RISC Solar and Wind Roof Garden Irrigation Project

Giorgia Franco

Dissertation submitted in partial fulfilment of the requirements
for the award of Degree of Master of Science in Renewable Energy and the Environment

Supervisor: Dr Maria M. Vahdati
School of Construction Management and Engineering
The University of Reading
September 2002

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Abstract

This project is part of an educational sustainable development programme carried out by the Reading International Solidarity Centre (RISC). 12 Solar Photovoltaic modules and a Rutland wind generator were donated to the Centre from a previous demonstration. The aim of this project is to assess the feasibility of using the above equipment to power in the summer, the irrigation system for RISC's roof garden and in the winter, the grey water system for a toilet in the RISC building. The water used will be rainwater collected from the roof garden and adjoining roofs.

The wind and solar resource in the area was analysed in order to establish the system's expected energy output over a year. The water balance was also considered to establish how much water can be collected and if it will satisfy the garden's requirements. It was subsequently possible to suggest two specific pumps that can be used for the system.

The results of this analysis show that the system cannot be standalone. The collectable water will not be enough to satisfy the system's requirements for 6 months of the year. It is also clear that the modules and generator are oversized for the system, and that the wind contribution is significantly smaller than that from the modules. In conclusion, other applications, such as fans for room ventilation, are suggested to make use of the excess energy therefore increasing the system's efficiency.

Acknowledgements

I would like to thank my supervisor Dr M. M. Vahdati and Dr A. E. Wheldon, without whose guidance this work could not have been possible and thanks to Mr T. Orpin for his help in practical matters. I would also like to thank Jessica and Martin at RISC and Mr Simon Wheeler for their time and co-operation and Mr Ken Spiers from the Meteorology Department for providing me with all the data I requested.

I would wish to show my greatest appreciation towards my colleague Emmanuel without whose help some of this work would have not been possible and finally a special thanks to Ana for her moral support throughout this project.

List of figures and tables

1. Introduction

This project is part of a greater initiative called ‘Growing our future’ undertaken by the Reading International Solidarity Centre (RISC), which is a development education centre working ‘with schools and community organisations to raise the profile of international issues and promote sustainable development, equality and social justice’ (25). ‘Growing our future’ consists of an environmental and sustainable development education programme utilising a section of the RISC building roof.

The roof in question needed to be replaced, it was then decided to build a garden on it in order to develop the following educational programmes.

- *Education & awareness-raising relating to sustainable development*
- *Biodiversity*
- *Waste minimisation*
- *Local food initiative*
- *Energy efficiency*

This project will only focus on the energy efficiency component, from its starting point through its development and hopefully to the installation.

Rainwater will be harvested and energy from a small wind generator and 12 solar PV (Photovoltaic) modules will be used to power two pumps, one to pump the harvested water to a header tank and the other to supply the irrigation system for the garden. The harvested water will be used for irrigation only during the summer months, while in the winter the idea is to use the water to flush a toilet in the Café.

Unlike most renewable projects that start from a theoretical idea, which is subsequently developed depending on the available funding, in this case the equipment was available from the start. Twelve 36Wp Newtec PV modules and a 72Wp @ 9.8 m/s Marlec Rutland wind generator were given to RISC after they stopped being used on a project on Caversham Court (21). In this case therefore, it is a matter of trying to make the equipment available serve the purpose of interest, rather than vice versa.

Solar energy has often been used for powering irrigation systems, especially in remote areas. Wind energy has also been widely used for many centuries in connection with water. It is very common in fact to connect a windmill directly to a pump to draw water from wells, which can then be used for irrigation as well as for domestic use, however this approach cannot be used in this case for the following reasons. Firstly, it requires the windmill to be placed directly above the water source, which would be impossible to achieve in this case. Secondly mechanical wind pumping cannot be easily integrated into a hybrid system involving solar power, which is what is aimed at here. Anyhow, the equipment available would not allow mechanical wind pumping because the windmill already contains a generator meaning that the output is electricity.

The idea is therefore to use the modules and the wind generator to produce electricity, which will be fed into battery storage. The batteries will then be utilised to power the two pumps.

The aim of this project was to assess the feasibility of using the PV modules and generator available at RISC to power a water pumping system for irrigation of the roof garden and flushing of the toilet, as part of an educational demonstration programme of sustainable development.

The main objectives were

- To design the irrigation and flushing system using the available equipment
- To assess the feasibility of the proposed system.

2. Literature Review

Water is essential for human life, for domestic use as well as for livestock consumption and crop irrigation, it is therefore no surprise that for many centuries humans have found different ways of making water readily available. At present most water pumping systems are powered by the electricity grid or by petrol/diesel engines and mechanical wind pumping has been widely used since as far back as the 1800s (6). Despite this, over half the population in rural areas of the world still does not have a safe water supply. They cannot use engine-driven pumps because of lack of fuel or servicing labour and the cost of extending the electricity grid is prohibitive. This is why there is interest in developing other ways of pumping water that could potentially solve the problem in remote areas (6). Although mechanical wind pumping is a very good solution in some cases, it has the main drawbacks that it needs regular maintenance and it is not very flexible in terms of location (4). More research however, has been taking place to develop wind-electric and solar pumping systems, which are particularly interesting in remote locations.

In the past twenty years modern high-tech small wind turbines and standard electric pumps have been developed to provide a reliable and cost effective alternative for water pumping. These new turbines (range of 50-10,000 W) have only three or four moving parts, they are strong enough to endure harsh weather conditions and do not require scheduled maintenance, which means that they can operate automatically for operational lifetimes of 20-30 years. They work at variable speed so that they can be easily matched with standard 50 or 60 Hz induction motors for centrifugal or diaphragm pumps (4).

Solar pumping systems have also gained popularity in recent years especially for their location flexibility, which results in price cuts when it comes to raw materials and labour hours by comparison with grid connection costs (16). Solar irrigation systems in particular are very appealing because there is ideal matching of supply and demand.

In a solar system the PV array can be connected directly to the pump, however in order to make use of all the power produced, it is advisable to connect to battery storage (9). This is due to the fact that often, when it is very sunny, the array will produce more power than is required, which will be lost instead of being stored for the times when there will not be enough irradiation to satisfy the irrigation requirements. Also AC pumps require an inverter, which considerably decreases the efficiency of the system and increases the initial costs (7, 11), therefore DC pumps are usually preferred. Both centrifugal and diaphragm pumps can be used; centrifugal pumps are more effective when the head is low and the water requirement is high, while positive displacement pumps are more effective with high heads and small loads (9). On the irrigation side, methods that require low heads and use small amounts of water, such as trickle systems, are to be preferred to other more intensive methods such as sprinklers (11). This is simply because stand-alone irrigation systems are designed to be as power efficient as possible and therefore will tend to use the least energy intensive watering system.

When comparing wind-electric to solar pumping they both have similar advantages over engine powered and grid connected pumping systems. The first advantage is that these systems can be used in remote areas, saving in materials, labour, maintenance and other costs. Secondly, being standalone, they are much easier to install, meaning that even technical amateurs can do it. Thirdly, once they are in place, they are reliable, require low maintenance and last for a long time. This is demonstrated by the fact that the operating costs of solar pumping systems range from 1/30 to 1/3 of those of diesel pumping, depending on the wage level of the country concerned (11). Finally solar and wind pumping systems represent a sustainable solution that is more environmentally friendly than the alternatives (16, 14).

The main problem with these methods is the initial investment required. Solar systems especially, require considerable investment at the start, which affects the overall cost when considered as ‘equivalent annual cost’ over the useful lifetime of the equipment. Assuming a present PV cost of 4 $/W, a trickle irrigation system run on PV was found to be 50% more expensive than the same system run on diesel. The same study also showed that once PV prices will reach 1 $/W, solar pumping will become competitive (11). In small systems that require few PV modules, the investment costs are often lower than those of getting a connection to the grid and the fact that their running costs are very low makes solar preferable to petrol/diesel engine driven pumps. It was also found that for areas with even modest wind resources (>4 m/s), wind-electric pumping systems are a simple and cost-effective alternative to diesel pumps (4).

Overall solar water pumping systems are advisable and most cost-effective for applications with low power requirements and therefore a small water requirement (typically [m^3 of water × m of head] <300 m^4/day) and a minimum monthly average solar irradiation >5 kWh/(d m^2) (9). In particular, there are many successful examples of small solar irrigation systems in Europe, these use trickle water distribution and appear to be a better solution than fuel powered systems. The advantages are both environmental and economical and are most apparent when the system is applied to small crop fields and remote areas (17). Wind electric systems on the other hand, are more cost-effective for higher power outputs. Typically when the water requirements are between 200 and 10,000 m^4/day and the average annual wind speed at 10 m is above 4-5 m/s (4).

Site conditions are critical when considering solar or wind powered pumping systems, however in most cases the remote areas in question have considerable amounts of solar irradiation and the wind resource required for wind-electric systems is modest. Furthermore, more interest and research is going into hybrid wind and solar water pumping systems. This could be a perfect solution in many places where neither of the two resources are enough to fulfil the requirements. In fact, it is often found that wind and solar energy complement one another very well (see Fig. 1), therefore the sum of the two could prove to be enough to power a pump (14).

In this project, the choice of designing a hybrid system, although motivated by the nature of the equipment available, could prove to be the perfect solution, given that Reading is not renowned for being particularly sunny or windy. At the same time, the idea of recycling collected rainwater to use in the irrigation and grey water systems represents a further step towards sustainability that is definitely worth considering, especially in locations where clean drinkable water is scarce.

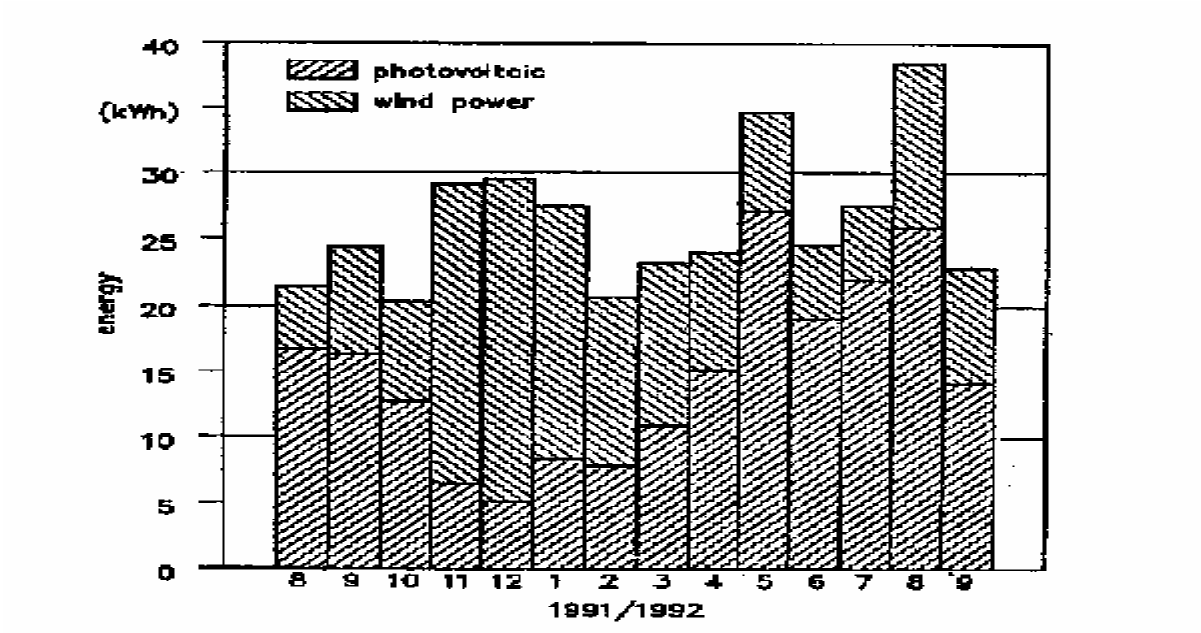

Figure 1. *Energy yield per month of a 220 W PV plant and a 300 W wind driven generator to supply the Daffnerwald Alm in the Bavarian Alps (14)*

3. Equipment testing

Most of the equipment necessary for the system came from a previous project, therefore it needed to be tested to make sure that it was all working to specification.

The equipment available consists of:

- 12 Newtec 36 Wp PV modules (see Appendix 1 for details)
- 1 Rutland 910 wind generator by Marlec (see Appendix 2 for details)
- 1 Solsum 5.6X charge controller
- 2 Delco 12 V 115 Ah deep cycling batteries
- 1 Siemens digital multimeter
- 1 OK 485 PC interface
- 1 Ammeter
- Lengths of DC wiring

9 of the PV modules and the Rutland generator were tested. The rest of the equipment was found to be functioning by the company that will be responsible for the installation.

