HYBRID SYSTEMS PROJECT: DEMAND ANALYSIS AND COST-BENEFIT ANALYSIS

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September 1998
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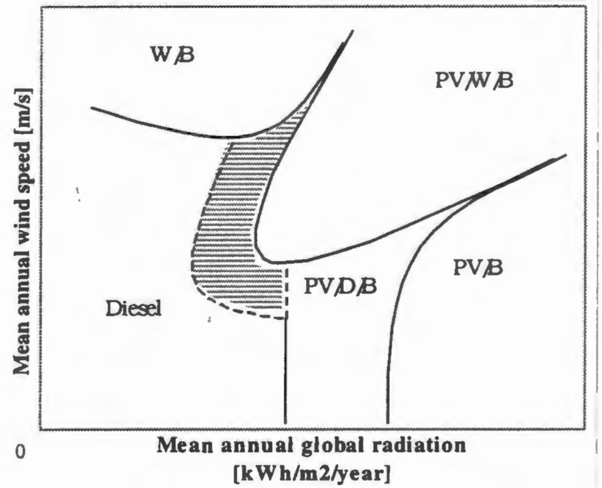
EXECUTIVE SUMMARY

The aim of this report is to investigate the financial and economic suitability of various hybrid systems under different conditions representing typical situations around South Africa. This has been done by choosing eight typical loads, climatic resources for nine locations and five hybrid system configurations. Performance simulations were then run for all combinations of these variables. These computer simulations are based on hourly data and a rough system design of the hybrid configuration. Results of the simulations show how successful each system is in meeting demand and also maintenance, overhaul and replacements requirements of the system over a twenty-year lifetime. These are used to perform the financial and economic analysis.

Five of the eight loads were constructed by estimating appliance usage for each of a rural clinic, rural school, entrepreneurial development centre (EDC), rural dairy farming centre and rural crop farming centre. The other three loads namely S1, S2 and S3 were obtained by scaling and extrapolating from loggings at a farm. Climatic resources for eight sites were obtained from the South African Weather Bureau in the form of hourly measurements of wind speed, temperature and radiation for a one-year period. A ninth site was created by scaling data from other sites to obtain the required wind speed and radiation. Hybrid system configurations used were diesel-only, photovoltaic/battery (PV/B), photovoltaic/diesel/battery (PV/D/B), wind/battery (W/B) and photovoltaic/wind/battery (PV/W/B). Rough design was done by allocating each component of the hybrid system a percentage of the load to cover.

In the financial analysis the present value of all the costs incurred by each system are calculated and unit energy cost determined from the total electricity supplied over the systems lifetime. These system costs are compared for each load type to determine the cheapest hybrid configurations as climatic resources vary, and these plotted on axes representing wind speed and radiation. The plots of the cheapest systems were found to maintain their general shape for different loads as shown in the figure below.



Although the general shape of the plot was maintained, it is most typical of the medium load case of roughly 7MWh/year to 12MWh/year. The hybrid systems were rough-sized and were not optimal in configuration. Optimally designed hybrid systems would have been cheaper and would probably have resulted in a shift of the plot down and to the left. This would mean that some of the regions in the plot which are now more suited to diesel-only systems could show preference to (optimally configured) hybrid systems.

For the low-load cases of 513kWh/year and 716kWh/year (clinic and school respectively), hybrid systems were cheaper than diesel-only systems for all the radiation and wind speeds used. For these loads, this would show on the plot as a leftward and downward shift of all the curves until complete removal of diesel only systems.

Hybrid systems for higher load applications (up to about 12MWh/year) were competitive with diesel-only systems within the wind speeds and radiation of the scenarios used. Which system was cheaper depended on the wind and solar resources of the site in question. Diesel-only systems are preferred for sites with a combination of low wind speed and radiation. At a slightly higher load than the EDC of roughly 15MWh/year (for the dairy farm centre) wind/battery systems were still competitive (at high wind speeds) with diesel-only systems, but PV systems were not (for the radiation limits used). At an even higher load of about 26MWh/year (for the crop farm) diesel-only systems were the cheapest within the wind speeds and radiation considered.

Hybrid systems seem most suitable for lower load applications of less than about 700kWh/year but compete with diesel systems for loads up to roughly 15MWh/year depending on site resources. They could also be the best option at even higher loads if optimally designed as opposed to rough sized systems are used.

The economic analysis was performed using cost-benefit analysis (CBA) techniques, which are detailed in the body of the report. Essential steps in performing CBA are omission, addition and revaluation of items from the financial analysis to show the effect on the country as a whole of implementing the project. Financial costs are revalued to show what the cost to the country is and as such, items like taxes, levies and interest payments are removed. Income (or benefit) is valued as what a customer is willing to pay and not what is actually paid. A real economic discount rate of 5% is used to determine the present value of future costs (the financial discount rate used is 8%). The effect of a lower discount rate is heavier weighting of future values.

Using generalised scenarios meant that actual benefits for the CBA could not be estimated and the economic analysis was based on comparison of the economic costs of the different systems. The results in terms of the economically cheapest systems do not vary significantly from the financially cheapest systems. The financial and economic costs vary most significantly in diesel price and discount rate. The economic diesel price is about 52% of the financial price, as the financial price constitutes a major tax portion. Systems consisting of diesel gensets compared to PV and wind systems, usually have lower initial costs but higher running costs. The effects of the lower economic diesel price and lower economic discount rate work against each other with the result that in general, the financially cheapest systems (at a discount rate of 8%) are the same as the economically cheapest systems at a discount rate of 5%.

The general shape of the areas where the different hybrid systems were found to be the cheapest (economically) is the same as that presented earlier for the financially cheapest systems. As loads increase there will be a general shift of all the curves to the right and up: diesel systems become more favourable. On the scale used for the plots the shift will be more to the right than up i.e. PV/B systems becomes more expensive faster than W/B systems.

Sensitivity of the results to discount rate and diesel price was determined. At higher discount rates, systems with diesel generators become economically more favourable than other systems. Systems with wind turbines are favoured to systems with PV at high discount rates. This is a result of wind turbine overhauls and other operating and maintenance costs, compared to almost none associated with PV. Increasing the discount rate resulted in a shift in most of the boundary lines to the right and down. The W/B and diesel/only areas shifted right and upwards, effectively expanding the region in which diesel only is the cheapest. These shifts were seen to be more into PV than wind systems (on the scale used). Increasing load also showed a rightward and upward shift of the lines.

An increase in diesel price results in a left and downward shift of all the regions into the diesel-only area as well as a narrowing of the area where PV/D/B systems are the cheapest. Variations in diesel price are seen to significantly affect the cheapest systems for loads between roughly 7Wh/year and 12MWh/year. This is the range where hybrid systems and diesel-only systems are the most competitive and as such is also most affected by any changes in discount rate.

The determination of the economically cheapest systems was done without the inclusion of benefits (willingness to pay) as these were not expected to change significantly for the different systems. The net present economic costs serve as an indication of the value of the benefits needed to make the project break-even economically.

