at a higher temperature than the air, with the result that heat is transferred from the ground to the air. The rate of heat transfer depends on the wind speed such that the *lower* the wind speed the *higher* the ambient temperature. At night the ground can become colder than the air by radiating to the sky, and so at night a reduction in wind speed can lead to a reduction in ambient temperature and hence to an increase in building energy consumption.

Reduced wind speed could also lead to increased building energy consumption in other ways, such as by causing an increase in the use of internal clothes driers.

It is not only through wind speed reduction that a shelter barrier can influence building energy consumption. It can also influence the long wave radiation environment. This can reduce radiative heat losses from a building, particularly at night when the sky temperature can be very low. The barrier then, from the building's viewpoint, replaces a part of the cold sky with its own, usually warmer surface.

A shelter barrier can also reduce a building's passive solar gain. The main effect is blockage of beam radiation, the blockage of diffuse radiation and of radiation scattered from the ground being less important [5]. In much of the heating season in the U.K. the Sun is low in the southerly sky. Furthermore, the prevailing wind is from the south west and this remains the case even if the wind speed and ambient temperature are taken into account i.e. in the wind chill rose that would be used in the calculation of building heat losses [3]. Therefore, there can be a serious conflict between using a shelter barrier to reduce wind speed and preventing such a barrier causing serious reductions in passive solar gains.

In the literature values for the overall domestic energy savings for a sheltered house compared to an unsheltered house range from 3 to 40%, and there have been qualitative studies also [3, 5 9]. Given the many parameters that characterize building design, building use, microclimate, and shelter barriers and their effects on microclimate, such a wide range of values is very unsurprising!

Our work, reported below, is on the effects of shelterbelts on microclimate and is mainly experimental. There have been relatively few previous experimental studies on shelterbelts (barriers made of vegetation) [10–14], though there has been other work on artificial barriers [e.g. 15, 16]. The work on shelterbelts has been almost entirely on long, straight, uniform belts of old hedges or trees, on flat, otherwise fairly open country. Their effects have been studied, in the main, in relation to the protection of crops and livestock. From this work it is clear that the zone of appreciable shelter extends mainly on the downwind side for a distance of the order of 10 H where H is the height of the shelterbelt. The downwind shelter profile depends on the porosity of the belt, that is, on how substantial it is. The less substantial the belt the broader and shallower the shelter profile. For non-porous belts the wind speed behind the belt can be as little as 15% of the free field value, but at 5 H downwind this has already risen to about 60%. For a 'loose' belt the corresponding figures are about 40% and 50%. The porosity of the belt also effects the degree of turbulence downwind, and in addition can influence the direction of air flow such that downwind of very low porosity barriers reversed flow can occur [16].

There are few data on the effect of shelterbelts on ambient temperature. Caborn [11] and van Eimern [12] have reported rises of the order of 0.5 to 1 C averaged over night and day, with a cooling effect at night and a greater warming effect during the day. They report that the effect is greater for dry soils, smaller the more cloudy it is, and smaller the greater the wind speed. In an extensive review, Marshall [13] has given day and night profiles of temperatures that show a maximum effect during the day of a 15% increase in ambient temperature (of 20°C?) 4 H downwind and a small cooling effect of no more than 5% during the night. Ujah and Adeoye [14] have reported that maximum temperatures can be as much as 2 C higher in sheltered areas, whereas the minimum temperatures show no correlation with shelter, the overall effect being an increase in average temperatures in sheltered areas.

In the next section, we present our measurements on the effect of single shelterbelts on microclimate within the city of Milton Keynes. These are 'real' shelterbelts of non-ideal form in non-ideal surroundings, some consisting of old vegetation whilst others are recent landscaped planting. The belts thus typify the sort often encountered in the U.K. in rural and urban settings.

In section 3 we present data on combinations of shelterbelts, and in section 4 we present a method of estimating any reduction in passive solar gain caused by shelter barriers. In section 5 we draw together our main conclusions.

2. THE EFFECT OF INDIVIDUAL SHELTERBELTS ON MICROCLIMATE

At various days in the period October 1984 to May 1985 (which includes the heating season) we obtained wind and temperature profiles across five shelterbelts in Milton Keynes. Two of these consist of old hedges and trees. The other three have been planted more recently by MKDC, mainly to provide visual screening.

2.1. *The shelterbelts that we have investigated*

It is difficult to specify adequately a real shelterbelt on a real site. Table 1 goes some way towards a specification (the density of a belt is a measure of its porosity). Note that all the belts run roughly north west–south east. Further details of these belts, and of other aspects of our work, can be found in [3].

Initially, the shelterbelt in Tinkers Bridge was not on the list, but earth-moving operations near the Peartree Bridge shelterbelt caused us to abandon it and substitute Tinkers Bridge. There were no substantial changes at any of the other shelterbelts, apart from autumn defoliation and spring foliation, and a small amount of trimming, probably of marginal significance.