3.1 PV modules

The test consisted in measuring the current-voltage characteristic for every module and comparing it with the manufacturer's curve. To achieve this, the current and voltage from the module were measured through different levels of resistance, at a constant level of irradiance. The measurements had to be taken quickly to minimise variations in the irradiance.

Equipment

9 Newtec PV modules

1 Variable resistor 0 – 35.6 Ω

1 Sampling resistor 0.005 Ω

1 Potential divider 11.78 and 120 kΩ

1 Campbell scientific CR10X datalogger

1 kipp SP-lite semiconductor solarimeter 14.77 μV/W m^{-2}
Various wiring and connectors

Method

The module was connected in series with the variable resistor and the datalogger was used to log the module voltage and current and the solar irradiance measured with the solarimeter. The voltage was measured across the potential divider connected in parallel with the module (between A and B) and the current was measured through the sampling resistor connected in series (between B and C) as shown in Fig. 2. This was done because the datalogger only measures voltages up to 1000 mV. The potential divider is used to make the measurement one order of magnitude smaller than its true value. The current cannot be measured directly, therefore a sampling resistor was introduced and the voltage measured across it used to obtain the current.

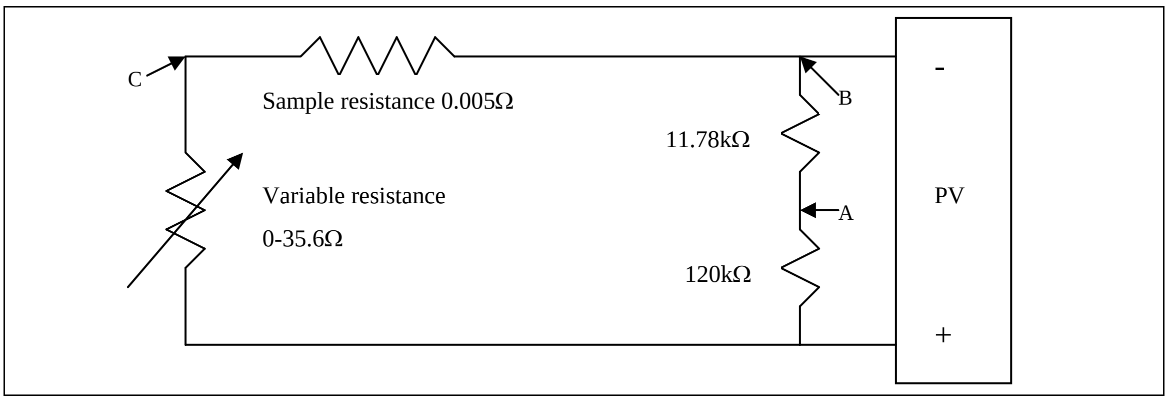

Figure 2. *PV logging system circuit*

The datalogger was programmed to take measurements of the three variables stated above every 1/8 of a second as described in Appendix 3.
The experiment consisted in exposing one module at a time to sunlight, connecting it to the circuit and varying the resistance from 35.6 to 0 Ω. The resistance could be varied over a period as short as half a minute in order to have as little variation as possible in the incoming solar radiation.

The process was repeated three times for every module in order to have the possibility to choose the cycle with the most constant irradiance (Fig. 3).

Figure 3. *PV module testing on the Engineering Department roof*

Once the data was collected, it was converted in values of irradiance, voltage and current using calibration constants that were calculated at the start of the experiment as described in Appendix 3.

It was then possible to choose the data set with the least variation in solar irradiance and plot current against voltage to obtain the I-V characteristic for each module. The experiment was carried out once on a sunny day and once on a cloudy day to obtain results at two different levels of irradiance.

Results

The measured I-V curve was plotted on the same graph as the manufacturer's curves at set irradiances to draw some comparisons. The curve for one of the modules is shown in Fig. 4. The curves for the other modules are given in Appendix 4.

From Fig. 4 it is clear that the module in question seems to behave as expected with an I-V envelope which is consistent with the manufacturer's information, however both the current and the voltage appear to be lower than what they should be. The lower current can be explained by a natural decrease in efficiency with use, which will be more apparent at higher levels of irradiance. The open circuit voltage (predicted x-axis intercept) should be 14.5 V but in the tests it was only measured to be about 12 V, this is probably due to temperature. The manufacturer's data is in fact obtained at 25°C, which is probably different from the temperature at which the experiment was carried out. An attempt was made, during the sunny day experiment, to measure the temperature on the back of each module using a thermocouple. However the readings obtained did not make sense, maybe the thermocouple was not functioning properly or the new logger program was incorrect.

The I-V characteristics of all the other modules show the same features as described above and despite the temperature issue, all the modules appear to be working properly and therefore can be used for the system.

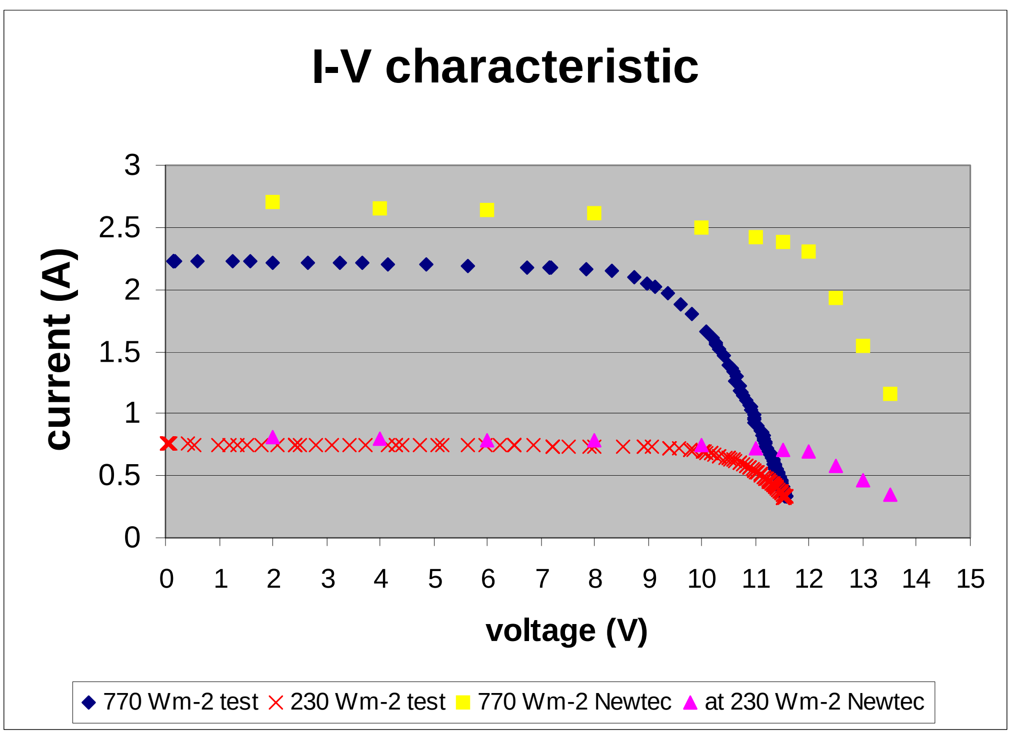

Figure 4. *I-V characteristic for module 1*

3.2 Rutland wind generator

The generator was set up outside on the Meteorology Field Site and connected to charge a battery. This location was chosen because it is where wind speed and direction measurements are taken every 5 minutes. The current and voltage from the wind-charger were measured in order to plot current against wind speed and power (obtained as current × voltage) against wind speed and compare these graphs with those obtained from Marlec.

Equipment

1 Rutland 910 wind generator on a 1.79 m stand

1 12 V 75 Ah deep cycling battery

1 Sampling resistor 0.005 Ω

1 Potential divider 11.78 and 120 kΩ

1 Campbell scientific CR10X datalogger

Various wiring and connectors

Method

The generator was connected to the battery, the sampling resistor was connected in series to measure the current across it (between B and C) and the potential divider was connected in parallel with the battery to measure the voltage (between A and B) (Fig. 5).

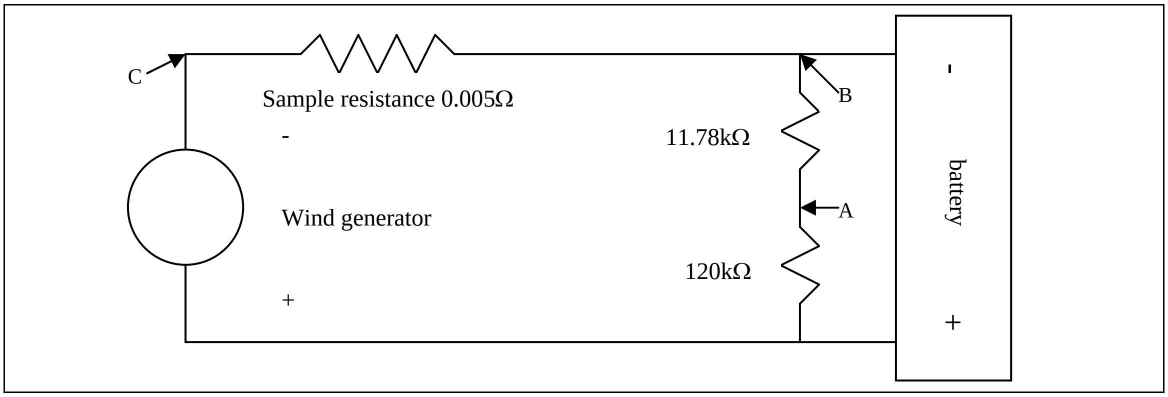

Figure 5. *Rutland logging system circuit*

A new program for the datalogger was written as described in Appendix 3, so that it would take measurements every second and average them every minute.

Wind speed data in 5 minute intervals at a height of 10 m was obtained from the Meteorology Department and converted to what would be expected at 1.79 m assuming $speed \propto height^{1/7}$. The current and voltage data recorded in the datalogger were then averaged over the same 5 minute intervals as the wind data making it possible to plot a graph of current and power against wind speed. The experiment was carried out for 5 days between the 25th and 30th of June 2002, which gave a total of 1,582 points that could be plotted against wind speed. The full graphs are shown in Appendix 5, these however show a significant amount of scatter because of the great variability of wind speed with time. In order to compare the experimental results with the manufacturer's data only a few points were taken from the two graphs, as shown in Fig. 6 and 7.

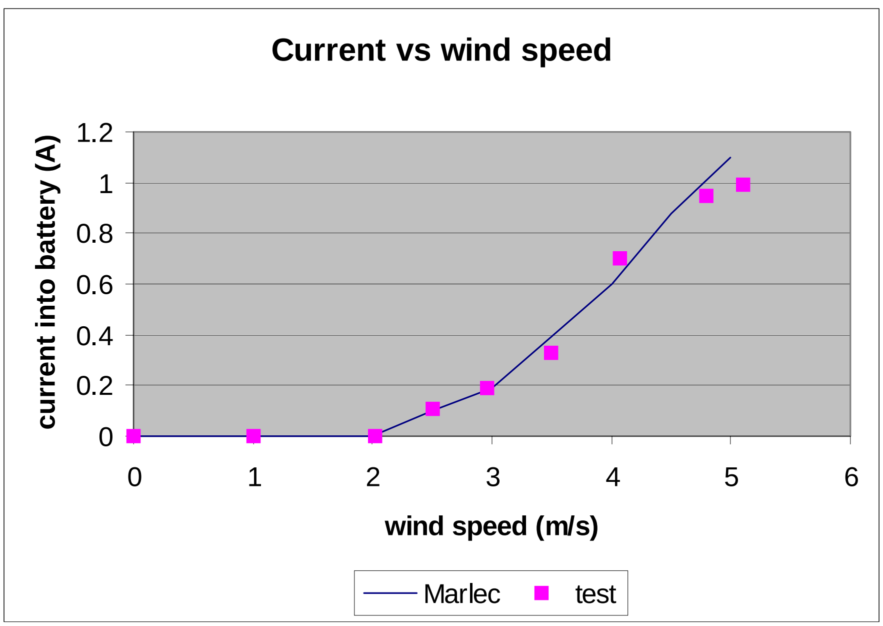

Figure 6. *Current vs. wind speed*

Results

From Fig. 6 and 7 it is clear that the experimental results are very similar to the manufacturer's information. There is some scatter, which depends on a combination of experimental error due to the system used to collect the data and a human error while reading the values from the graphs provided by Marlec. The manufacturer's graphs in