The report has identified loads and climatic resources for which a particular hybrid configuration (if any at all) may be more suited than others. This has been done to determine financial and economic suitability. The regions where hybrid systems are better suited than diesel-only systems is conservative as rough-sized (as opposed to optimal) hybrid configurations were compared to diesel-only systems. CBA was performed as far as determining economic costs on all the systems but benefits could not be estimated for generalised projects. The economic net present costs are to be used as a measure of the indirect benefits required for a project to be feasible.

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Part 1: Identication of scenarios and financial analysis

1 Identification of scenarios

Possible scenarios for hybrid systems are chosen on which to perform performance and financial simulations and finally cost-benefit analysis (CBA). The cases chosen are relevant and reflective of the South African situation with respect to climate, load and socio-economic conditions. The variables in the scenarios are demand patterns, weather resources and hybrid system configurations.

1.1 Demand profiles

The choice of demand profiles is largely based on discussions of possible pilot projects at the Hybrid Workshop (Queenstown, 28 May 1997). Five of the eight projects chosen are a rural clinic, a rural school, an entrepreneurial development centre (EDC) and two rural farm centres. These load profiles were constructed by estimating appliance usage within each hour. A simplifying assumption that each appliance stays on for the whole hour was made. The three others (S1, S2 and S3) are scaled from data logged at a farm in Upington over 10 days. Scaling was necessary to ensure that a wide range of loads is covered. Data for seven of the ten days was then repeated to obtain a yearly profile. Other possibilities considered but not used were technical schools, radio repeater stations, tourist facilities, mini-grids (generally implying larger loads) and expanding existing systems at schools and clinics.

1.1.1 Rural clinic

The loads in the rural clinic are modified from a load assessment example in the RAPS manual (DMEA 1992). Only refrigeration and lighting are considered. The vaccine refrigerator and freezer each draw 5A at 12V DC with duty cycles for winter and summer of nine and twelve hours per day respectively. This duty cycle is raised from the recommended one of six hours per day to account for private use by the clinic staff. Essential lighting for night-time cases is achieved with four 15W DC lights for four hours per night, for an average of three nights per week. Lighting in the consulting rooms is done with four 15W DC lights operated for eight hours per day in winter only. Two hours a day would have been sufficient if lights are only turned on when required for examinations, reading and writing. This was considered very unlikely in practice. Figure 1 shows the daily load profile and its breakdown can be found in appendix A. Average demand is 1.4kWh/day.

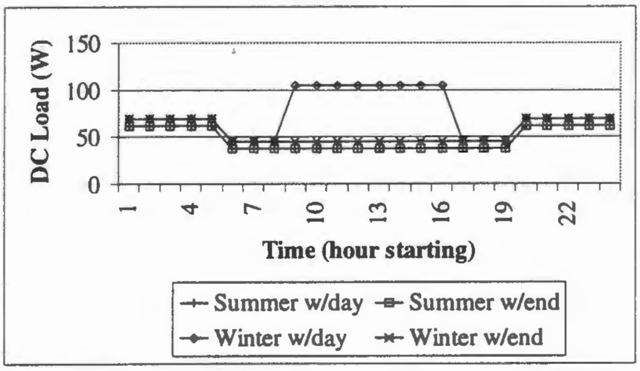


Figure 1: Daily load profile for the rural clinic

1.1.2 Rural school

Loads in a typical rural school are based on current Eskom practice for non-grid electrification, visits to rural schools in the Queenstown area and a design example in Raps design manual (DMEA 1992). Two classrooms consist of eight 40W DC lights which are operated three hours a day at night on weekdays and an additional four hours per day in winter (weekdays). Outdoor lighting is supplied by one 11W DC light operated three hours per night on weekdays. An 80W AC television and 15W AC video machine are used four hours a day, Monday to Saturday. A computer and overhead projector consuming 150W AC each are also operated for three hours Monday to Saturday and 1.5 hours on weekdays respectively. Average demand is 1.9kWh/day. Possible variations in practice are the use of a kettle and radio if a power point is available to staff. Appendix A contains details of individual load use and figure 2 shows the daily AC and DC load profiles.

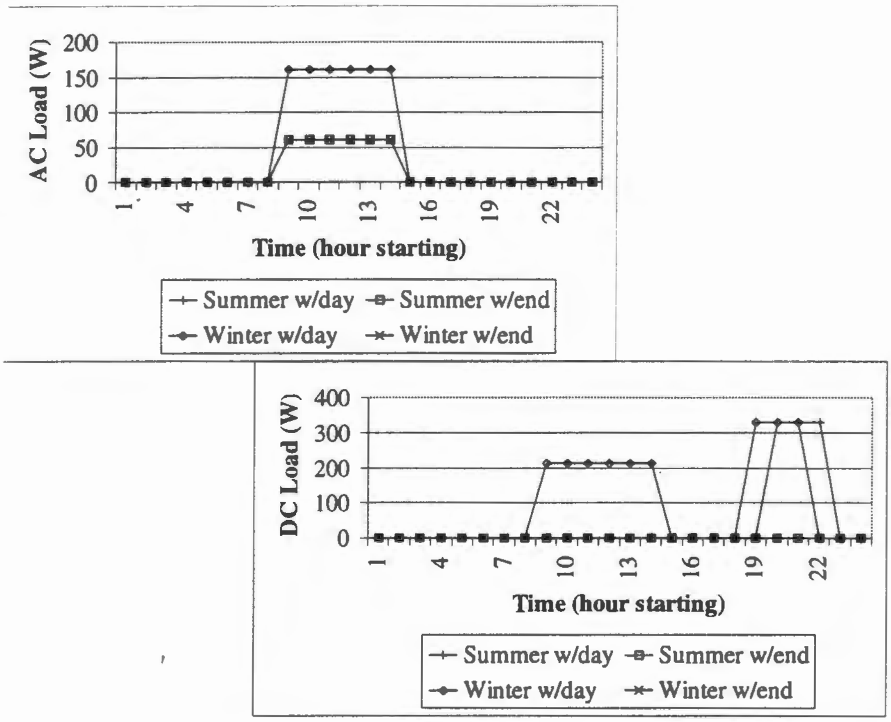


Figure 2: Daily load (AC and DC) profiles for the rural school

1.1.3 S1, S2 and S3

The profiles for these loads are based on loggings at a farm over a ten-day period. A weekly cycle was assumed, as profiles for days 8, 9 and 10 were very similar to those for days 1, 2 and 3. This seven-day profile was repeated to create a yearly profile. The ratios used to scale the profiles were chosen such that their demands are approximately 4.7, 10 and 20kWh/day. Details of the logged and scaled data are in appendix A. The weekly profile for S3 is shown in figure 3. All loads are DC.