2.2. *Method of investigation*

The wind speeds, directions, and ambient air temperatures were measured in the vicinity of each shelterbelt with two weather stations, one acting as a fixed reference, the other as a portable station that visited a given set of sites along a line perpendicular to each shelterbelt. The reference station was located in as near free wind field conditions as was possible for each belt.

The reference station measured wind speed, direction and ambient temperature at a height of 2.15 m. This station was set up at the beginning of each run and took data throughout the run. During this time the portable station took data sequentially at each portable site, for about 15 minutes at each site. The portable station measured wind speed and ambient temperature at heights of 1.15 m and 2.15 m, and wind direction at 2.15 m. Wind speeds were measured with cup anemometers, the plane of cup rotation always being parallel to the ground. Windvanes yielded wind directions and shielded platinum resistance thermometers yielded ambient temperatures. Note that a cup anemometer measures the magnitude of the wind vector component in the plane of cup rotation, and that our windvanes measured the direction of this same component.

Let V_{port} denote the wind speed at 2.15 m at a portable site averaged over the time (about 15 minutes) spent at that site and let V_{ref} denote the wind speed at 2.15 m at the reference site averaged over the same time. Thus $V_{\text{port}}/V_{\text{ref}}$ is a good measure of the *effective shelter* at that site during that particular time interval. In like manner we have obtained the average wind directions, and also the average ambient temperatures T_{port} and T_{ref} and hence have obtained $\Delta T = (T_{\text{port}} - T_{\text{ref}})$. The one standard deviation accuracies are of the order of $\pm 10\%$ in $V_{\text{port}}/V_{\text{ref}}$ at the higher wind speeds, increasing to $\pm 20\%$ at the lower speeds, $\pm 5°$ in wind direction, and $\pm 0.2°$C in ΔT.

Measurements were taken during daylight hours on a number of days from October 1984 to May 1985. In all cases the winds blew from the southerly side of the shelterbelt within about ±40° of the direction perpendicular to the belt.

2.3. *Results*

Figure 1 summarizes our results on the effect of shelterbelts on wind speed. In order to facilitate comparison between the various shelterbelts we have plotted $V_{\text{port}}/V_{\text{free}}$ against the distance from the upwind/downwind surface of the belt in terms of the shelterbelt height H ignoring the contribution of trees to H and taking the height of the higher of two parallel belts (Table 1). $V_{\text{port}}/V_{\text{free}}$ is readily obtained from $V_{\text{port}}/V_{\text{ref}}$ and is more convenient than the latter because the reference site was not in the same relative position for each shelterbelt. For Abbey Hill, Knowlhill and Milton Keynes Bowl V_{free} has been taken to be at $5H$ upwind. To the accuracy of our measurements this can be regarded as sufficiently far upwind to be the free field [11]. For the other two shelterbelts the site upwind is not open and so we have taken V_{free} to be that at the reference site, $15H$ downwind in both cases, again in the free field. Thus, in all cases $V_{\text{port}}/V_{\text{free}}$ is also a good measure of the *effective shelter* at each portable site, and is a somewhat better measure than $V_{\text{port}}/V_{\text{ref}}$ when comparing one belt with another. Each carries about the same accuracy.

In obtaining the graphs in Fig. 1, allowance has been made for the effects of crop growth upwind of the Knowlhill and Milton Keynes Bowl shelterbelts in late April and early May 1985. However, this only effects one run in each case.

Allowing for the effect of the crop growth by no means eliminates the scatter in the data points underlying the graphs in Fig. 1. This scatter is of the order of ±30%, significantly greater than the estimated reproducibility of measurements by the equipment. It is likely that much of this extra scatter arises from differences between runs in the degree of variability of the wind in speed and in direction, and in the degree of turbulence. Note that no significant correlation of $V_{\text{port}}/V_{\text{free}}$ with *average* wind direction has been found, even though the average wind direction varied from one run to another from about +40° to about −40° with respect to the direction perpendicular to the belt.

The direction of the wind at the reference site typically varied by the order of ±10° during a run. The difference in direction between the reference site and a portable site was rarely greater than the order of ±10°. There is thus no evidence of reversed flow at 2.15 m.

Broadly speaking, the data in Fig. 1 are similar to those reported earlier [10–14], surprisingly so in view of the non-ideal form of our belts and their sites. The more dense (less porous) shelterbelts give quite good shelter over a narrow zone close to the belts whereas the less dense shelterbelts (which are of medium porosity) give rather less good shelter over a wider zone further downwind. A comparison of Fig. 1 (a) with Fig. 1 (b) shows that a seasonal effect is discernible. This is a new result. The defoliated ('leaves off') curves correspond to complete or very nearly complete defoliation of the deciduous species (Table 1), but the 'leaves on' curves correspond to mid to late autumn and mid to late spring, when, for some runs, the deciduous plants were only partly in leaf. Nevertheless, it is clear from Fig. 1 that inferior shelter is provided in the more defoliated state.