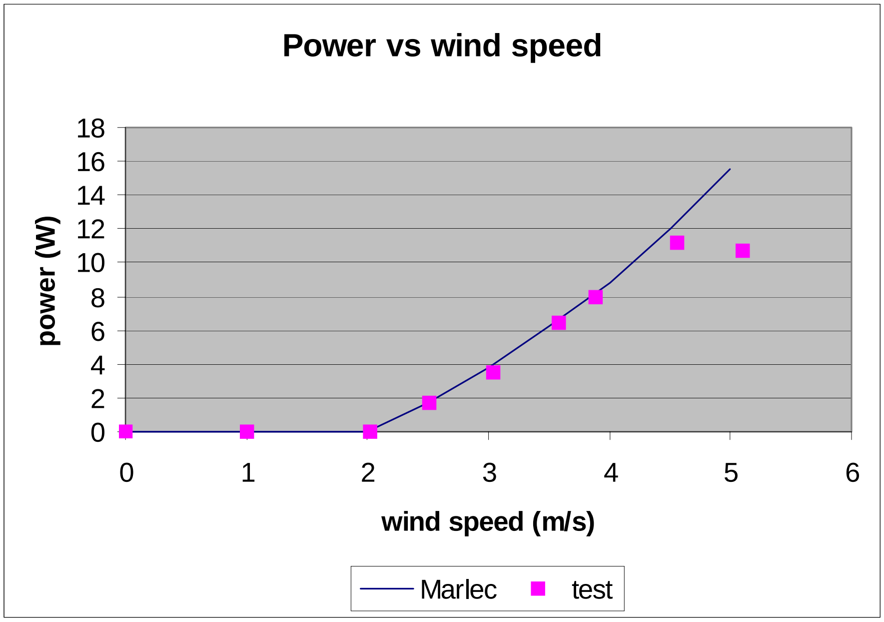

Figure 7. *Power vs. wind speed*

fact, do not have very high resolution and the measured wind speeds did not exceed 5 m/s, reading errors will therefore be more significant because the actual values are small. The scatter is also partly influenced by the variation in the terminal voltage of the battery, however this was not measured during the experiment therefore it is impossible to assess to what extent it influences the results.

Overall, it is possible to say that the generator is working to specification and can therefore be used for the irrigation system.

4. Meteorological data collection and analysis

In order to assess the energy output that can be expected from the PV array and from the wind generator when installed it was necessary to assess the solar and wind resource on site. This meant obtaining information on wind speed and direction and on solar irradiance (total and diffuse) for the Reading area.
Given that the Meteorology Department runs a weather station on the University Whiteknights Campus, which is not very far from the roof garden, this appeared to be the best source for meteorological data to use. Values for the above variables measured in 5 minute intervals were obtained for the whole of the year 2001. However, one year of data would not be a representative sample on which to base the design of the system, therefore long term average data was required. This was obtained for a time period of 30 years (1971-2000) however it was only possible to obtain monthly average wind speed values and monthly average hours of bright sunshine. This information had to be converted into a form that could be used for predicting the system's energy output.

To assess the amount of rainwater that can be collected to use for the irrigation system it was also necessary to obtain rainfall and evaporation data for the area. 30 year monthly average rainfall values were obtained from the Meteorology Department, however evaporation is not measured on campus and had to be calculated.

4.1 Solar data

In order to calculate the amount of electrical energy produced it is necessary to know the solar irradiation hitting the surface of the PV modules. The 30 year average data in hours of bright sunshine was converted using approximate relationships as shown in Appendix 6, in order to obtain monthly average irradiation values on the module's surface.
The results of this analysis are shown in Fig. 8.

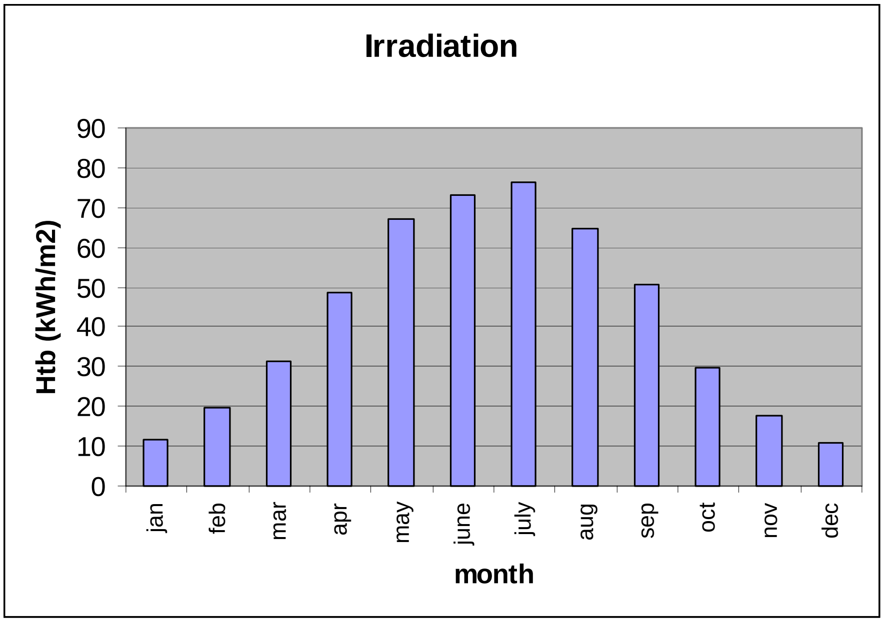

Figure 8. *Solar resource on the module surface (see Appendix 6 for actual data)*

4.2 Wind data

Wind speed is constantly varying and a wind generator produces a different amount of power depending on the speed to the power of three therefore, in order to assess how many Joules are produced in a given period, it is necessary to know the frequency distribution of the wind speed. The best solution would be to have long term wind data measured in short time intervals because, as for any statistical analysis, the greater the data set, the better the distribution. However this information is very rarely available and usually only one year of data measured in short intervals (every few minutes) is considered.

The 30 year average data was only available in the form of monthly averages, therefore the 5 minute 2001 data was used. This may be done in the assumption that the actual distribution of wind speeds at a given site does not vary significantly from year to year. The monthly average wind speeds for 2001 were compared with the 30 year averages to check that 2001 was not significantly different from the average (Fig. 9).

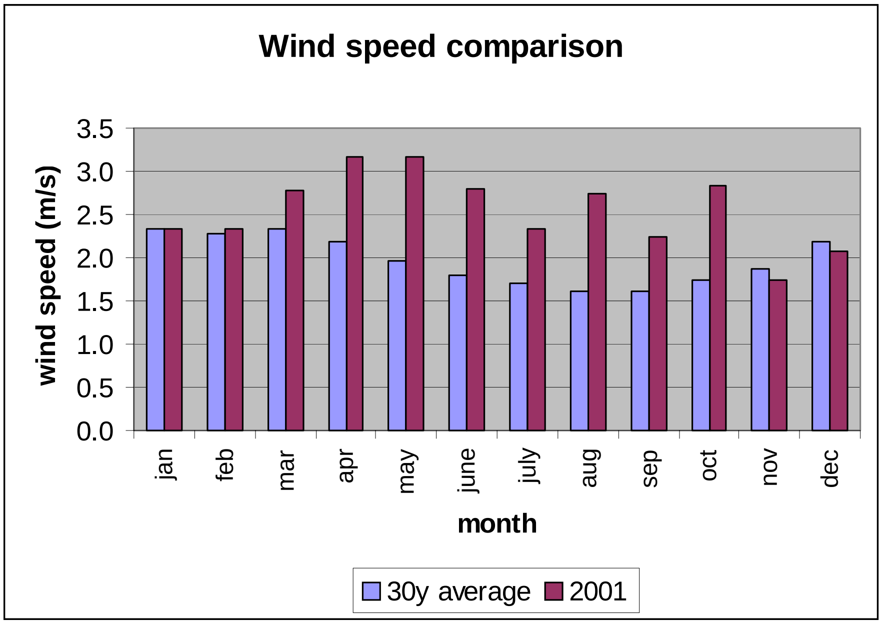

Figure 9. *Average monthly wind speed comparison*

From Fig. 9 it is clear that 2001 was windier than average, the difference is especially considerable between March and October. However there was no other choice but to use the 2001 data for the analysis, therefore it will have to be remembered, when analysing the results, that they will be an overestimation of what could be expected over an average of 30 year.

A full description of the statistical analysis can be found in Appendix 7, the result of which is shown in Fig. 10.

The calculated Weibull distribution was compared with the frequency distribution of the actual data, which shows that the two curves are very similar. It is therefore reasonable to use the Weibull distribution to assess the energy produced by the generator.

The energy pattern factor *ke* defined as $\left(\overline{u^3}\right)/\left(\overline{u}\right)^3$ was also calculated and its value was found to be 2.25. This shows that the measured values fit reasonably well a Weibull distribution given that the value of *ke* corresponding to a shape factor k = 1.7 (as in this case) on the *ke* vs. k graph for a Weibull distribution is 2.3, which is very close to the

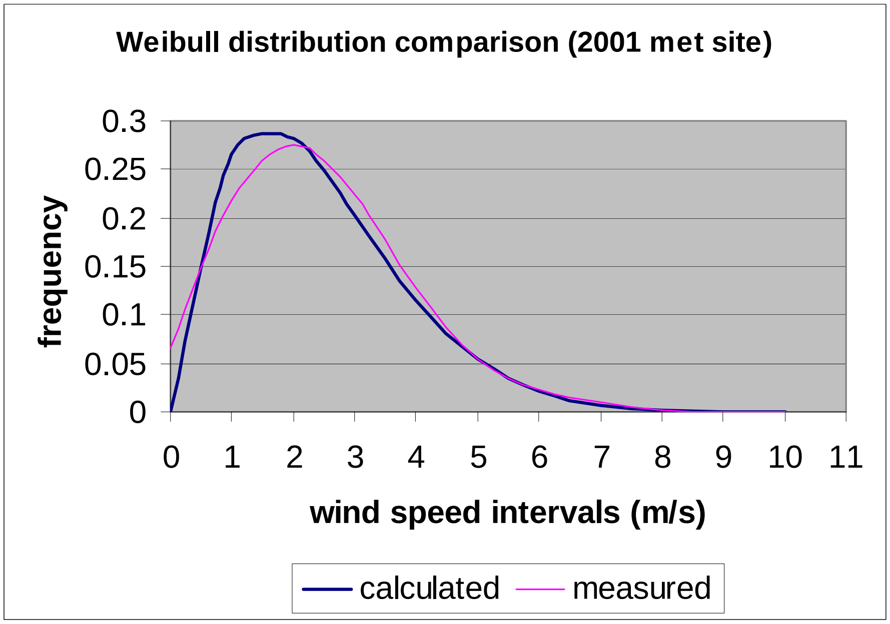

Figure 10. *Measured and calculated wind speed frequency distribution for Reading (10 m hub height)*

value calculated (5). This same analysis was carried out for each month of the year 2001, in order to enable the calculation of the generator's monthly energy output.

A frequency analysis of the wind direction was also done to establish the main wind direction in Reading (Fig. 11).

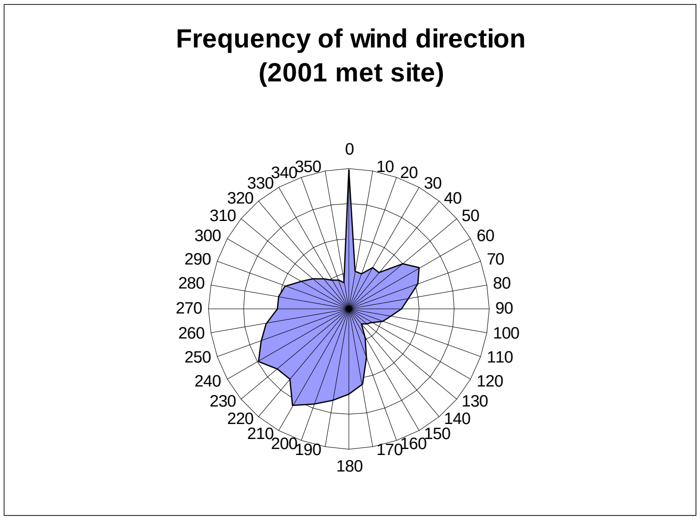

Figure 11. *Wind rose for Reading 2001*

This however is not very significant in this instance given that there is only one location where the generator can be installed, irrespectively of predominant wind direction.

In the same data set maximum wind speed in 5 minute intervals were considered to make sure that the wind generator would withstand gusts. The maximum ever wind speed recorded in 2001 was found to be 20.8 m/s, which is within the limitations set by the generator’s manufacturers (18).