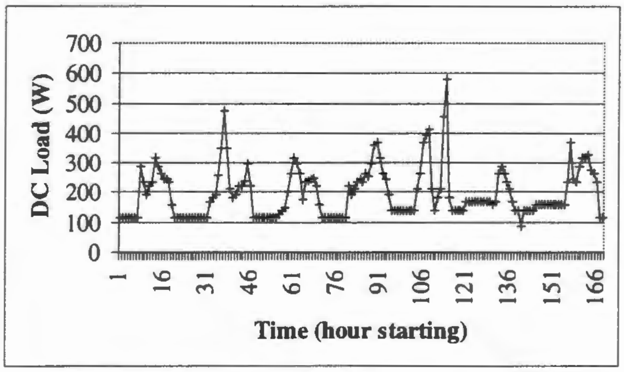


Figure 3: Weekly load profile for the S1 load

Graphical profiles for S2 and S3 are not repeated but the average and peak demands are shown in table 1.

Table 1: Average and peak demand for the S1, S2 and S3 loads

	Logged data	S1	S2	S3
Daily load [kWh/day]	40.03	4.71	10.02	20.02
Annual load [kWh/year]	14651	1723	3666	7326
Peak load [W]	4950	582	1238	2475
Ratio to logged data	n/a	1/8.5	¼	1/2

1.1.4 Entrepreneurial development centre

EDCs are centres, which provide workshop facilities for productive activities. Typical loads include lighting, soldering, welding, drilling, grinding/sanding and lathing. Other loads also assumed are refrigeration, and use of a fan, kettle and radios. No change in loads was assumed between summer and winter, and weekday and weekends. This assumption was made because users of the facilities are self-employed and would not be forced to work at fixed times. Sundays, would probably however, be less busy. The loads listed are only typical and several others like sewing and water pumping are possible. Appendix A contains details of individual appliance usage, which cumulatively result in a load profile as shown in figure 4. The average load is 33kWh/day.

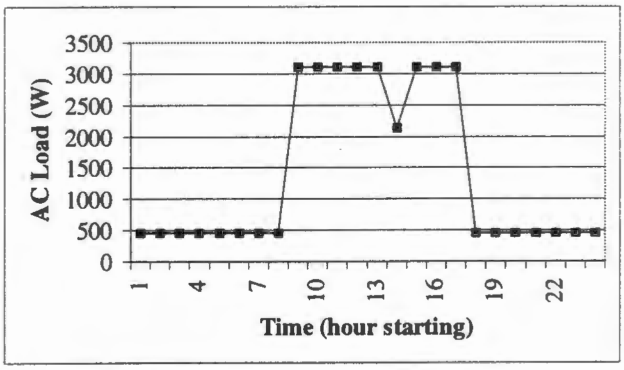


Figure 4: Daily load profile for the EDC

1.1.5 Rural centre – dairy farming

The dairy farming rural centre (for 50 cows) is very similar to the crop farming rural centre. Only variations are mentioned. The crop-farming centre will not have the 4kW mill, but will have additional cooling (250W) for milk and a cow unit (400W) for milking cows. Feed processing is considered marginally viable for 50 cows and was not included in the load but is a possibility. Water heating (3kW) for dairy hygiene is also not included as a load but could be included as a non-essential load. Figure 5 shows the daily load profile (details in appendix A). Average load is 43kWh/day.

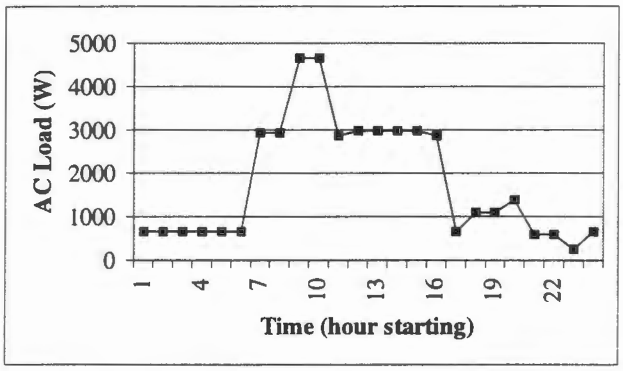


Figure 5: Daily load profile for the rural dairy-farming centre

1.1.6 Rural centre – crop farming

Rural centres serve as places, which offer common farming services in small farming communities to several individuals. Typical loads were obtained from EDRC's 'Hybrid system design as applied to RDP projects'. Loads are refrigeration for storage of perishables prior to marketing, milling (4kW), water pumping (2.5kW), lighting (40W for maintenance and 40W for organisational development activities) and powering of maintenance tools (750W) and audio-visual equipment (310W). Summer/winter and weekday/weekend loads are considered identical and all loads are AC. The 2kW fridge and 2kW freezer operate for fours a day in the daytime but are shuttled – freezer in the morning and fridge in the afternoon. The mill will operate for eight hours a day during normal working hours and is the main load. Water is pumped for six hours a day from the early hours of the morning. Maintenance would be done for three hours in the evening – tools and maintenance lights will be used. Maintenance lights will also be allowed for, for two hours every morning without the use of electrical tools. General lighting is for seven hours every night, the computer (200W) for 6 hours and the radio (10W) for seven hours during the day. The television (70W) and video cassette recorder (30W) are used for five and three hours a day respectively, in the evening.

The TV and VCR if used for organisational development activities would also probably be used during the day. The same applies to maintenance, which cannot wait. The largest load – the 4kW electrical-powered mill – is based on surveys and still has to be proven as a continuous daytime load. The whole demand profile is largely dependent on the milling. The load profile is shown in figure 6 and load details are in appendix A. Average load is 72kWh/day.

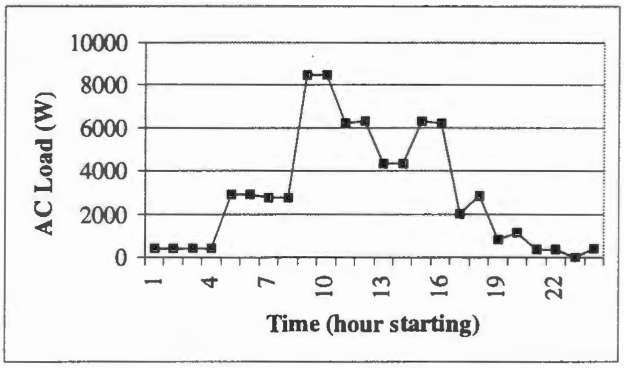


Figure 6: Daily load profile for the rural crop-farming centre

1.2 Weather regimes

Wind and solar resources were chosen to cover a wide range of low, medium and high resources. Hourly measured data for a one-year period for wind speed, global radiation and temperature were obtained from the South African Weather Bureau (SAWB) for several sites.

Eight actual stations were selected and one hypothetical site referred to as 'Hypo 1' was formulated by scaling data from the other sites. This was done as none of the other eight sites had both a low radiation and a low average wind speed. Mean radiation, wind speeds and elevation of the sites used are shown in Table 2. 'Long-term' values are those obtained from literature on radiation (Eberhard 1990) and wind (Diab 1995) resources. These values would have been calculated from long-term measurements. 'Short-term' refers to the averages for the actual hourly data used in the simulations.