Regardless of the state of foliation it is clear from Fig. 1 that the *less* substantial belts (Abbey Hill and Knowlhill—Table 1) provide the greater downwind range (in terms of H) of sheltered ground, the other belts providing a greater range upwind and a greater degree of shelter in the immediate vicinity of the belt. Bearing in mind that our data were obtained at 2.15 m, this conclusion is independent of the ratio of this height to the belt height (Table 1). Our work adds significantly to the data on this effect.

Table 1. The shelterbelts that we have investigated

Location	Age years	Species	Height	Density	Length	Orientation[1]	Surroundings
Abbey Hill	5–6	Mixed deciduous plus some evergreens	$\simeq$2.85 m plus trees up to $\simeq$4.50 m	Medium, but more dense up to $\simeq$1.50 m	$\simeq$80 m	225°	Short grass (a golf course). Site slopes down slightly to north west. Other obstructions distant except for north west continuation of hedge at 200° orientation
Knowlhill	Old	Mixed deciduous with few evergreens	$\simeq$6.00 m plus two trees up to $\simeq$12 m	Medium	$\simeq$220 m	202°	Short grass on northerly side; winter wheat on other side. Site slopes down slightly to north east. A bank terminates north west end, and a hedge at 220° orientation the other end
Milton Keynes Bowl	Old	Mixed deciduous with few evergreens	$\simeq$13.5 m, plus a parallel belt $\simeq$4 m high, 21 m distant on southerly side	Medium, but more dense up to $\simeq$4 m	$\simeq$200 m	212°	Short grass on northerly side; winter wheat on other side. Modest upward slope away from belt on northerly side. Both ends continue with lower belts and various low obstacles
Peartree Bridge	7–8	Mixed deciduous with few evergreens	Two parallel belts, each $\simeq$3.45 m high, 10.4 m separation	Very dense	$\simeq$200 m	246° (mean) concave on southerly side, 230°–260°	Short grass on northerly side; wide road then steep bank on southerly side. Belt continues, curving on south east end, turns sharply towards northerly side at north west end
Tinkers Bridge	<2	90% willow, 10% field maple	$\simeq$4.8 m part of which is an embankment	Very dense	$\simeq$150 m	259° (mean) concave on southerly side, 250°–270°	Short grass on northerly side, then housing and hedging about 100 m distant. Wide road on top on embankment on southerly side, then a slope down. Upward slopes plus hedging at each end.

Note: (1) This is the azimuthal bearing of a line perpendicular to the shelterbelt (south-west has a bearing of 225°).

Table 2. Linear regression coefficients for ΔT versus V_{port}/V_{ref}

$\Delta T = A + B\,(V_{port}/V_{ref})$ where ΔA and ΔB are the standard deviations
where r is the correlation coefficient

Shelterbelt	A	ΔA	B	ΔB	r^2
Abbey Hill	0.75	0.17	−0.75	0.22	0.174
Knowlhill	0.08	0.14	+0.04	0.19	0.001
MK Bowl	0.14	0.10	−0.20	0.13	0.117
Peartree Bridge	0.57	0.12	−0.60	0.18	0.344
Tinkers Bridge	0.96	0.11	−1.09	0.16	0.746
Energy Park	0.55	0.07	−0.53	0.08	0.16

The temperature differences ΔT have been plotted versus V_{port}/V_{ref}, and a linear regression performed. There is so much scatter in these graphs that there is no significant advantage in using (T_{port}/T_{free}) for ΔT, rather than (T_{port}/T_{ref}). Much of this scatter doubtless arises from the effect on ΔT of microclimate variables other than V_{port}/V_{ref} such as V_{ref}, and on others that were not monitored, such as insolation, water content of the air, and so on. In spite of this scatter, there is, in most cases, a clear correlation between a rise in ΔT and a fall in V_{port}/V_{ref}, and thus the more sheltered the region the higher the ambient temperature. The results (in °C) are summarized in Table 2. In terms of the tabulated *squares* of the correlation coefficients (r^2) the effect is significant at Abbey Hill, Peartree Bridge and Tinkers Bridge, and is clearly insignificant only at Knowlhill. Broadly speaking, if the local wind speed is very much less than the free field wind speed then the *daytime* ambient temperature in Milton Keynes will be between about 0·5°C and 1°C higher in the sheltered zone.

The correlations in Table 2 are in broad agreement with earlier data [10–14] and add significantly to the quantitative data on ambient temperature versus degree of shelter.