4.3 Hydrological data

Water collected

The 30 year average monthly rainfall values were available, however monthly values for evaporation had to be calculated using a computer model called CROPWAT available in the Soil Science Department. In order to run the model it is necessary to input monthly average values for the following variables: mean daily temperature, rainfall, hours of bright sunshine, wind speed and relative humidity. All of these variables were available from the Meteorology Department and were again 30 year averages, it can therefore be assumed that the results from the model will be reasonable estimates of 30 year average evaporation on a bare soil surface in Reading.

The garden surface will actually be covered by vegetation, this means that the evaporation rate will be higher than that calculated over bare soil because the plant leaves significantly increase the area over which evaporation can occur. Typically if the precipitation is 550 mm, on a vegetated soil an evaporation of 450 mm can be expected, while on a bare soil it would be about 350 mm (15). It is however very difficult to estimate evapotranspiration (evaporation from soil and plant surface) therefore the analysis here will have to be done using bare soil evaporation.

The runoff from the roof garden surface was calculated for each month of the year, assuming that the amount of water retained in the soil will remain constant throughout the year.

$$RUNOFF(mm) = RAINFALL(mm) - EVAPORATION(mm) \quad (1)$$

The runoff values in millimetres were multiplied by the surface area of the roof garden in m^2 to give the total amount of water running off the roof in litres.

The adjoining roofs were then considered. Their surface, not being covered in soil, will have a much lower evaporation, which was assumed to be on average only 30% of the water precipitating. 70% of the mm of rainfall for each month were then multiplied by the projection on the horizontal of the surface in m^2 of the adjoining roofs from which the guttering can be extended to the collection tanks, to give the water collected in litres.

The water from three hand basins in one of the offices' toilets could also be collected. In this case it was assumed that each basin is used 10 times a day for an average time of 7 s at a water flow rate of 0.25 l/s, therefore the amount of water collected could be calculated as follows:

$$water(l) = \left(0.25(l/s) \times 7(s)\right) \times 10 \times 3 \quad (2)$$

The three components mentioned above were added together to give the total amount of water collected each month.

Water required

The irrigation water requirement for each plant in the garden in the summer was given by RISC to be 0.5 l/day.

Knowing that there are 250 plants in the garden, and given that the irrigation is going to be drip fed to each plant, the total water requirement was calculated as:

$$plant.req(l) = 0.5(l/day/plant) \times 250(plants) \times month(days) \quad (3)$$

The natural irrigation was calculated assuming that each plant would directly absorb the rain falling on a surface of 10 cm^2 surrounding it.

$$nat.irrigation(l) = rain(mm) \times 0.01(m^2) \times 250(plants) \quad (4)$$

This was subtracted from the amount of water available for runoff. The water required for artificial irrigation could then be calculated.

$$irr.needed(l) = plant.req(l) - nat.irr(l) \quad (5)$$

In the winter, the toilet was assumed to be a water saving one that uses 5 l per flush. It was also assumed that it will be used on average 50 times/day, so the average monthly water requirement will be:

$$water.needed(l) = 5(l/flush) \times 50(flush/day) \times days/month \quad (6)$$

The values of water collected and required for each month were plotted together to show the overall water balance of the system (Fig. 12).

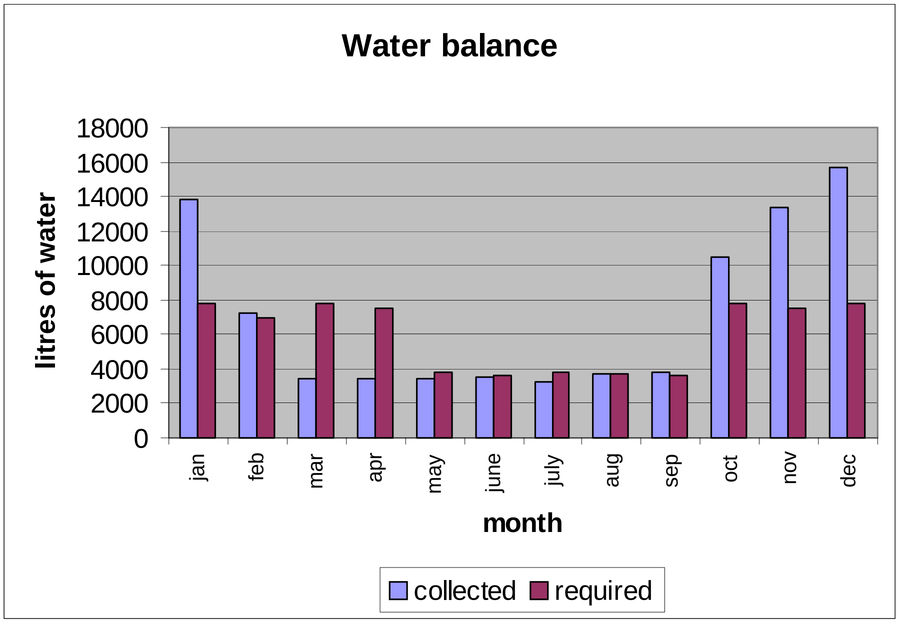

Figure 12. *Comparison between amount of water required and amount available from collection (see Appendix 8 for actual data)*

From this graph it is clear that, a part from September, during the irrigation period (May-Sep.), the water required is always slightly greater than the water collected. This means that the irrigation system will never fulfil the plant water requirements. The balance is only slightly negative most of the time (with exception of July), therefore only a small amount of water will have to be obtained form a mains supply, which is already available on the roof.

In the winter the collected water is much greater because the evaporation does not exceed the rainfall over the garden, therefore runoff can be obtained from a greater surface area. The water collected will be used to feed a toilet in the Café, however even in this case for March and April the amount collected will not be enough to satisfy the requirements. The toilet will also have to be connected to the main grey water system.

A separate analysis of the roof garden and the adjoining roofs + the hand basins showed that between March and September no water is collected from the garden because the evaporation is too high, therefore all the water collected comes from the adjoining roofs and the basins. In the winter however, the contribution from the garden is vital (Fig. 13 and 14).

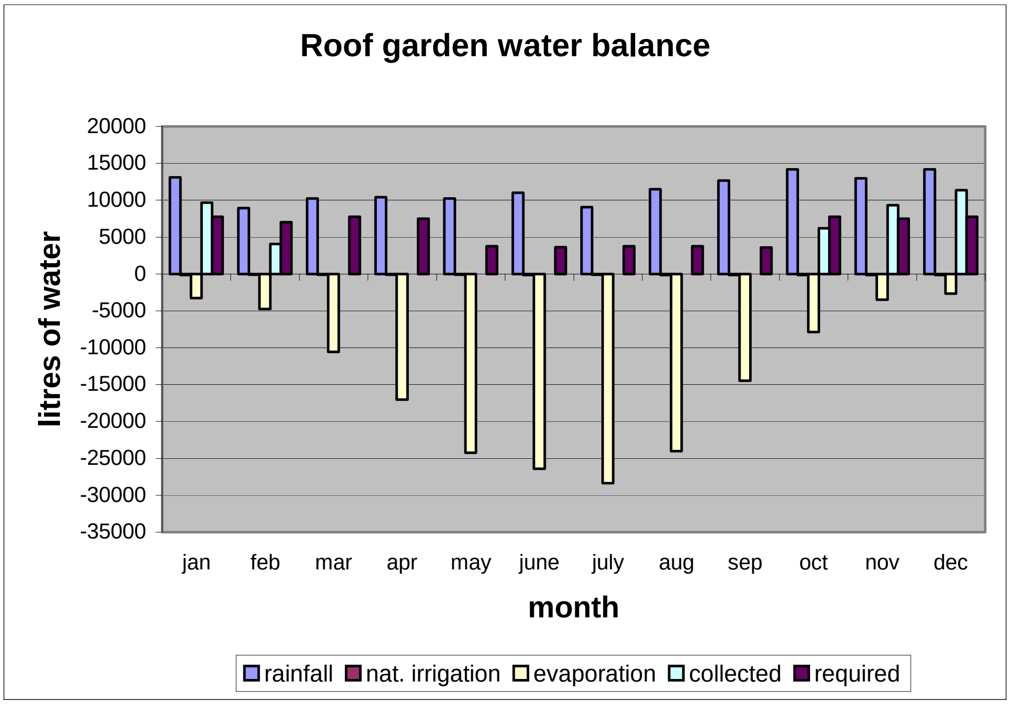

Figure 13. *Garden roof water balance (see Appendix 8 for actual data)*

Although this analysis showed that the irrigation requirements could not be completely fulfilled by the harvested water, RISC decided to go ahead with the idea accepting the fact that there will be the need for backup from the mains supply from time to time.

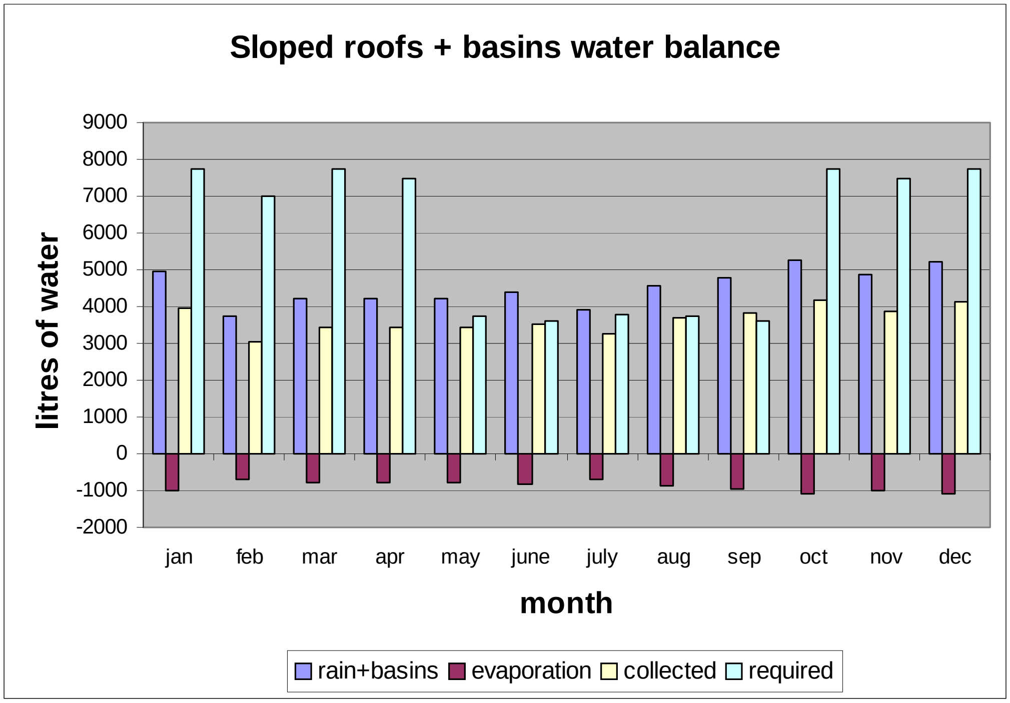

Figure 14. *Sloped roofs and basins water balance (see Appendix 8 for actual data)*

5. Energy output

5.1 Solar output

Once the average solar irradiation incident on the modules' surface was calculated, it was possible to calculate the theoretical energy output of the PV array.

Each module has a Watt peak rating of 34 Wp therefore the array of 12 modules will have a rating of 34×12 = 408 Wp. From this the rated energy output can be calculated as follows:

$$output(Wh) = rating(Wp) \times irradiation(kWh/m^2) \qquad (7)$$

In order to account for losses in the system, such as connection losses, battery charge/discharge losses etc, a performance ratio for the system has to be considered. This can be assumed to be 55%. Therefore the new formula will be:

$$output(Wh) = rating(Wp) \times irradiation(kWh/m^2) \times PR = 408 \times H_{t\beta} \times 0.55 \qquad (8)$$

The results of these calculations are plotted in Fig. 15.