Table 2 : Mean radiation, wind speed and elevation of the sites used

	Mean radiation [kWh/m^2/year]		**Mean wind speed [m/s]**		**Elevation [m above sea level]**
L=long-term *S=data used*	*L*	*S*	*L*	*S*	
Hypo1	896	808	1.8	2.1	1000
George	1679	1235	2.1	3.5	221
Durban	1598	1472	3.0	4.2	0
Port Elizabeth	1792	1612	4.2	5.6	0
Cape Town	1915	1759	4.1	5.8	0
Bethlehem	2115	1922	3.8	2.9	1680
Springbok	2150	2171	4.6	4.6	1000
Irene	1943	2199	2.3	3.3	1524
Upington	2244	2817	2.9	3.9	836

1.3 Hybrid systems configurations and sizing

Systems chosen are diesel only, PV/battery (PV/B), PV/diesel/battery (PV/D/B), wind/battery (W/B) and PV/wind/battery (PV/W/B). Other choices of hybrid configurations were available, such as wind/diesel and wind/diesel/battery systems but were not chosen to keep the initial scenario set as simple as possible.

The chosen hybrid systems were designed using a rough rule of thumb sizing technique for each demand profile and site. Initial rough sizing of the hybrid systems is based on the Sandia (1995) design recommendations and minutes of a hybrid systems workshop (Seeling 1996). Diesel only systems are sized so that the genset covers peak load. Other systems sizing are described below.

1.3.1 PV/battery

PV was designed around the design month – the month with the highest ratio of load to insolation. The PV size (area) was calculated to match the average amp-hour (Ah) load per day to the radiation (in kWh/m^2/day) for the design month after taking efficiencies and losses into account. The battery was sized to provide three days of storage, except for the clinic where six days of storage was provided for, as very high reliability is required there.

1.3.2 PV/diesel/battery

The design method used for the PV/diesel/battery system is very similar to the one for the PV/battery system. The diesel generator was sized to cover the peak load after derating the generator output power for altitude, typically 3.5%/300m above sea level. The PV and battery are sized as for the PV/battery system, except that the PV need not cover the full load and the required days of storage can be reduced. PV was designed to cover 40% of the annual load and the battery, to provide two days of storage. These sizes are chosen at random within a reasonable range.

1.3.3 Wind/battery

The design of wind/battery systems follows the same pattern as PV/battery systems, starting with the determination of the design month, which is the month with the highest ratio of load to (monthly) wind power density. The wind turbine generator (WTG) is sized to meet the peak load after accounting for battery, converter and wiring losses. The minimum area swept by the rotor was determined so that the extractable power density (roughly 25% of the power in the wind) is sufficient to cover peak load. The battery capacity will be determined using the same method as for the PV/battery system (two days of storage except for the clinic).

1.3.4 PV/wind/battery

The proportion of the load to be served by PV and by wind was decided as 50/50, which is a random split of the share. The rest of the sizing process for the PV and wind are identical to the previously described methods. The battery was designed to provide three days of storage.

2 Financial analysis

Performance simulations were run on the scenarios described earlier and the life cycle and unit energy costs calculated for each of these systems. The systems were then compared to each other both in terms of performance and cost to determine which the cheapest system would be for each site. As each site was characterised by a different wind speed and radiation, it would then be possible to determine the best system configuration as wind speed and radiation vary.

2.1 Methodology used

The hybrid system simulation program Hybrid2 was chosen to run the simulations as it has been verified against logged data and has the capability to do financial calculations (Baring-Gould 1996). It was developed by the National Renewable Energy Laboratory (NREL) and the University of Massachusetts.

Performance simulations were done on hourly weather and load data for a period of one year and financial calculations were done for a 20-year period but based on the results of the performance simulation of one year.

All costs were entered into Hybrid2 which calculates, for each of the twenty years, the organisation and management (O&M) costs, fuel costs (where applicable), and capital and replacement costs. Capital and replacement costs from Hybrid2 were checked and corrected. This was necessary due to inconsistencies and shortcomings in the financial simulation of Hybrid2. This was done in constant prices (with inflation effects not taken into account). Costs were totalled for each of the twenty years and the net present value (NPV) calculated using a discount rate of 8%. The NPV was then amortised into an annual amount over the project life using the discount rate. Dividing the amortised annual amount by the annual energy supplied yielded the levellised cost of energy per kWh. No revenue from electricity sales was assumed.

The nine sites that were used for the simulations are shown in figure 7, with an indication of their mean wind speeds and radiations (Table 2 shows exact values). The sites were chosen to obtain as broad a range of wind speed and radiation as practically possible.

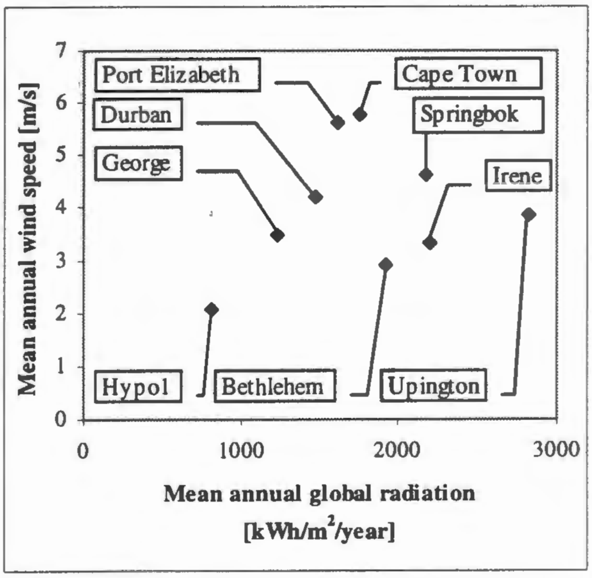


Figure 7: Resources of the sites used in the simulations

Results in the form of unit energy cost were obtained for all the chosen scenarios for each site. Several difficulties were encountered in analysing dependency of cost to site resources. Firstly, due to the nature of the wind speed and radiation of the chosen sites as seen in Figure 7, it becomes difficult to attribute trends in cost curves to either wind speed or radiation on their own. The second difficulty encountered as a result of rough sizing was ensuring that all systems had equal reliability. To make comparisons fair, systems not covering 95% of the load were not considered acceptable. Another difficulty was encountered as a result of the fact that the hybrid system designs were not optimal, but merely rough designs based on assigned proportions of load coverage by the different hybrid components. Furthermore actual components were used in the rough sizing process, which necessitated discrete component sizes (rounded up to the next available component size). This introduced the possibility of system oversizing and associated cost increases for some hybrid systems, as the designed systems were discrete but a continuous trend was sought from the results.

The financial results for each load were analysed using tables, correlation coefficients and plots of the cheapest systems. Correlation coefficients were calculated for energy cost with respect to both radiation and wind speed to determine the level of dependency of system costs on these resources. The correlation coefficient is a useful measure of the linear association between two sets of data. This coefficient must lie between –1 and +1 and coefficients close to –1, 0 and +1 represent inverse linear, no linear and direct linear relationships respectively.