Note that our data in Fig. 1 and Table 2 apply to a height of 2.15 m above the ground. However, it is likely that similar data will be obtained at other heights, except *very* close to the ground, or above heights comparable to that of the belt, or close to barriers denser than those we have studied.

Further details of our work on these shelterbelts can be found in [3].

3. THE EFFECT OF GROUPS OF SHELTERBELTS ON MICROCLIMATE

We have measured wind speed, direction, and ambient air temperature at eleven sites in the Milton Keynes Energy Park area, on various days from December 1983 to May 1984 and from October 1984 to May 1985, in the main before significant area development. We thus concentrated on days in the heating season. Figure 2 shows the location of these sites in the Energy Park area. Note that each site is surrounded by a *group* of shelterbelts, mostly old hedges of hawthorn a few metres high, plus some elms, and that the area is *not* level. This figure also shows our data in the form of wind roses at each site: these will be discussed below. Indeed the general processing of our data and its subsequent presentation in the form of wind roses is of as much interest as the specific data itself.

3.1. *Method of investigation*

The same reference and portable stations were used as in section 2. For each run the reference station was set up at either site 10 or site 11 in Fig. 2, both sites being fairly exposed, and took data throughout the time that the portable station was taken once to each of 11 sites, taking data for between 15 and 30 minutes at each site. Note that the portable station did visit the reference site: this was one way of cross-checking the instruments. Measurements were taken during daylight hours and included all wind directions.

We have correlated our data with Meteorological Office hourly measurements at the three nearest stations, Wyton, Brize Norton, and Elmdon, each being several tens of miles away. These stations surround Milton Keynes, and we have shown that the wind speed and direction during a given hour averaged over these three sites represent the wind speed and direction during the same hour at a weather station operated for a few months at a very exposed site in Milton Keynes, at the standard Meteorological Office height of 10 m, to ±10% in speed and ±10° in direction. Therefore, as elaborated below the continuous record from these three stations, plus our correlations, enable the winds at the 11 sites to be estimated at *any* time before development. This will aid in any future assessment of the effectiveness of new shelterbelts in the Energy Park.

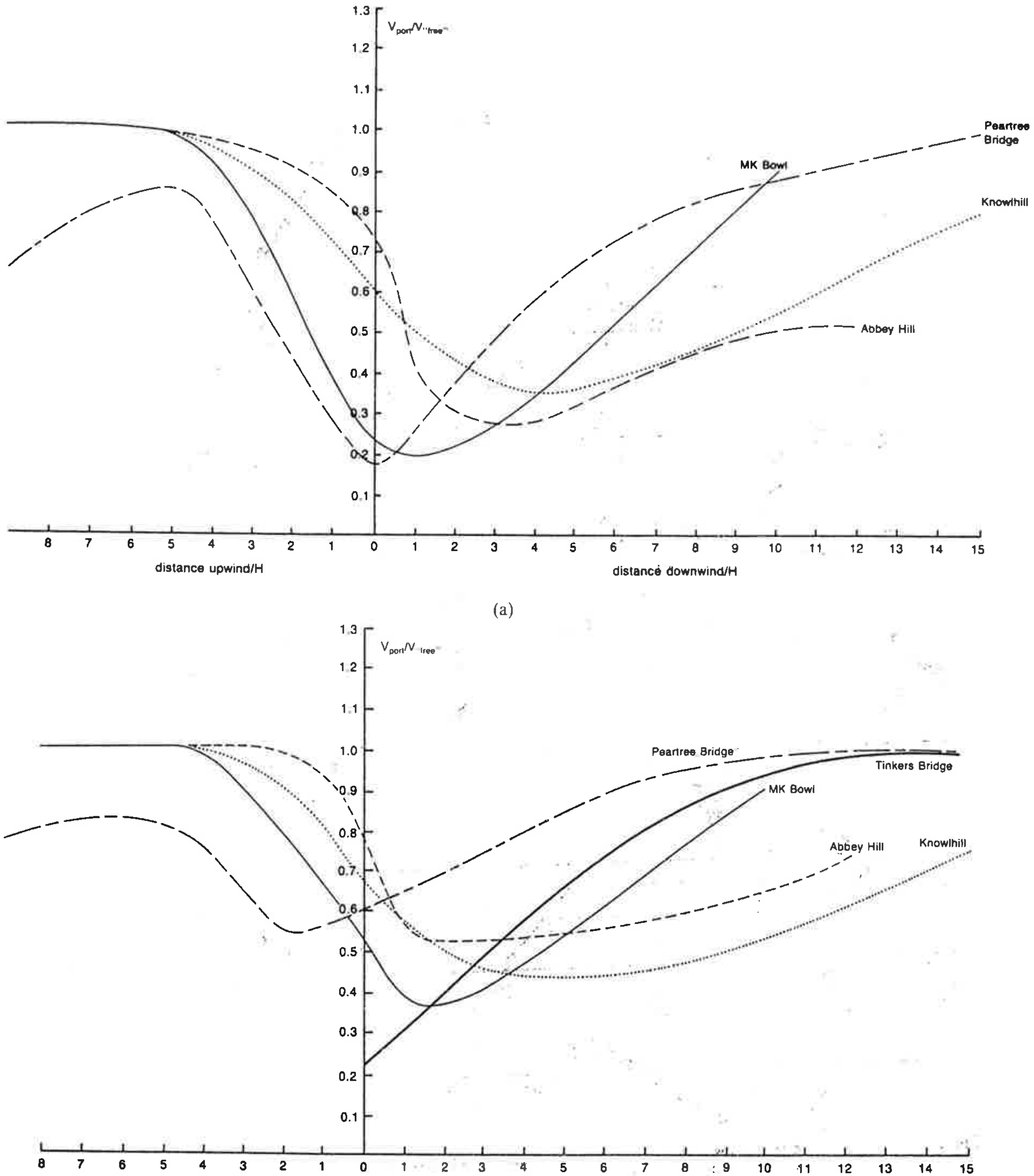
The wind speed measurements at each portable site have been 'tagged' with the wind direction at the reference site averaged over the period of measurement at the portable site. Sometimes there were significant differences between the directions at the more sheltered portable sites and the simultaneous directions at the reference site. However, there was rarely any difference greater than about 30° between the direction at the reference site, and the direction that was the simultaneous average over the three Meteorological Office stations. Thus, this Meteorological Office average can, at almost any time, be taken as the wind direction at the more exposed sites in the Energy Park area, and indeed throughout Milton Keynes.