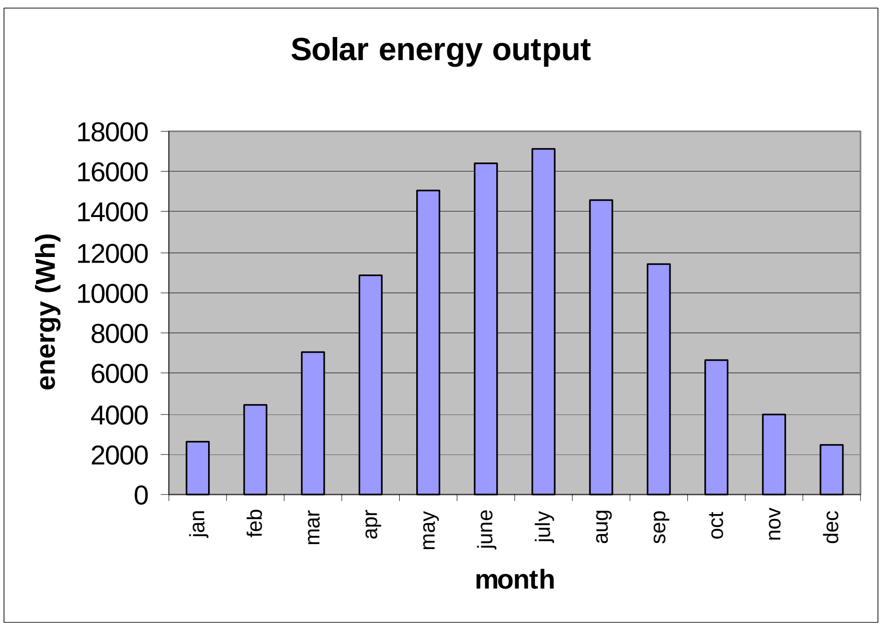

Figure 15. *Potential energy output from the solar system (see Appendix 9 for actual data)*

This calculation was carried out on the assumption that none of the modules ever experience any shading.

It is evident that this plot has a very similar shape to that of the irradiation in Fig. 8. This is expected given that the amount of energy generated by the modules is directly dependent on the amount of solar irradiation hitting their surface.

5.2 Wind output

The frequency values for each wind speed interval calculated from the Weibull distribution in Section 4.2 for each month were converted into number of hours/month during which each wind speed occurred. For the same speeds the rated power output of the generator was read off the power envelope supplied by Marlec (Appendix 2).

The energy output for each month could subsequently be calculated as follows:

$$output(Wh) = \sum_{u=0}^{n} P_u(W) \times t_u(h) \qquad (9)$$

where u is the wind speed interval

P_u is the rated power at a given wind speed and

t_u is the frequency in number of hours for which the wind speed is within u.

In order to make the monthly output comparable with that calculated for the solar system it was necessary to consider losses in battery charge/discharge. A reasonable assumption for this was considered to be a loss of about 25%.

The results in Fig. 16 show that the wind energy output can vary significantly from month to month, without a specific trend. The very low values obtained for April, September and December however, can be explained by the fact that in these months the data was not complete. For example, in the whole of September only 7 days were available for the analysis. Overall, there is significant variation from month to month but the trends do not necessarily reflect those found when looking at the monthly average wind speeds (Fig. 9). This can be explained by the fact that although a gust can significantly increase the average speed, it does not necessarily increase the energy

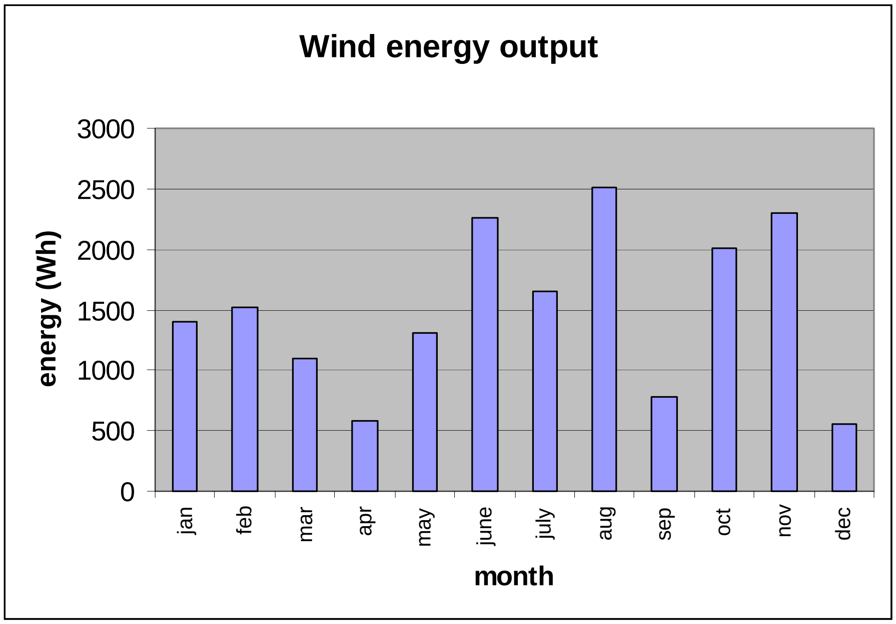

Figure 16. *Potential energy output from the wind system (2001 data) (see Appendix 9 for actual data)*

output accordingly. The annual output was also calculated and found to give an average of 1163 Wh/month, which is consistent with the monthly results.

It is clear here that even in a windy month, the generator will only produce about 2 kWh, which is just about as much as the lowest monthly PV array output. This is because most of the time, the wind speed ranges between 0 and 3 m/s. Therefore for a lot of the time the generator will not be producing any power because it does not start generating until the wind speed is above 2 m/s. Once it is considered that 2001 was windier than average, the significance of the wind component in the long term decreases even more.

5.3 Total output

The sum of the solar and wind output for each month gives the total output that could be expected from the system on average (Fig. 17). When looking at the two components, it appears very clear that the solar contribution is far greater than the wind contribution and it is responsible for the trends in output throughout the year, as shown by the shape of Fig. 17. The output will range between 2 and 18 kWh a month, with the maximum being in July and the minimum in December.

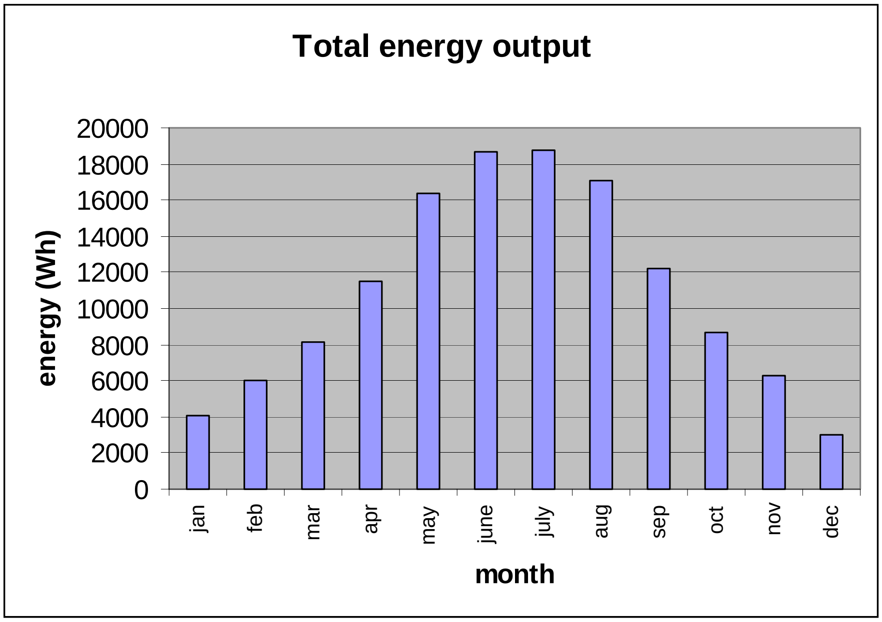

Figure 17. *Total potential energy output (see Appendix 9 for actual data)*

It has to be remembered however, that the data used for the wind analysis refers to 2001 while the solar analysis is based on 30 year averages. In addition, the wind output will be much more variable, from year to year, than the solar output. However the fact that the solar contribution is far greater than the wind component, means that the analysis is still worthwhile, despite these inaccuracies.

6. Pump specifications

A first pump is for displacing water from the collection to the header tanks. A second one is for delivering the water from the header tanks to the plants. A diagram of the system is shown in Fig.18.

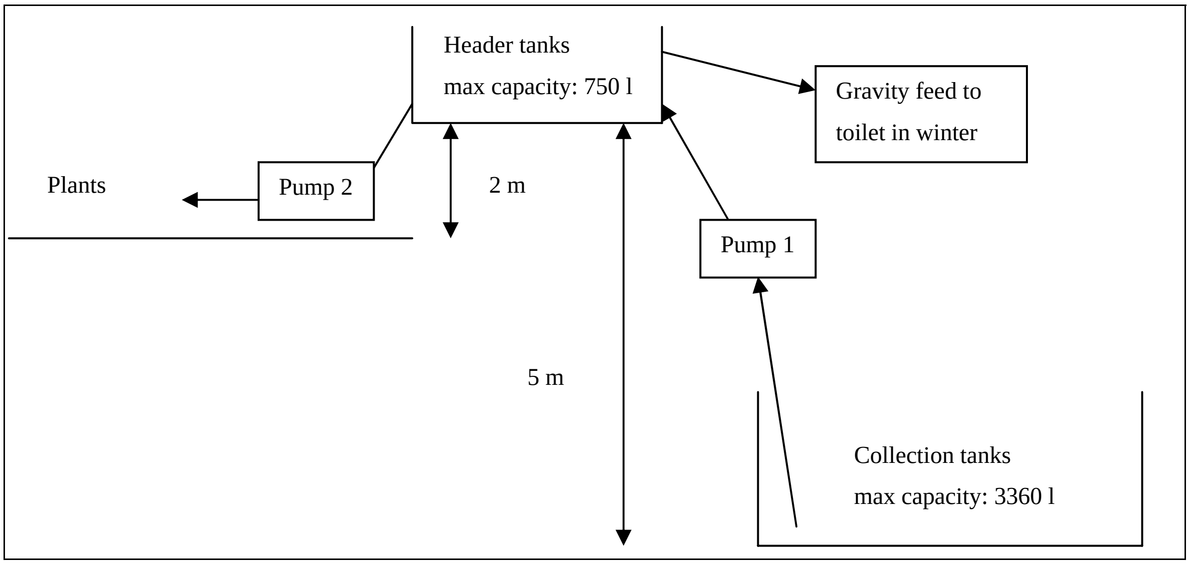

Figure 18. *Pumping system diagram*

The storage capacity for pump 2 was limited to 750 l because two header tanks were already available. This is a reasonable size given that it will allow a six days autonomy for the irrigation system during the summer:

$$autonomy = \frac{750(l)}{125(l/d)} = 6days \quad (10)$$

It is usually suggested to account for 3 to 7 days autonomy when designing an irrigation system (12), therefore this case is within the range. During the winter, if the tanks get filled completely every day, the storage will allow for 150 flushes per day, which appears to be plenty for a single toilet.

$$flushes = \frac{750(l)}{5(l/\ flush)} = 150 \quad (11)$$

The collection tanks capacity was limited by the surface available for their location. The idea was to use a number of standard garden water butts connected together to limit costs. The space allocated to the collection tanks has a surface area of about 10 m^2 about 3.5 of which are occupied by a ladder. Assuming that a standard 210 l water butt (22) occupies a surface area of 0.4 m^2, 16 butts could be used:

$$butts = \frac{(10-3.5)(m^2)}{0.4(m^2/butt)} = 16.25 \qquad (12)$$

The total collection capacity will be 16×210 l = 3360 l. Such a capacity is not enough to collect all the water available in very wet periods, however these only occur very occasionally so the loss is not too significant. Using daily data it was calculated that in the year 2001 the collectable water exceeded 3360 l for only 7 days (2% of the year). A cumulative calculation was also carried out taking into account that in a rainy day not all the collected water is pumped to the header tank and there is therefore some left to be added to that collected the next day. In this more realistic situation it was found that for 29 days (8% of the year) the collectable water exceeded the tanks' capacity.

Although these calculations could only be based on the year 2001 and were carried out under a number of assumptions (see Section 7.1), they are still very useful. In fact they show that although the tanks' capacity is not enough to collect all available water, it is still sufficient for over 90% of the year.

6.1 Collection to header tanks

The parameters that are known and are to be considered in the choice of this pump are as follows.

- The pump will have to work on DC current and at 24 V.
- The static head is 5 m (Fig. 18), an estimated 10% is added to take into account for friction losses in the pipe (dynamic head), therefore the total head will be 5.5 m.
- The maximum amount of water to be pumped in a day is 750 l, required to fill the header tanks when it is empty.
- The minimum energy available to the pump is that calculated in Section 5.3 for December and it is equal to 2,980 Wh.

In Section 2 it was found that for low head requirements centrifugal pumps are to be advised, therefore this was the type that was considered. Although various pumps designed for solar pumping systems fitted our requirements, in order to contain costs the market for recreational vehicles and boats was preferred and the following solution was found.

AMAZON centrifugal/in-line pump LVM(24V) 117

At 24 V it runs at 1.5 A meaning that it has a power requirement of 24×1.5 = 36W

It works at a range of 0 to 10 m head and at a flow between 0 and 18 l/min. It is manufactured in the UK and costs £36.14 (24).