Plots of the cheapest systems are modifications of figure 7 with site names removed for clarity. For each point (representing a site) on figure 6 the cheapest off-grid system is determined. By grouping the cheapest hybrid systems of each type together, areas on figure 7 can be identified where a particular hybrid/off-grid configuration would be expected to be the cheapest. These areas are then demarcated by boundaries for the purpose of identifying trends.

Results of the simulations for the clinic load are analysed in some detail and then the results of the analysis for the other four systems are presented by increasing load.

2.2 Clinic load

The clinic has a DC load of 513kWh/year (1.4kWh/day). The costs of supplying electricity to the EDC are shown in Table 3, where site names have been reduced to their first letter. System costs for which the performance simulation showed that less than 95% of the annual load was covered have been underlined. Percentage load coverage is also shown in Table 3 adjacent to their respective system costs. Note that systems with 95% load coverage may be underlined: this is because their load coverage would have been less before rounding off. Cheapest systems for each site are in bold.

Table3: Electricity costs [in R/kWh] and load coverage [%] for the clinic

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	53.18	100%	20.96	79%	**21.82**	100%	25.72	56%	22.74	69%
G	53.00	100%	14.86	78%	**20.06**	100%	15.73	87%	14.12	91%
D	53.05	100%	13.30	87%	**19.47**	100%	11.85	93%	12.00	94%
P	53.00	100%	12.40	94%	18.51	100%	11.22	95%	**10.86**	98%
C	53.05	100%	12.86	96%	16.92	100%	9.77	94%	**11.79**	100%
B	53.30	100%	**11.34**	95%	18.41	100%	14.64	79%	14.70	96%
S	53.18	100%	11.01	98%	17.42	100%	**9.36**	97%	10.26	100%
I	53.22	100%	**10.85**	100%	17.45	100%	21.86	92%	15.66	99%
U	53.27	100%	**10.87**	100%	15.36	100%	13.55	91%	10.99	100%

Correlation coefficients of systems' costs with respect to radiation and wind speed are shown in Table 4.

Table 1: Correlation of costs to radiation and wind speed for the clinic

System	*Correlation of costs w.r.t radiation*	*Correlation of costs w.r.t wind speed*
Diesel only	0.55	-0.55
PV/battery	-0.85	-0.48
PV/diesel/battery	-0.94	-0.50
Wind/battery	-0.38	-0.82
PV/wind/battery	-0.61	-0.80

The close to –1 correlations with respect to radiation for the PV/B and PV/D/B system costs (Table 3) imply the existence of strong inverse linear relationship – as radiation increases PV/B and PV/D/B system costs will decrease. Similar strong inverse relationships exist with respect to wind speed for both W/B and PV/W/B system costs. However, the PV/W/B system costs are seen to depend more on wind speed than on radiation. This is understandable as a cubic relationship exists between wind speed and wind electric power compared to a linear one between radiation and power from a PV system and a 50/50 split in energy share was assumed in the design.

A plot of the cheapest systems (based on costs in Table 3) for the clinic is shown in figure 8. Site names have been removed but are in the same location as they were in figure 7.

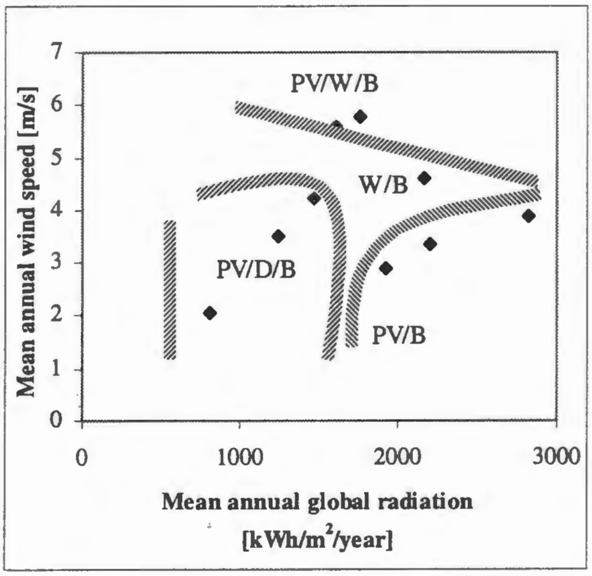


Figure 8: Cheapest systems for the clinic shown against wind speed and radiation

generator available was 600W and the clinic only required 105W. The area where PV/D/B systems are the cheapest has been limited to the left by a vertical line. This line serves to show that at some point (when radiation is low enough) it would be cheaper to operate a diesel-only system. The exact position of that line is not calculated.

2.3 School load

The school uses both AC and DC loads and has a load of 716kWh/year (1.9kWh/day). Correlation coefficients are similar to those of the EDC, except for the correlation coefficient of PV/W/B systems with respect to radiation, which is –0.11. This implies little or no relationship between PV/W/B system costs and radiation but this is explained by the electricity costs shown in Table 5, which also shows load coverage for the school and follows the same format as Table 4. The cost of electricity for the PV/W/B system for Irene (R33.39/kWh) explains the low correlation coefficient with respect to radiation. The reason for the high cost of wind turbines in Irene is its low design wind speed (2.3ms^{-1}) which is lower than the short term wind speed (3.3ms^{-1}) on which this analysis is based. This low design wind speed necessitated large (and therefore expensive) wind turbines to cover a 50% share of the load. This was, however, not the case for the same system (PV/W/B) for the clinic, whose annual load is only slightly smaller (513kWh/year as opposed to 716kWh/year). This is explained by their peak loads of 105W and 491W (for the clinic and school respectively) on which the rough sizing is partly based.

Table 5: Electricity costs [R/kWh] and load coverage [%] for the rural school

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	38.74	100%	18.92	75%	**17.11**	100%	36.21	89%	24.80	81%
G	38.56	100%	12.31	76%	**14.91**	100%	34.63	91%	16.92	88%
D	38.58	100%	11.00	86%	14.41	100%	**9.76**	97%	16.00	97%
P	38.52	100%	10.27	91%	13.93	100%	14.33	96%	**11.46**	99%
C	38.58	100%	10.61	93%	13.30	100%	14.43	96%	**9.82**	100%
B	38.91	100%	8.73	95%	14.63	100%	17.37	94%	**12.66**	98%
S	38.74	100%	**8.86**	96%	13.17	100%	14.11	97%	10.43	100%
I	38.85	100%	**8.60**	99%	13.58	100%	35.44	100%	33.39	99%
U	38.82	100%	**8.28**	100%	11.57	100%	11.30	95%	15.61	100%

Figure 9 shows the cheapest systems for the school. Dashed lines are used as they take up less space on the plot, but it should be remembered that they are still a broad and 'shady' boundary. The W/B system is seen to be the cheapest system at high wind speeds and low radiation, as was expected. A difficulty mentioned earlier is seen here – even though the clinic and schools annual loads are similar, the shape of the lines has changed significantly. This is because the cheapest systems for three sites close to the boundaries (namely Durban, Springbok and Bethlehem) have 'moved over to the other side'.