Next, the hourly values of the wind speeds at the three Meteorological Office stations have been averaged over the three stations and over all the hours in a run, thus yielding a single meteorological wind speed (at 10 m) for the run, V_m. This value has then been adjusted to the 2.15 m height of our sensors using a formula recommended by the Meteorological Office [17]

$$\frac{V_h}{V_{10}} = 0.233 + 0.656\,\log_{10}(h + 4.75) \qquad (1)$$

where V_h is the speed at height h (in metres), and V_{10} is the speed at 10 m height.

Other correlations exist [18] that would yield values of V_h/V_{10} up to a few percent different from those yielded by equation (1). For example, the Deaves and Harris



(a)

(b)

Fig. 1. Effective shelter versus distance from a shelterbelt for five shelterbelts in Milton Keynes (a) with the leaves *on* in autumn 1984 and spring 1985 (b) with leaves *off* in winter 1984–1985.

correlation [18] would yield values about 5% lower. However, for all correlations the procedure is the same, namely the conversion of V_m to a value, V_{met}, more appropriate to 2.15 m. Over the whole run, the period for which V_{met} is defined, the average wind speed observed at our reference station is denoted by V'_{ref}: this is the local run average. We have thus been able to establish, as a function of wind direction, the (smoothed) relationship between V_{met} and V'_{ref}. We have then obtained the ratio (V_{port}/V_{met}) as follows: (where := denotes 'becomes', and *not* 'equal to'):

$$\left[\frac{V_{port}}{V_{met}}\right] := \left[\frac{V'_{ref}}{V_{met}}\right]\left[\frac{V_{port}}{V_{ref}}\right] \tag{2}$$

where V_{port} is the average wind speed measured by a portable station at a site and where V_{ref} is the average wind speed measured during the same time interval (15 to 30 minutes) by the reference station at its site. Note