Full specifications given in Appendix 10.

From the above specifications and our requirements it was possible to calculate if the energy output from the solar array and wind generator would satisfy the pump's requirements.

At a head of 5.5 m the pump will run at a flow of 8.2 l/min so the time that it will have to run for to pump the maximum daily water requirement will be:

$$time(h) = \frac{750(l)}{8.2(l/m)} \times \frac{1(h)}{60(m)} = 1.5h \qquad (13)$$

so the energy required in a day will be:

$$output = 36W \times 1.5h = 54Wh/day \qquad (14)$$

however the pump will not be 100% efficient. An estimated efficiency of 75% can be considered, therefore the energy required will be: 54/0.75 = 72 Wh/day.

Even if for the whole of December the pump were to work at its maximum, which is a considerable overestimation,

$$output_{\max} = 72W \times 31days = 2232Wh < 2980Wh \qquad (15)$$

the maximum energy required will be less than the minimum energy available suggesting that the pump requirements do not exceed availability.

In conclusion the chosen pump appears to be sized well for the system since it is big enough to satisfy the flow and head requirements without exceeding the energy availability.

6.2 Header tanks to plants

A second pump has to be used to satisfy the requirements of the irrigation system given that the 2 m head does not produce enough water pressure to reach the end of the 31 m long garden. The system is drip fed, meaning that each plant is watered singularly, which is ideal here because it is very water efficient and it minimises energy requirements.

The specifications for the irrigation system were as follows:

- Each dripper delivers water at 2 l/hour.
- The ideal water pressure required to water the 31 m long garden is 30 psi (2 bar).

In this case the pump is used to increase the pressure of the water going through it, therefore pressure booster pumps were considered. The requirements that had to be met were as follows:

- The pump will have to run on DC current and at 24 V.
- It will have to run at 30 psi.
- The maximum amount of water to be delivered in a day will be 125 l of plant water requirement plus 25%, which represents the estimated losses in the system (13). The total will be 156 l.
- The minimum energy available to the pump is that calculated in Section 5.1 for September and it is equal to 12,181 Wh minus what is used for pump 1, given that this pump will only be used during the summer (May to September) together with pump 1.

Again the solution was found amongst the pumps used for recreational vehicles or small marine applications:

WHALE UNIVERSAL UP1225 24 V

The pump is manufactured in the UK and costs just over £70 excluding VAT (27). Full specifications given in Appendix 10.

This pump at 24 V can run at a pressure of 30 psi and at a current of 2.5 A (28). The power requirement will be 24×2.5 = 60 W. In these conditions the flow rate will be 3 l/min therefore the time it will have to run for to deliver the required water will be:

$$time(h) = \frac{156.25(l)}{3(l/m)} \times \frac{1(h)}{60(m)} = 0.87h \quad (16)$$

so the rated energy required in a day will be:

$$output = 60W \times 0.87h = 52.2Wh/day \quad (17)$$

assuming a 75% pump efficiency the energy required will be: 52.2/0.75 = 69.6 Wh/day.

If for the whole of September the pump were to work at its maximum, which is a considerable overestimation,

$$output_{\max} = 69.6W \times 30days = 2088Wh \quad (18)$$

Even assuming that in the same month pump 1 were also used at its maximum, the maximum energy required would still be less than the minimum energy available.

$$output_{\max} = 2088Wh + 2232Wh = 4320Wh < 12181Wh \quad (19)$$

This assumption is contradictory because it would mean that at the same time there would be maximum rainwater collected as well as maximum irrigation required, which is impossible, given that they complement each other. However it is just to demonstrate that it can be safely expected that the pump requirements will always be satisfied by the system.

7. System design

The solar system will consist of 4 strings in parallel, each of 3 PV modules in series. This arrangement will allow the highest charging efficiency as well as meaning that if one of the modules fails, only its string will fail and not the whole array. The wind generator will be in parallel with the PV array and they will both charge the two batteries, connected in series. The batteries are then used to power the two pumps that are connected in parallel so they can run at different currents. Fig. 19 shows the circuit diagram of the electrical side of the system.

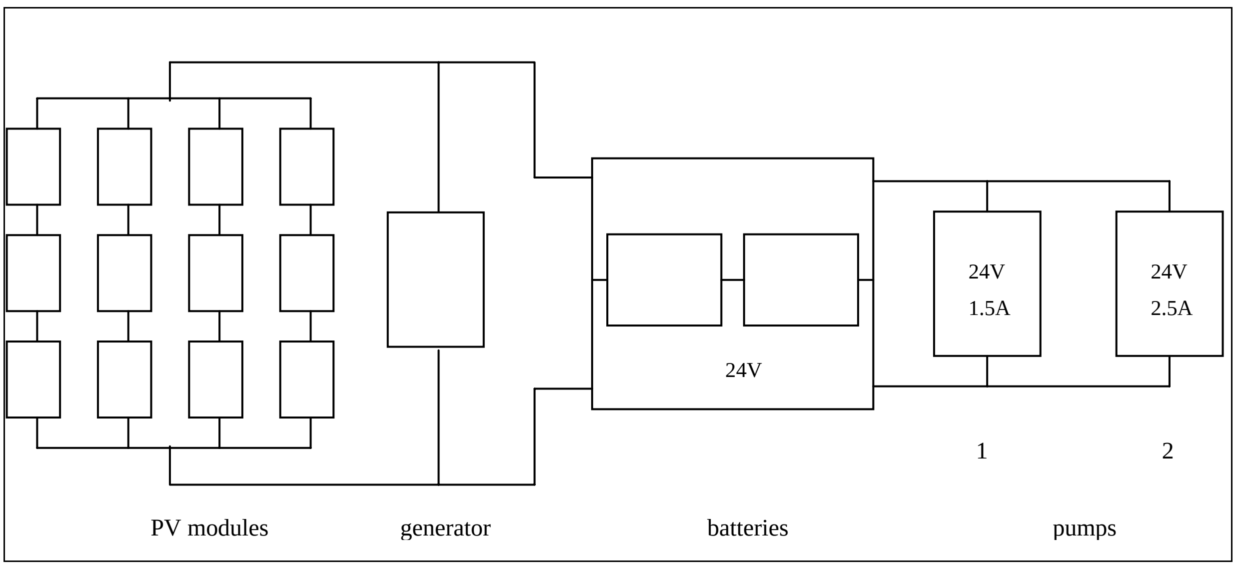

Figure 19. *System diagram*

This component and the hydraulic component (Fig. 18 in Section 6), are very much dependent on each other. On an average summer's day enough water has to be collected and enough energy has to be produced to charge the batteries. The batteries will then power the first pump and the water pumped to the header tanks will be distributed to the plants by the second pump. However each day is not independent from the next.

During rainy times only part of the collected water will be pumped to the header tanks there will therefore be some left in the collection tanks to be added to that collected the next day. In the same way the charge in the batteries will not be all used every day, some days there will be some left, while some days the modules will produce more energy than can be stored and it will therefore be lost.

In order to assess if the system would withstand these day to day alterations a model was written to simulate what would happen during a year's operation. This was done only taking into account the solar component for simplicity, given that the wind contribution is not very significant for most of the year. To account for the wind energy a day by day statistical distribution of the 5 minute data would have been required. This would have been very time consuming with little gain given that the smaller the time period, the more inaccurate the Weibull approximation and consequently the daily output results.

7.1 Day to day simulation

The starting point was chosen to be daily data for the year 2001 for the number of hours of bright sunshine (N), the total irradiation on the horizontal (H_{th}) and the millimetres of rainfall.

The same steps described in Sections 4.1 and 5.1 were followed to calculate the array energy output for each day of the year in Wh. Knowing that the system runs on 24 V and assuming a battery charging/discharging efficiency of 75% it was possible to calculate the charge going into the batteries daily.

$$charge(Ah) = \frac{P(Wh)}{24(V)} \times 0.75 \qquad (20)$$

In order to calculate the amount of water collected and required it is necessary to know the daily evaporation rate. The same monthly average values from Section 4.3 were used. This is a very rough approximation given that the evaporation rate will vary significantly from day to day depending on amount of rainfall, temperature and many other variables. However this was the only available solution at the time.

The runoff and the total water collected each day were calculated following the same procedure as in Section 4.3.

The next step was to calculate the amount of water that is needed to satisfy the plant requirements. Each plant requires 0.5 l of water per day, some of which will be satisfied by natural rainfall. The artificial irrigation required each day was calculated as in Section 4.3. 25% was subsequently added to account for losses in the irrigation system (as explained in Section 6.2) to give the total water to be collected daily to satisfy the plant requirements.

During the winter it is assumed that on average the toilet will be flushed 50 times a day and therefore at 5 l/flush the water requirement will be of 250 l/day.

The next step was to connect each day to the day before to account for 'leftovers'.

Starting on the first day of the year with empty collection tanks, all the water will be collected up to a maximum of 3,360 l (max. capacity). Of this, up to 750 l will be pumped to the header tanks. The difference between what is collected and what is pumped will represent what is left in the collection tanks and can be added to what is collected the next day and so on for the whole year. Knowing the amount of water pumped, the flow rate and power requirements of pump 1, the energy used each day to pump water from the collection to the header tanks was calculated as in Section 6.1.

The water pumped by pump 1 represents what is available for irrigation during the summer and for toilet flushing in the winter. In the summer, each day the water pumped by pump 2 will be all of that in the header tanks, if this is less than the plant requirements. If there is more water available, only the required amount will be pumped. What is not used (for irrigation or flushing, depending on the season) will remain in the header tanks and has to be considered when calculating how much water can be pumped by pump 1. The amount of water pumped for irrigation each day together with the flow rate and power requirements of pump 2 allow to calculate the amount of energy used each day for the irrigation during the summer months (see Section 6.2). This can be added to that used by pump 1 to give the total daily energy requirement of the system throughout the year, which can be compared with the amount available from the batteries.

The two batteries have 115 Ah charge capacity, however because they are connected in series their capacity will be half that: 57.5 Ah. Assuming a depth of discharge of 50% the charge available for use will vary from 0 to 28.75 Ah.

Assuming that on the first day the batteries are fully charged, the energy available for use will be: charge(Ah)×24(V). This minus the energy used for pumping on that day will be the energy left in the batteries. Dividing this by 24 V and considering 75% battery charge/discharge efficiency will give the leftover charge. This can be added to the charging obtained on the next day up to a maximum of 28.75 Ah because above that the charge controller will cut in.

The results of this thorough simulation showed very clearly what already appeared to be the conclusion of the monthly analysis, which is that the limiting factor of the irrigation system is the amount of water that can be collected.

The balance between actual water pumped and irrigation and toilet requirements shows that for 44.5% of the year there is not enough water available to satisfy the requirements. In Fig. 20 it is shown that the deficit is varying between 0 and 100 l during the summer and between 0 and 200 l in winter. The number of days in which there is a deficit however, are mostly clustered together during dry periods.

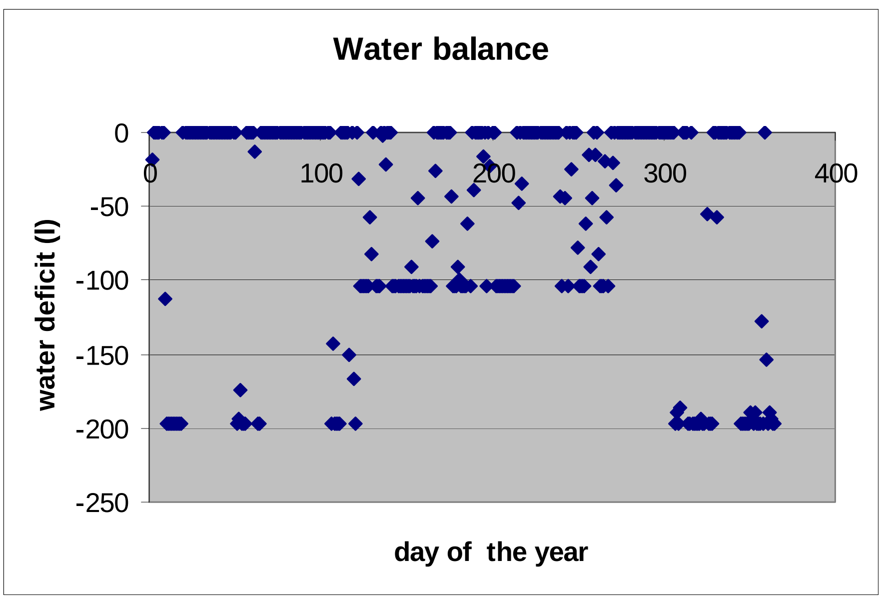

Figure 20. *Water balance for 2001*

From Fig. 20 it is also apparent that the water deficit occurs more often in the irrigation system. In this case, for 61% of the summer there is a water deficit, while in the winter the deficit occurs only 33% of the time.