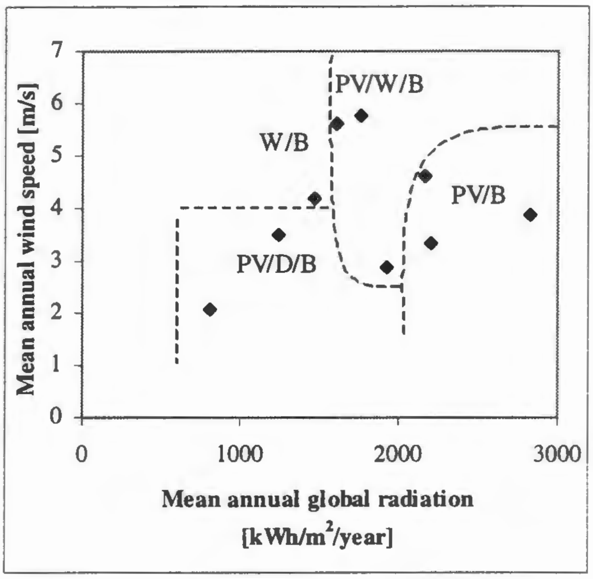


Figure 9: Cheapest systems for the school shown against wind speed and radiation

2.4 S1

The S1 is a DC load of 1.7MWh/year (4.7kWh/day). Correlation coefficients are very similar to those of the clinic and are not reproduced. Table 6 shows the electricity costs as well as the load coverage for the S1 load.

Table 6: Electricity costs [R/kWh] and load coverage [%] for the S1 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**18.37**	100%	14.40	83%	18.89	100%	24.32	62%	14.62	80%
G	16.87	100%	8.77	82%	16.21	100%	7.97	94%	**7.57**	97%
D	16.87	100%	7.76	92%	15.38	100%	14.35	99%	**7.20**	100%
P	16.87	100%	7.29	98%	14.33	100%	**5.11**	99%	6.13	100%
C	16.87	100%	7.91	98%	13.08	100%	**5.09**	100%	6.67	100%
B	18.50	100%	**6.10**	99%	15.55	100%	15.06	93%	8.82	100%
S	18.37	100%	6.50	100%	13.64	100%	**5.02**	99%	5.77	100%
I	18.47	100%	**6.51**	100%	13.51	100%	16.03	100%	9.40	100%
U	18.39	100%	**6.17**	100%	11.20	100%	7.44	97%	6.74	100%

Cheapest system configurations for the S1 load are shown in figure 10. The location of the areas where PV/B and diesel only systems are the cheapest is self-explanatory.

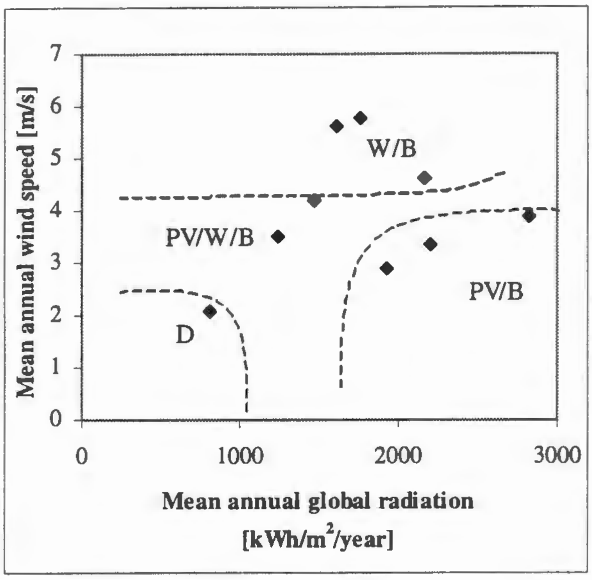


Figure 10: Cheapest systems for the S1 load

2.5 S2

The S2 is a DC load of 3.7MWh/year (10kWh/day). Correlation coefficients are very similar to those of the clinic and are not reproduced. Table 7 shows the electricity costs as well as the load coverage for the S2 load.

Table 7: Electricity costs [R/kWh] and load coverage [%] for the S2 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**11.84**	100%	13.65	83%	14.48	100%	14.29	93%	12.40	96%
G	11.70	100%	8.01	81%	12.70	100%	**8.38**	100%	9.91	97%
D	11.70	100%	7.08	92%	12.43	100%	7.26	100%	**6.46**	100%
P	11.70	100%	6.63	98%	11.85	100%	7.70	99%	**5.38**	100%
C	11.70	100%	7.28	98%	11.35	100%	7.66	100%	**5.70**	100%
B	11.97	100%	**5.47**	99%	11.65	100%	8.25	97%	8.81	100%
S	11.84	100%	5.80	100%	11.24	100%	**4.26**	99%	5.03	100%
I	11.94	100%	**5.81**	100%	11.21	100%	14.61	100%	10.23	100%
U	11.85	100%	**5.54**	100%	10.08	100%	7.31	99%	5.92	100%

Cheapest system configurations for the S2 load are shown in figure 11. The location of the areas where PV/B and diesel only systems are the cheapest is self-explanatory.

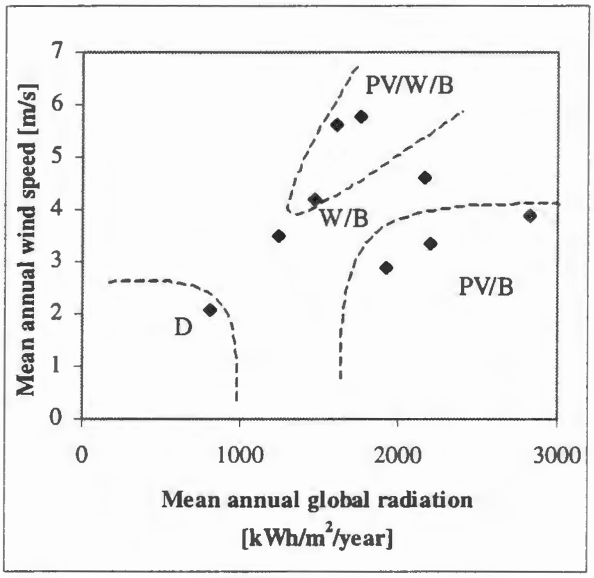


Figure 11: Cheapest systems for the S2 load

2.6 S3

The S3 is a DC load of 7.3MWh/year (20kWh/day). Correlation coefficients are very similar to those of the clinic and are not reproduced. Table 8 shows the electricity costs as well as the load coverage for the S3 load.

Table 8: Electricity costs [R/kWh] and load coverage [%] for the S3 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**6.79**	100%	13.35	83%	10.55	100%	12.65	83%	12.11	96%
G	**6.70**	100%	7.67	81%	8.62	100%	9.35	100%	7.15	100%
D	6.70	100%	6.80	93%	8.49	100%	10.96	100%	**6.68**	100%
P	6.70	100%	6.34	98%	8.18	100%	**4.49**	99%	5.10	100%
C	6.70	100%	6.99	98%	7.86	100%	**4.68**	100%	7.09	100%
B	6.87	100%	**5.19**	99%	7.88	100%	7.96	97%	6.45	99%
S	6.79	100%	5.57	100%	7.66	100%	**4.41**	100%	4.75	100%
I	6.85	100%	**5.58**	100%	7.64	100%	14.34	100%	9.95	100%
U	6.80	100%	5.26	100%	6.89	100%	**5.17**	98%	6.16	100%

Cheapest system configurations for the S3 load are shown in figure 12. Compared to the plots for the smaller loads, diesel only systems for the S3 load are seen to become more competitive.