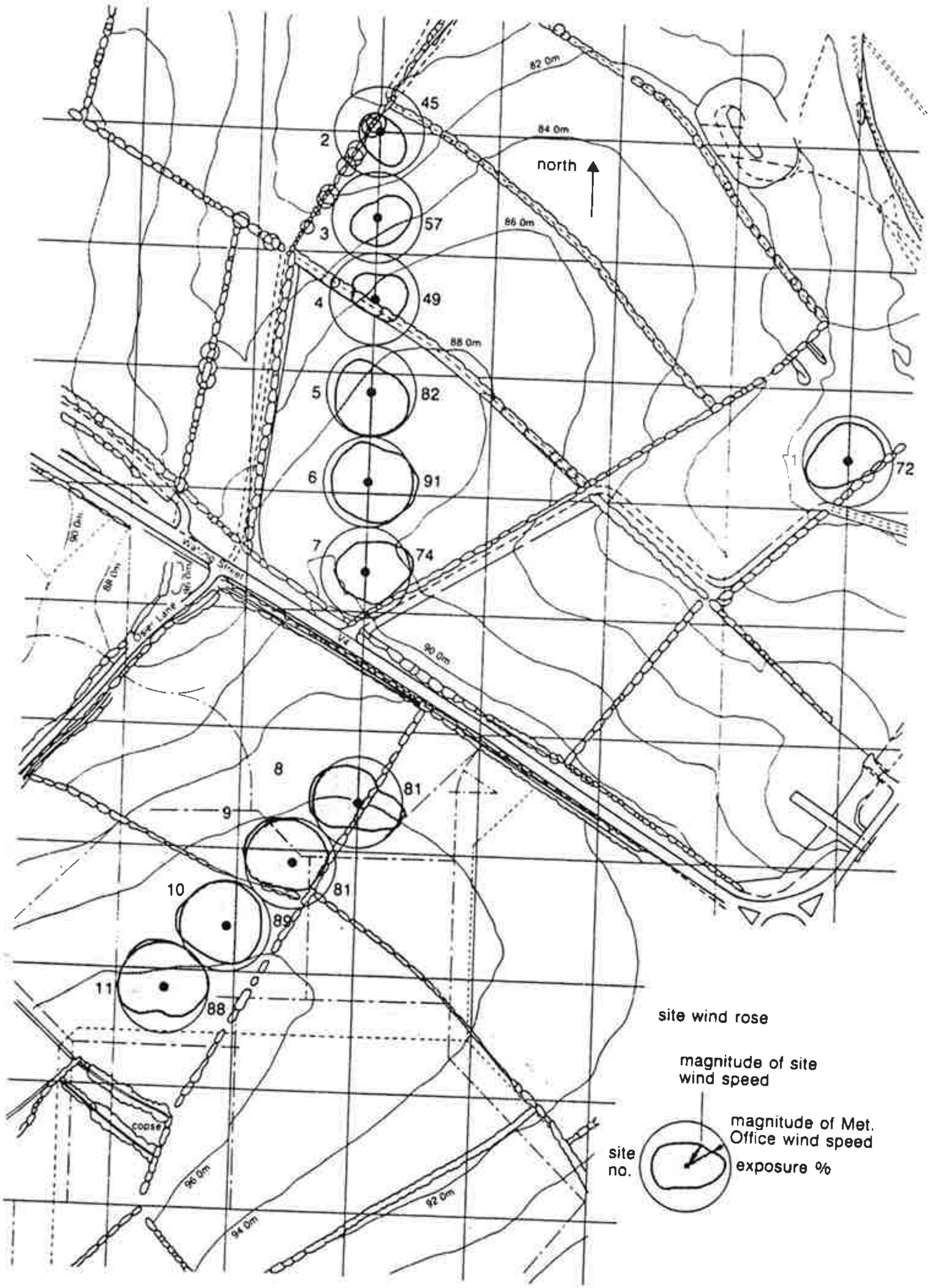


Fig. 2. Wind roses for eleven sites in the Milton Keynes Energy Park area (before area development) in the 1983–1984 and 1984–1985 heating seasons. Each grid square is 100 metres along a side.

that V'_{ref} is *not* the same as V_{ref}, the former being the average wind speed over the whole run. Note also that the use of run averages for V'_{ref} and V_{met}, rather than averages over shorter times, reduces problems associated with the difference in time at which similar wind patterns occur at the Meteorological Office sites and the Energy Park area.

From our values of V_{port}, V_{met}, and the associated directional data, it should be possible to estimate V_{port} (for the pre-developed state of the Energy Park area) for each of the 11 sites at any time.

3.2. *Results*

Figure 2 shows a summary of all our data in the form of a wind rose centred on each of the 11 sites. At each site a point on the boundary of the shaded area gives the value of V_{port}/V_{met} at that site for a wind coming from the direction of the boundary to the centre of the wind rose, this being the direction of the wind at the *reference* site. The circle surrounding each rose corresponds to $V_{port}/V_{met} = 1$. The wind speed ratios are accurate to about ±10%, and the direction to about ±5 .

Sites 2, 3 and 4 were influenced by crop growth which covered the whole field. These crops grew to a height of about half a metre by May each year. This reduces the ratio of wind speed at 1.15 m to that at 2.15 m. However, crop growth has had a remarkably small effect on V_{port}/V_{met}. This suggests a rather sharp change in wind speed versus height.

In obtaining these wind roses, we have given low weight to the relatively few data that correspond to significant foliation or to area development. Thus the wind roses are for the defoliated state before much area development had occurred. It is however the case that better shelter occurs under (partial) foliation than under defoliation.

At each site the degree of shelter correlates with the disposition of the hedges in a qualitatively reasonable manner. Furthermore, the topography in Fig. 2, revealed by the altitude contours, shows that, on the whole, the lower lying sites are the better sheltered. The higher sites are rather exposed, with, for most wind directions, $V_{port}/V_{met} \simeq 1$.