This model also shows that the energy produced by the array is more than enough to fulfil the pump requirements. This is demonstrated by the fact that during most of the year the batteries are fully charged as shown in Fig. 21.

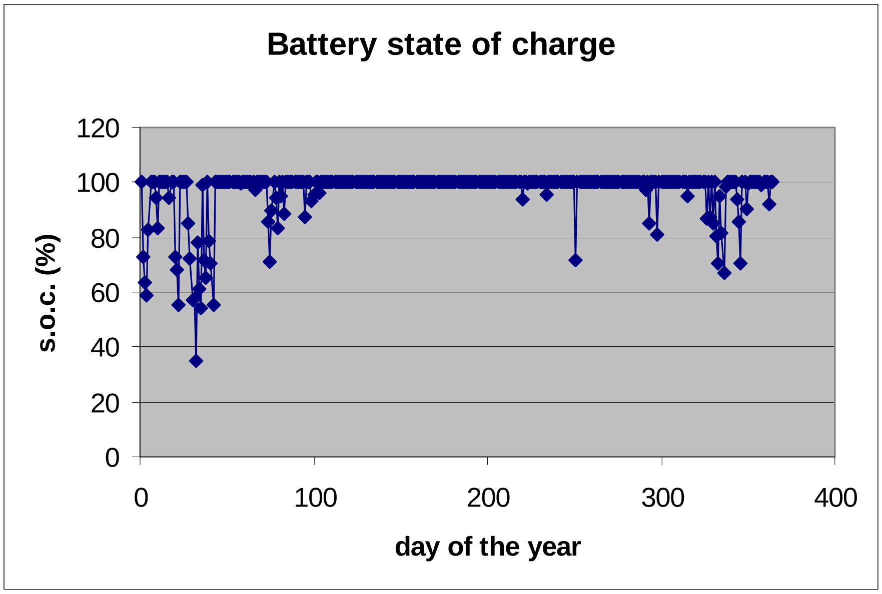

Figure 21. *Battery daily state of charge*

A copy of the model is given in Appendix 11.

7.2 Limitations and improvements

Throughout the analysis of the system that was carried out in this project many assumptions had to be made and many calculations were based on approximate formulas. Efficiency values for the modules, batteries and pumps were assumed, however the main reasons for inaccuracy are due to the meteorological data used. In many instances there were gaps in the data sets that had to be filled by averaging, however the time period over which the data was recorded is the main issue.

The solar irradiation values calculated using 30 year monthly average data (Section 4.1) are significantly lower than those obtained in the simulation carried out for the year 2001 (Section 7.1). This could be because 2001 was a much sunnier year than average, but more probably the difference lies in the analysis. The calculations to obtain irradiation are integrated over time, it is therefore understandable that the smaller the time interval the more accurate the result. In order to assess the magnitude of this variation the irradiation for July 2001 calculated in the simulation was compared to that obtained using 5 minute irradiance measurements. It was found that the latter was 68% greater than the former. This difference can only be attributed to the mode of calculation and it strongly suggests that the monthly values calculated in Section 4.1 are an underestimate of the real irradiation.

In the case of the wind data analysis, the shortfalls of using only one year's data have already been discussed in Section 4.2.

In the water analysis the main problem was the evaporation rate. The values obtained from the CROPWAT model were satisfactory for the monthly analysis however they are the major shortfall of the daily simulation. The daily evaporation values used are probably a considerable overestimation of the real evaporation rate.

The best way to carry out a more thorough analysis would be to run the day by day model over 30 years and obtain measured values of evaporation. This however would require a huge amount of raw meteorological data, which in this instance was not available.

In conclusion, the energy produced by the array and the amount of water collected in reality would probably be higher than predicted. Overall however, the results obtained from the monthly analysis are consistent with those obtained from the day by day simulation suggesting that despite the inaccuracies, the main findings are correct.

7.3 Practical issues

At the time of installation there are also various practical issues that need to be addressed. In Section 3.1 it was noted that the lower open circuit voltage recorded during the testing was probably due to temperature. This issue will have to be addressed after installation (although it is not ideal). Another aspect that needs addressing is if any shading will occur on the installed array. If this is the case, the amount of irradiation lost because of it should be assessed, for example via a simulation programme such as PVSyst.

On the electrical side, control systems will have to be in place to ensure that both pumps are pumping only when required and that pump 2 is working at the required current and flow rate.

Some sort of water filtering will have to be in place at least in the collection tanks to avoid the pump being clogged by any kind of debris.

In addition, the collection tanks will all be connected together so that the water level will be the same in all of them. However, given the significant variation in amount of collected water throughout the year there is the issue that when it does not rain very much, there will be little water distributed in all the butts. It will therefore be impossible to harvest even the little water available. A way of tackling this problem could be to position the butts at different levels, with the ones furthest away slightly higher up, so that when there is little water it will flow downwards by gravity to the butt where the pump and the collection point are located. However standard water butts do not have the tap right at the bottom, therefore the water contained between the bottom and the level of the tap in each butt will never be harvested. In order to solve this, a hole would have to be made at the bottom of each butt and used to do the connection. Otherwise the possibility of using a different type of tank could also be investigated although this might increase costs.

8. Discussion

8.1 System feasibility

The aim of this project was to assess the feasibility of using the equipment available at RISC for the garden irrigation system. To achieve this a preliminary system was designed and its feasibility subsequently assessed.

Once it was established that the equipment was working to specification, the first step was to assess the availability of the main resources for the irrigation system. This consisted in establishing the amount of solar irradiation and wind speed available on site as well as the amount of water that could be collected. It was then possible to calculate the amount of energy obtainable from the PV array and the wind generator. With the above information and the plant water requirements two pumps were chosen for pumping the water up to the header tanks and for delivering it to the plants.

This preliminary analysis was mainly based on 30 year average data measured on the university campus and it was carried out on a monthly basis. The months used for sizing the system in the winter (when only pump 1 will be in operation) and in the summer (when both pumps will be operating) were December and September respectively. These were in fact calculated to be the months with the highest loads on the system.

The analysis showed first of all that the energy produced by the wind generator was significantly smaller and much more unpredictable than that produced by the solar array. The PV array is the major energy source and alone it was found to produce enough energy for the system. Even assuming that each day pump 1 would pump enough water for a six day, the sum of the two outputs is still sufficient to run the system.

The analysis however showed that the water collected from the various surfaces available, will not always be enough to satisfy the system's requirements. In the winter there will be enough water to flush the toilet in the Café except for March and April. In the summer, the water collected will satisfy the irrigation requirements only in September, while between May and August there will always be a deficit.

A second more thorough analysis was subsequently carried out using daily data for the year 2001, but only considering the solar component. A model was constructed to simulate the day by day variations in the battery state of charge, the collection and header tanks water level and consequently the amount of water available for pumping.
The results of this second analysis emphasised with more accurate results what was already found during the first one. For 44.5% of the year there is a water deficit, which is the limiting factor for the system's operation given that the energy is never running short.
RISC are aware of the system's limitations and accept the fact that, at times, connection with the mains will be required. Despite this, they will go ahead with the installation.

8.2 Potential improvements

The results show that the system is not sized to its maximum efficiency because of the initial arrangement. The starting point is using the donated equipment to satisfy the irrigation and toilet flushing systems while ideally the equipment should be chosen subsequently, to fulfil the desired requirements. The idea of using recycled rainwater for irrigation is not completely achievable in practice because there simply is not enough water available. In addition, the PV array and generator are oversized for the system's requirements. Despite this, the system can still be installed successfully as an educational tool even though it will not be standalone.
Given that the energy produced exceeds the requirements, in order to increase efficiency additional applications should be considered.
At the beginning of the project there were talks of doing a small water feature in the garden to attract local wildlife, this could be a possibility if RISC were still interested. A more attractive alternative could be installing some fans in the Café that can be connected to the system. An average ceiling fan has a wattage of 60 W (23), given that during the summer about 600-650 Wh will not be used every day (see simulation), two of such fans could be used for up to 5 h a day. It has to be considered however that the fans run on AC current therefore an inverter would be required. Even if the inverter were to cut the energy available by 50% (which is an overestimation), there would still be a couple of hours worth of ventilation a day. This would be a very good demonstration since it would

be in the Café for everyone to see and it would also be coupled well with the availability of excess power. The array will in fact produce large amounts of power during sunny days that will most probably also be hot and therefore require ventilation.

Other sources of water could be found to achieve a standalone system. All the easily accessible roof surfaces surrounding the garden have already been considered, however on the opposite side of the header tanks, relative to the collection tanks, there is a roof that could be used for collection. In this case however, another small pump would be required because this roof is at a lower level than both the header and collection tanks.

More elaborate solutions could be found but these would probably significantly increase costs. For example in arid regions, air water collectors are often used. These are simple devices that condense water out of the atmosphere, however they need a large surface area and it would be difficult to find an appropriate location for them on the roof (20).

8.3 Further applications

It was stated in Section 2 that solar and wind irrigation systems are already wide spread in agriculture and this study demonstrates that they can also be successfully applied on a much smaller scale.

Although the system designed here is not perfectly sized, the idea behind it is very valuable and could be developed further on an even smaller scale. An average terraced house garden, consisting mainly of lawn and a few flowerbeds could probably be irrigated satisfactorily by a system similar to the one described here. A single water butt could be used to collect rainwater and a correctly sized PV module could produce enough to power a small drip irrigation system. In such a situation the system would probably work more effectively without battery storage given the perfect coupling between solar resource and irrigation requirements.

On the other hand, on a large scale hybrid solar-wind irrigation systems could prove to be very successful. The solar component would produce energy when the water needs to be delivered to the plants during dry periods, while the wind component would probably produce more energy when it rains and water needs to be collected and pumped to a storage tank.

9. Conclusions

This investigation has shown that the PV modules and the wind generator available produce more than enough to power the system of interest, even though the wind contribution is much smaller than that of the PV. This is why it was suggested that other applications be connected to the system in order to use most of the energy produced and increase the overall efficiency. The limiting factor for the functioning of the system will be the amount of water collected, making it impossible for the system to run totally independently from the water mains.

The calculations carried out to assess the feasibility of the system had to be based on a series of assumptions and approximations, which, to some extent, could be minimised if the meteorological data available were more specific. However very often, when sizing such systems, the data available is less specific than what was used here. Despite the estimated nature of the analysis however, the results are very useful to show what can be expected from the system once it will be in operation.

The hybrid system analysed here could prove to be of interest both on a smaller as well as larger scale, however the site considered must have enough sun as well as wind resource to make the choice economically viable. It is also advisable to do the analysis starting from what the water requirements are and subsequently choosing the PV modules and wind generator to match them rather than vice versa.

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Appendices

Appendix 1

Appendix 2

Appendix 3

Campbell datalogger CR10X software programmes used for the testing of the equipment.

PV testing

A new software was used and it took my colleague Emmanuel A. Essah and myself three days to write a functioning programme. A channel was assigned to each variable and its corresponding connecting position on the datalogger was established, together with the range of mV required. Subsequently a command to carry out the measurement was introduced, setting the output flag to high. Each variable was sampled after setting a storage area for the measurements.

```
;{CR10X}
;
*Table 1 Program
  01: 0.125     Execution Interval (seconds)

1:  Volt (Diff) (P2)
 1: 1        Reps
 2: 13        25 mV Fast Range
 3: 1        DIFF Channel
 4: 2        Loc [ irrad     ]
 5: 1.0       Mult
 6: 0.0       Offset

2:  Batt Voltage (P10)
 1: 3        Loc [ battery   ]

3:  Volt (Diff) (P2)
 1: 1        Reps
```

2: 15 2500 mV Fast Range
3: 2 DIFF Channel
4: 4 Loc [voltage]
5: 1.0 Mult
6: 0.0 Offset

4: Volt (Diff) (P2)
1: 1 Reps
2: 13 25 mV Fast Range
3: 3 DIFF Channel
4: 5 Loc [current]
5: 1.0 Mult
6: 0.0 Offset

5: Do (P86)
1: 10 Set Output Flag High (Flag 0)

6: Set Active Storage Area (P80)
1: 1 Final Storage Area 1
2: 25 Array ID

7: Real Time (P77)
1: 111 Day,Hour/Minute,Seconds (midnight = 0000)

8: Sample (P70)
1: 1 Reps
2: 2 Loc [irrad]

9: Sample (P70)
1: 1 Reps

```
 2: 3        Loc [ battery   ]

10:  Sample (P70)
 1: 1        Reps
 2: 4        Loc [ voltage   ]

11:  Sample (P70)
 1: 1        Reps
 2: 5        Loc [ current   ]

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

Wind generator testing

This was done in the same way as for the PV testing but an averaging function was also introduced. The execution interval was set to 1 second and once the channels were defined and the flag was set to high, a function to average every channel over a minute was introduced. The storage area was set and the command to sample the averages was introduced.