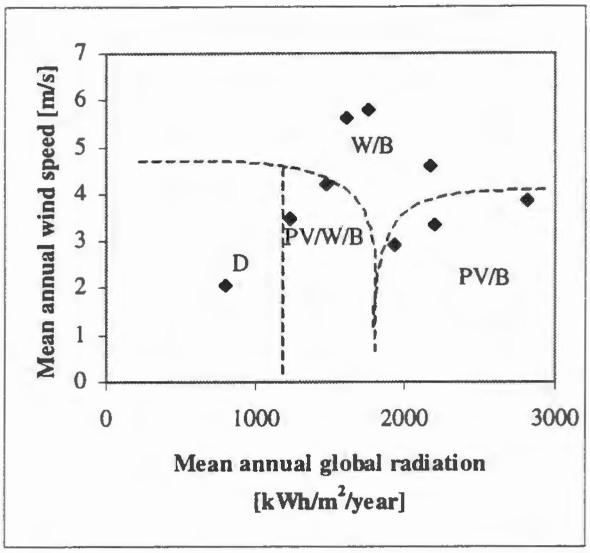


Figure 12: Cheapest systems for the S3 load

2.7 Entrepreneurial development centre

The EDC has an AC load of 12.4MWh/year (33kWh/day). Correlation coefficients are very similar to those of the clinic and are not reproduced. Table 9 shows the electricity costs as well as the load coverage for the EDC.

Table 9: Electricity costs [R/kWh] and load coverage [%] for the EDC

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**5.03**	97%	13.31	82%	8.85	100%	12.97	66%	12.07	81%
G	**4.85**	100%	7.77	79%	6.65	100%	5.66	92%	5.98	95%
D	**4.85**	100%	6.88	90%	6.20	100%	5.39	94%	5.84	96%
P	4.85	100%	6.35	96%	5.99	100%	**3.66**	97%	4.62	100%
C	**4.85**	100%	6.94	97%	5.84	100%	5.34	99%	4.96	100%
B	5.42	100%	**5.18**	98%	5.82	100%	7.43	98%	6.84	97%
S	5.03	97%	5.51	100%	5.55	100%	3.86	91%	**4.27**	100%
I	**5.41**	100%	5.52	99%	5.42	100%	8.83	99%	7.13	100%
U	5.00	98%	5.20	100%	**4.96**	100%	5.94	88%	5.23	100%

The location of the areas where W/B, PV/W/B and PV/B are the cheapest is self-explanatory. The PV/D/B system would, however, have been expected to fall in a region with lower radiation than the PV/B area.

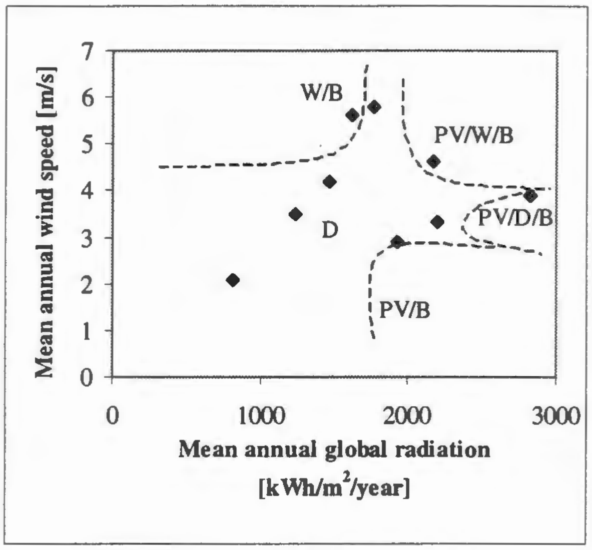


Figure 13: Cheapest systems for the EDC

It must be noted that the hybrid systems in the simulations are not optimally designed but the result of rough rule-of-thumb sizing. If optimal hybrid systems were used, it is likely that the areas between W/B and PV/W/B and between PV/W/B and PV/B would be occupied by non-diesel hybrid systems. Optimal hybrid systems may even shift into areas of low radiation and wind speed, which are currently only feasible for diesel-only systems.

2.8 Dairy farm

The load for the dairy farm is 15.7MWh/year (43kWh/day) AC. Table 10 shows electricity costs for the dairy farm load. Diesel only systems are the cheapest for all sites considered except for Port Elizabeth and Cape Town, where W/B systems are the cheapest. The costs in bold (in Table 10) represent the cheapest systems excluding diesel-only systems.

Figure 14a shows the cheapest systems for a dairy farm load. Diesel-only systems are the cheapest systems except at high wind speeds (5.5m/s and higher), where W/B systems are the cheapest. However, diesel systems have 100% reliability. Wind systems are still competitive with diesel-only systems at high wind speeds but PV/B systems are not (in the range of radiation used). If diesel-only systems are excluded from the analysis as shown in figure 14b, for five of the seven sites where diesel-only was the cheapest the next cheapest is PV/D/B. For the other two sites W/B systems become the next cheapest.

Table 10: Electricity costs [R/kWh] and load coverage [%] for the dairy farm

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	4.27	100%	13.95	78%	**8.10**	100%	13.49	72%	12.17	74%
G	4.32	100%	8.13	75%	**6.31**	100%	6.19	94%	6.48	99%
D	4.32	100%	7.13	86%	5.68	100%	4.65	97%	5.43	99%
P	4.32	100%	6.50	94%	5.46	100%	**3.24**	98%	5.15	100%
C	4.32	100%	7.01	96%	5.38	100%	**4.23**	99%	5.89	100%
B	4.32	100%	5.31	95%	**5.11**	100%	7.68	94%	6.25	98%
S	4.27	100%	5.50	99%	4.89	100%	3.31	94%	**4.87**	100%
I	4.31	100%	5.50	99%	**4.90**	100%	11.91	100%	8.98	100%
U	4.27	100%	5.17	100%	**4.39**	100%	4.98	95%	4.98	100%