The two digit number at the side of each wind rose is the overall average value of V_{port}/V_{met} at that site, expressed as a percentage, and with the implicit assumption that the wind blows equally from all directions. If allowance is made for the different wind run from different directions during October to April, then more weight is given to the prevailing wind direction (south west) [2, 3]. The percentages for sites 1–11 in order, then become 76%, 43%, 59%, 30%, 86%, 89%, 67%, 84%, 80%, 91%, 86%. Allowance could also be made for the temperature of the wind versus wind direction. A wind-chill rose as defined in [3] would somewhat enhance the significance of northerly and easterly directions.

For our temperature data we have performed a linear regression between $\Delta T\ (= T_{port} - T_{ref})$ and V_{port}/V_{ref}, as in section 2. No attempt has been made to subdivide the data. The overall analysis yields the correlation shown in Table 2. Thus, if the value of V_{port}/V_{ref} is small then the sheltered area will be about 0.6 C warmer *during the daytime*. Again, as in section 2, much of the scatter in the data is due to the dependence of ΔT on factors other than V_{port}/V_{ref}. Note from Table 2 that the Energy Park data are broadly in accord with the shelterbelt data.

Further details of our work in the Energy Park area can be found in [2].

4. SOLAR ACCESS

In aiming for energy savings through the use of shelter barriers care must be taken to ensure that any such savings are not offset by a reduction in passive solar gain through shading. A useful tool for assessing the extent of any such reduction is the *butterfly diagram* developed by one of us (TO) [5]. This is a chart from which can be read the reduction in time-integrated irradiance on a vertical surface (such as a window) due to an element of barrier, height H, at a range nH and bearing θ. The overall reduction from an extended barrier is obtained by summing the reduction from each element.

TO has prepared several butterfly diagrams, each one being for a particular azimuth of the normal to the vertical surface (such as a window facing a particular direction), a particular opacity of the barrier, and a particular length of time over which the irradiance is integrated (usually the heating season).

The data base for all of the butterfly diagrams are monthly average records of global solar irradiation on a vertical surface for each hour of the day for the period 1972–1981 obtained by the Meteorological Office at Bracknell (U.K.). These averages have been manipulated to yield, for each hour of the day, *ten day* averages of *beam* solar irradiation on a vertical surface. Note that the neglect of the diffuse component, which is less susceptible to shading than the beam component, means that the butterfly diagrams somewhat over-estimate the reduction in irradiance. In addition to these irradiation data we also require the Sun's altitude and azimuth at 10-day intervals, for each hour of the day. The time-integrated reduction in insolation for each range and bearing can then be calculated. The use of 10-day rather than monthly data improves the accuracy of this integration.

Figure 3 shows one of the butterfly diagrams. This is for a *south facing* vertical surface, an opaque barrier and integration over the period from 13 October to 11 April. This diagram, and indeed any of the other butterfly diagrams, is to be used as follows.

(a) Draw the barrier on the diagram, using the scale length H given on each diagram. H is the vertical height of the top of the barrier above the point on the vertical surface in question (usually the centre of a window). (Note that the butterfly diagram can be re-scaled and prepared as an overlay such that H is given by the scale of the underlay.)

(b) List the figures in each sector of the diagram crossed by the barrier. If more than one circumferential sector in any radial sector is crossed by the barrier then choose the largest figure (this can somewhat overestimate the reduction in irradiance in some cases).

(c) Add the figures listed: the total gives the percentage reduction in beam irradiance over the period of integration.

Thus the reduction in passive solar gain associated with any shelter barrier can be obtained simply by placing the appropriate butterfly diagram prepared to the correct scale as an overlay on a plan drawing and summing the appropriate numbers.

Note that for an opaque barrier (to which Fig. 3 applies) the barrier can be far from opaque to the wind and thus be loose enough to provide good shelter. This is largely because wind does not require an unobstructed *straight* line to pass readily through an object, whereas a ray of light does.

Figure 3, and the other butterfly diagrams, plus the data in Fig. 1, show that effective shelter can be achieved without any serious reduction in passive solar gains.

Further details will be found in [5].

5. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Our work on single (non-ideal) shelterbelts has shown that the less substantial (the more porous) the belt the

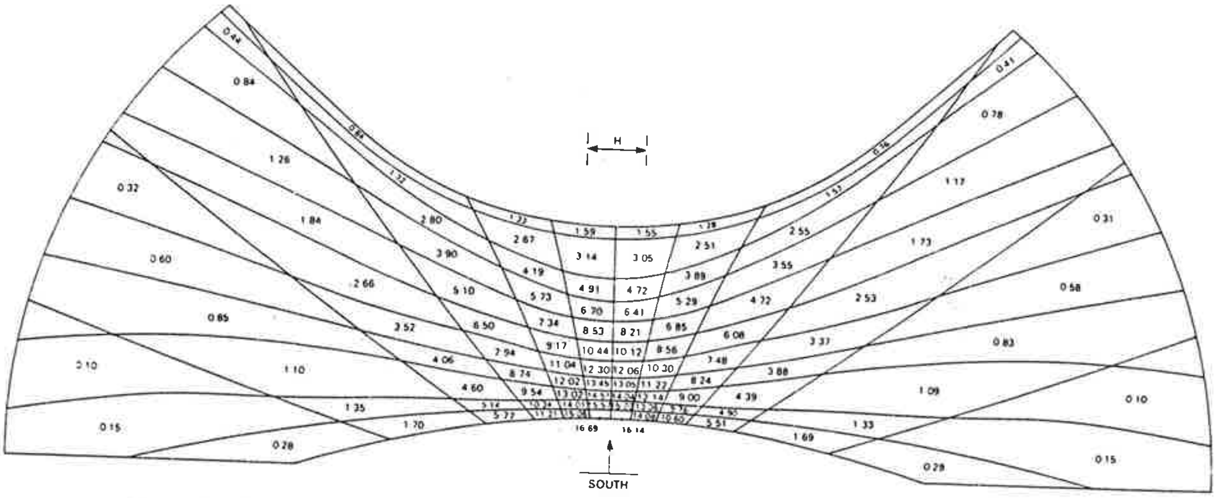


Fig. 3. A butterfly diagram for calculating the reduction in passive solar gain for a south facing vertical surface, resulting from an opaque shelter barrier height *H*, in the U.K. during the period 13 October to 11 April in a typical year.

broader and shallower the profile of wind reduction, the overall shelter being better than that provided by the more substantial belts. A seasonal effect has been discerned: the wind speed reduction in even a partially foliated state can be about double that in a defoliated state. The daytime ambient temperature at a well sheltered site can be as much as about 1°C higher than at a nearby unsheltered site.

Reasonable solar access in winter and adequate shelter from south easterly to south westerly winter winds can be achieved in the U.K. by placing a barrier about 3 to 4 *H* to the south of a building, the barrier having a height comparable to that of the building, though a shelter effect of the sort in Figs 1 and 2 will surely be modified by the presence of buildings. In the summer, because of the high noon altitude of the Sun, a separate row of trees can provide summer shade, a row that does not interfere with winter shelter and winter solar access.

Our work in the Milton Keynes Energy Park area has broadly confirmed the effect of shelter on daytime ambient temperature. It has also demonstrated the usefulness of the wind rose and the associated averages over wind direction, and that Meteorological Office data can be used as a reference standard even when the nearest weather stations are several tens of miles away. This work also acts as a case study on the effect of multiple shelterbelts and of land form on the wind. It shows that Milton Keynes is windy for an urban area in the middle of the U.K.; and that a shelterbelt has maximum effect (even allowing for wind-chill) when it is oriented north-west to south-east. This work (along with that of others) has influenced the plan for shelter planting in the Milton Keynes Energy Park.

Shelter barriers, by reducing wind speed and increasing ambient temperature, can clearly reduce the energy consumption of buildings near them. Any small rise in ambient temperature could be more significant than the reduction in wind speed. It has been estimated [5] that for buildings in the U.K. a rise in average ambient temperature of only 0.5 C yields about 9% reduction in energy consumption for space heating. However, the precise overall savings are very difficult to quantify, particularly because shelter barriers also *increase* energy consumption in buildings, in various ways. But shelter barriers have effects other than those relating to energy consumption in buildings, such as aesthetic influence, and an increase in outdoor comfort. The benefits that result from some of these other effects can outweigh energy considerations. To save energy it might be better in some cases to build better insulated, better draught-proofed buildings, the energy consumption of which is influenced less by shelter barriers.

Much further work could be done. In relation to single shelter barriers we could examine in more detail the effects of porosity, angle of incidence of the wind, variability of the wind in speed and direction, belt length, and the land form. In relation to ambient temperature we could examine the influence of many parameters particularly night versus day, the radiative exchanges between ground and sky often being the reverse of those during the day with the outcome that at night a sheltered area will usually be *cooler* than an unsheltered area.

Further work could also be done on possible disbenefits of shelter barriers, for example: on the use of clothes driers; on any tendency to over-compensate for reduced ventilation by window opening; on any reduced tolerance of decreases in indoor temperatures because of better outdoor thermal comfort. Another disbenefit requiring investigation is the capital and maintenance costs of shelter barriers.

Finally, further work could be done on: how buildings modify the shelter effect; on the effect of shelter barriers on heat loss from buildings; on outdoor thermal comfort; and on modes of transport adopted outdoors (for example bicycles versus buses and cars).

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