```
;{CR10X}
;
*Table 1 Program
  01: 1.0       Execution Interval (seconds)

1:  Batt Voltage (P10)
```

1: 1 Loc [battery]

2: Volt (Diff) (P2)
1: 1 Reps
2: 15 2500 mV Fast Range
3: 2 DIFF Channel
4: 2 Loc [voltage]
5: 1.0 Mult
6: 0.0 Offset

3: Volt (Diff) (P2)
1: 1 Reps
2: 13 25 mV Fast Range
3: 3 DIFF Channel
4: 3 Loc [current]
5: 1.0 Mult
6: 0.0 Offset

4: If time is (P92)
1: 0 Minutes (Seconds --) into a
2: 1 Interval (same units as above)
3: 10 Set Output Flag High (Flag 0)

5: Set Active Storage Area (P80)
1: 1 Final Storage Area 1
2: 17 Array ID

6: Real Time (P77)
1: 110 Day,Hour/Minute (midnight = 0000)

7: Average (P71)

```
 1: 1        Reps
 2: 1        Loc [ battery   ]

8:  Average (P71)
 1: 1        Reps
 2: 2        Loc [ voltage   ]

9:  Average (P71)
 1: 1        Reps
 2: 3        Loc [ current   ]

10:  Sample (P70)
 1: 1        Reps
 2: 1        Loc [ battery   ]

11:  Sample (P70)
 1: 1        Reps
 2: 2        Loc [ voltage   ]

12:  Sample (P70)
 1: 1        Reps
 2: 3        Loc [ current   ]

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

Calibration constants

The calibration constant for the solarimeter was given by the manufacturer. The voltage calibration was obtained by reading simultaneously the computer screen and the voltage across the potential divider using a voltmeter. The current calibration was obtained by reading simultaneously the voltage on the computer screen and the current across the sampling resistor using an ammeter. The ratio between computer and meter readings would give the calibration constants. Three measurements were made for each constant and the average of these was used.

The measurements divided by the constants (Tab. 3.1) gave the actual readings. In the voltage case, the readings had to be multiplied by 10 to account for the potential divider.

Test	Voltage	Current
PV	0.998 V/V	0.158 A/mV
Wind	0.989 V/V	0.311 A/mV

Table 3.1. Calibration constants

Appendix 4

Appendix 5

Appendix 6

The variable that needed to be calculated was $H_{t\beta}$, the total solar irradiation on a surface of slope β, which is the angle of inclination of the PV modules. In this case β will be 45° and the modules will be South facing. In order to obtain this variable a series of calculations had to be carried out in steps as shown in Fig. 1 below.

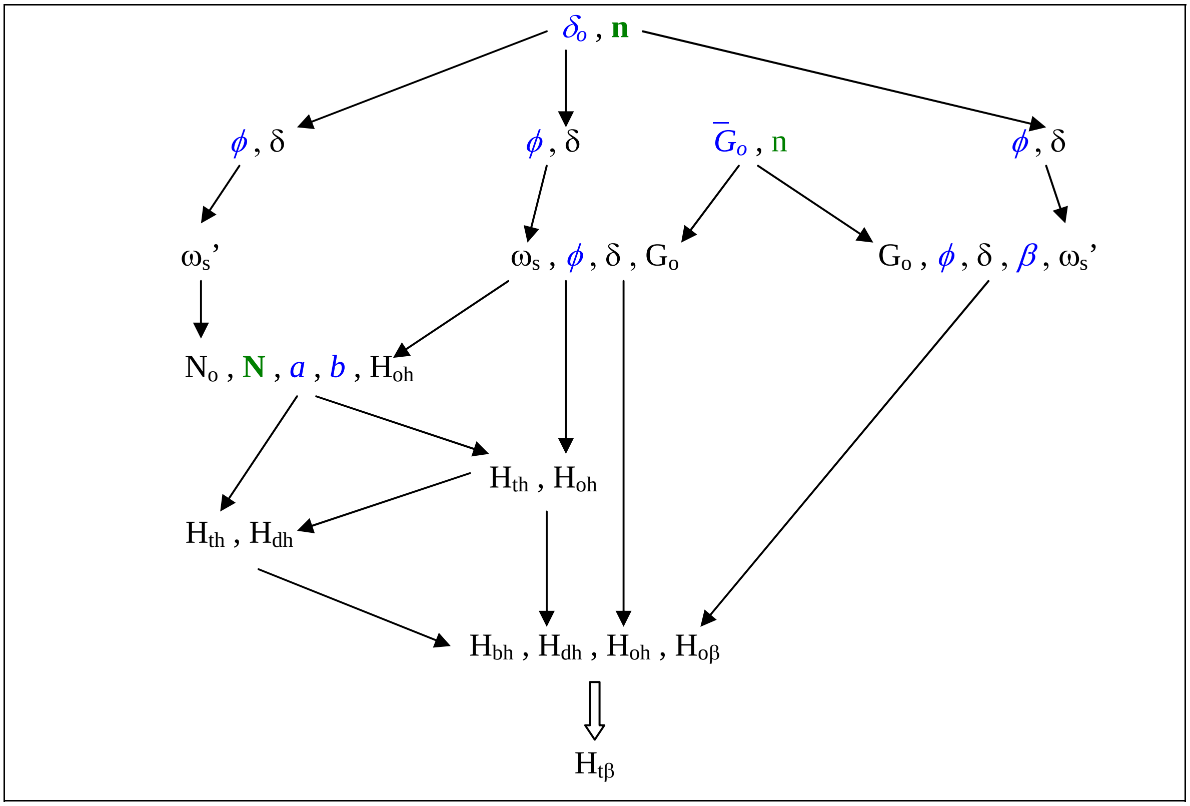

Figure 1. Steps to calculate $H_{t\beta}$

All symbols in Fig. 1 are explained below.

Constants (italics values):

δ_o is the tilt of the axis of the Earth relative to the orbital plane and it is equal to 23.46°

ϕ is the latitude, which in Reading is 51.5°

$\bar{G}_o$ is the solar constant and it is equal to 1370 W m^{-2}

β is the slope of the modules and it is equal to 45°

a and b are the Angstrom coefficients (different for each month of the year) and they are calculated from a nearby site that has both measurements of total irradiation and hours of bright sunshine. In this case these coefficients were obtained from a site in Bracknell, which is only about 17 km away from Reading (8).

The bold symbols are the measurements obtained from the Meteorology Department: N is the number of hours of bright sunshine and n is the day of the year starting to count from January 1st.

The symbols in black had to be calculated as follows.

$$\delta = \delta_o \sin[360°(284 + n)/365] \qquad (1)$$

is the declination angle.

$$G_o = \overline{G_o}[1 + 0.033\cos(360° n / 365)] \qquad (2)$$

is the extraterrestrial beam irradiance depending on the time of year.

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta) \qquad (3)$$

is the sunset or sunrise hour angle for a horizontal surface.

$$\omega_s' = \cos^{-1}(-\tan\phi \tan\delta) \quad \text{(winter)} \qquad (4)$$

$$\omega_s' = \cos^{-1}(-\tan(\phi - \beta)\tan\delta) \quad \text{(summer)} \qquad (5)$$

is the sunset or sunrise hour angle for a sloped surface. These are then used to calculate the solar time at which the sun rises and sets:

$$t_{solar} = \frac{\pm \omega_s'(rad)}{(\pi/12)} + 12 \qquad (6)$$

$$N_o = t_{sunset} - t_{sunrise} \qquad (7)$$

is the maximum possible number of hours of bright sunshine.

$$H_{oh} = (86400 G_o / \pi)(\cos\delta \cos\phi \sin\omega_s + \omega_s \sin\delta \sin\phi) \qquad (8)$$

is the total irradiation at the top of the atmosphere on the horizontal (ω_s has to be in radians).

$$H_{th} = H_{oh}\left[a + b\left(\frac{N}{N_o}\right)\right] \qquad (9)$$

is the total irradiation at ground level on the horizontal.

$$H_{dh} = H_{th}\left[0.75 - 0.60\left(\frac{H_{th}}{H_{oh}}\right)\right] \quad (10)$$

is the diffuse component of irradiation on the horizontal.

$$H_{bh} = H_{th} - H_{dh} \quad (11)$$

is the beam component of the irradiation on the horizontal.

$$H_{o\beta} = (86400G_o / \pi)(\cos\delta\cos(\phi - \beta)\sin\omega_s' + \omega_s'\sin\delta\sin(\phi - \beta)) \quad (12)$$

is the total irradiation at the top of the atmosphere on an inclined surface (again the hour angle has to be in radians).

So finally,

$$H_{t\beta} = H_{bh}\left(\frac{H_{o\beta}}{H_{oh}}\right) + H_{dh} \quad (13)$$

is the total irradiation at ground level on an inclined surface (20).

Equations 1 to 8 and 12 were calculated for 3 days in each month and averaged to give a single average value per month. These were then used to calculate a monthly value of the other variables to finally give the monthly values of $H_{t\beta}$ as shown in Tab. 1 below.

Month	***$H_{t\beta}$ (kWh/m^2)***
January	11.83
February	19.86
March	31.40
April	48.57
May	67.28
June	73.29
July	76.21
August	64.87
September	50.80
October	29.76
November	17.60
December	10.82
Total	502.29

Table 1. Solar resource on the module surface

Appendix 7

A reasonable full statistical description of wind data can be given by the Weibull distribution, which can be described by the following formula.

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (1)$$

where *f(u)* is the probability that the wind has a given velocity *u* and *k* and *c* are the shape and scale parameter respectively.

$$F(u) = 1 - \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (2)$$

The cumulative version of the Weibull distribution shown in Eq. 2 defines the probability that the wind speed is less than u and can be used to determine *c* and *k* for a particular data set.

The 5 minute 2001 data from the Meteorology Department was found to vary between 0 and 9.7 m/s. Eleven wind speed intervals were then considered: form 0 to 0.5 m/s, from 0.5 to 1.5 m/s and so on up to 9.5-10.5 m/s. Then the frequency with which the wind speed was found to be within each interval was calculated. It was subsequently possible to calculate ln[-ln(1-F(*u*))] and plot it against ln(*u*). The slope of this graph gave the value of *k* and the intercept was –*k*ln(*c*), making it possible to obtain *k* and *c* for the given data set (10). Once these parameters were calculated it was possible to calculate the Weibull distribution of wind speed for Reading.

Appendix 8

Total monthly water balance

Month	collected	required
	l	*l*
January	13649	7750
February	7114	7000
March	3450	7750
April	3429	7500
May	3454	3758.5
June	3539	3624.75
July	3243	3772
August	3678	3744.25
September	3829	3606.25
October	10331	7750
November	13197	7500
December	15497	7750

Monthly water balance on the garden

Month	rainfall	evaporation	collected
	l	*l*	*l*
January	13112	3278	9685
February	8910	4752	4056.75
March	10230	10582	0
April	10406	17028	0
May	10252	24222	0
June	11022	26400	0
July	9064	28380	0

August	11506	24002	0
September	12650	14454	0
October	14190	7854	6174.75
November	12958	3498	9312.75
December	14168	2662	11345

Monthly water balance on adjoining roofs + basins

Month	**rainfall**	**evaporation**	**collected**
	l	*l*	*l*
January	4965.1	1001.28	3963.82
February	3738	680.4	3057.6
March	4231.5	781.2	3450.3
April	4223.8	794.64	3429.16
May	4237.1	782.88	3454.22
June	4380.6	841.68	3538.92
July	3934.7	692.16	3242.54
August	4556.3	878.64	3677.66
September	4795	966	3829
October	5239.5	1083.6	4155.9
November	4873.4	989.52	3883.88
December	5233.9	1081.92	4151.98

Appendix 9

Monthly rated output

Month	**Solar (Wh)**	**Wind (Wh)**	**Total (Wh)**
	30 year data	*2001 data*	*solar + wind*
January	2655	1403	4058
February	4457	1519	5975
March	7046	1091	8137
April	10899	577*	11477
May	15098	1314	16412
June	16446	2261	18707
July	17102	1649	18750
August	14557	2515	17072
September	11400	781*	12181
October	6678	2010	8688
November	3949	2305	6255
December	2428	552*	2980

* these particularly low values are due to insufficient data

Appendix 10

Appendix 11

File name of simulation model: model.xls