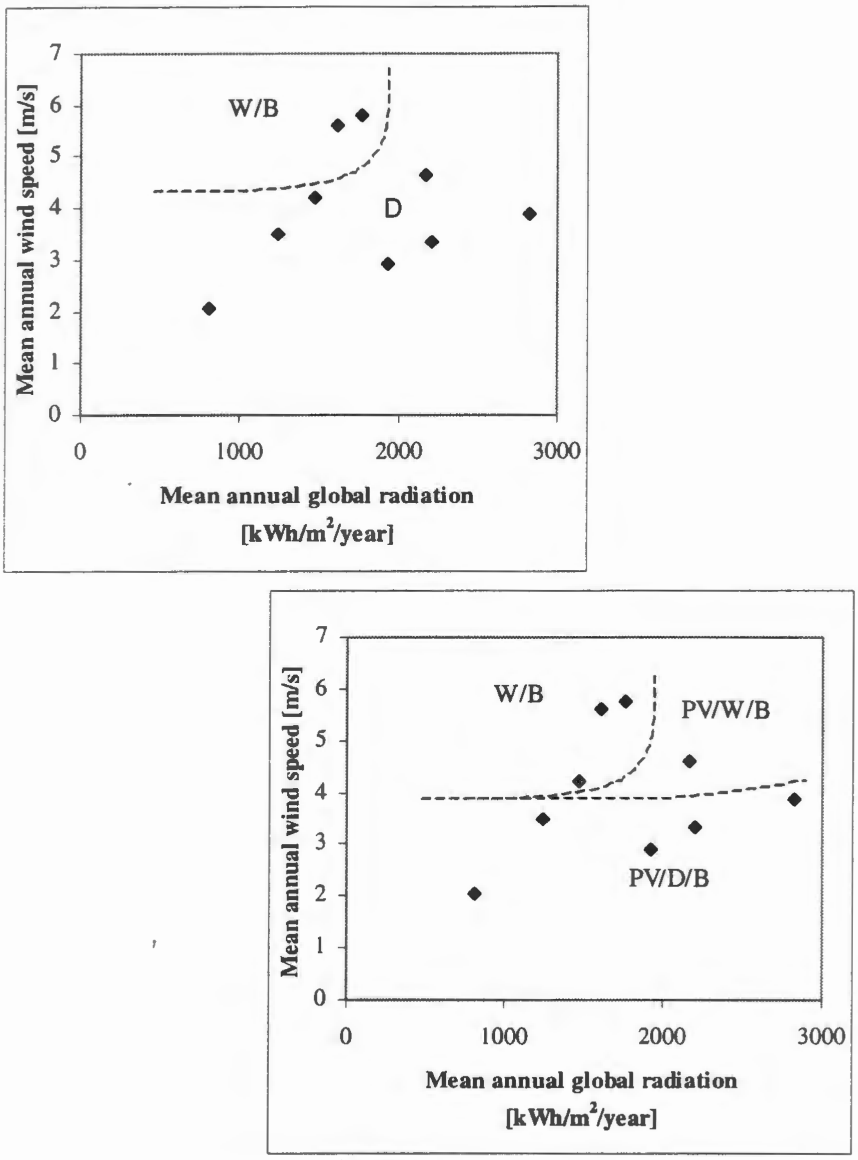


Figure 14: a)Cheapest systems and b) Cheapest systems excluding diesel-only for the dairy farm

2.9 Crop farm

The AC load for the crop farm is 26.2MWh/year (72kWh/day). Table 11 shows the electricity costs and load coverage using the same convention as table 10. Diesel-only systems are the cheapest within the wind speeds and radiations used and the next cheapest systems are plotted in figure 15.

Table 11: Electricity costs [R/kWh] and load coverage [%] for the crop farm

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	3.07	100%	13.65	80%	**7.02**	100%	13.73	76%	12.64	84%
G	3.00	100%	7.46	77%	**5.07**	100%	6.60	93%	6.37	96%
D	3.00	100%	6.94	87%	**4.94**	100%	5.36	97%	5.67	100%
P	3.00	100%	6.97	86%	**4.91**	100%	3.63	88%	4.90	94%
C	3.00	100%	6.89	96%	4.83	100%	**3.56**	96%	5.06	100%
B	3.99	100%	5.15	96%	**4.89**	100%	8.11	91%	6.83	99%
S	3.07	100%	5.38	99%	4.42	100%	3.45	93%	**4.30**	100%
I	3.97	100%	5.39	99%	**4.72**	100%	10.85	97%	7.98	100%
U	3.07	100%	5.20	97%	**4.52**	100%	5.83	85%	5.18	97%

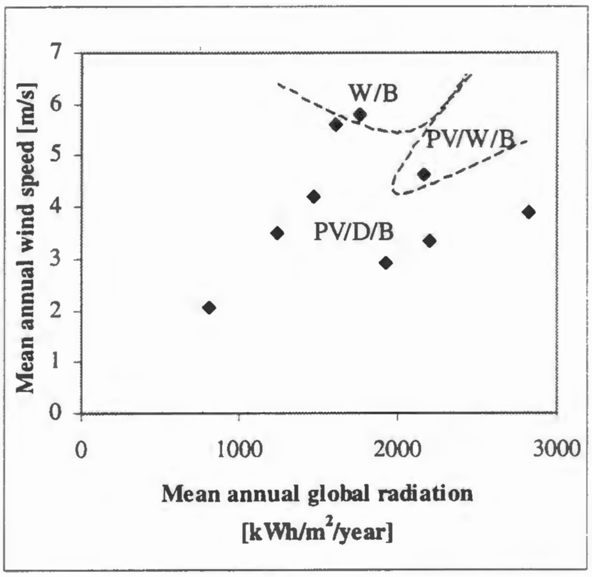


Figure 15: Second cheapest systems (after diesel-only) for the crop farm

At such high loads a diesel-only system seems recommendable followed by a diesel hybrid system (PV/D/B). However, the hybrid systems being compared to the diesel generator are not optimal in design and could be more competitive if they were optimised.

2.10 Results overview

Figure 16 shows the shape of the ranges where the hybrid systems considered were found to be the cheapest. The lines show the general shape valid for low load applications such as the school and clinic. The shaded area represents a region where either diesel-only or PV/D/B systems are the cheapest. PV/D/B systems were also sometimes seen to be the cheapest in a narrow region between PV/W/B and PV/B, particularly when alternative hybrid systems were under-designed.

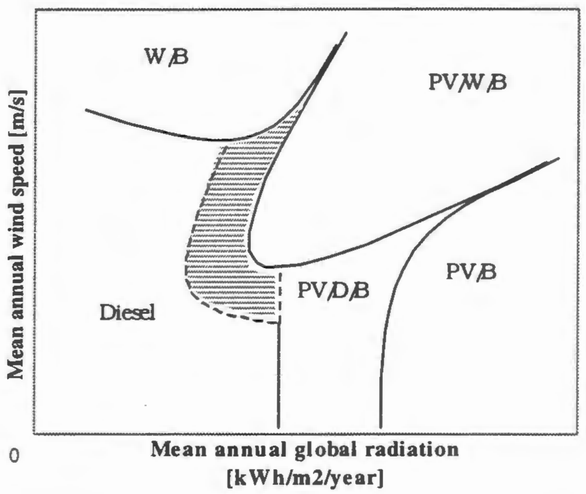


Figure 16: Cheapest systems generalised for all loads

For high load applications such as the farm centres (with intensive tool use), diesel systems seem the cheapest option. Even in a hybrid configuration, the system using diesel generators proved to be the next cheapest (after diesel-only) for a large portion of the radiation and wind speeds used. This could however have shifted in favour of other hybrid systems had they been optimally configured. It is expected that the position (on a different scale) of the boundary lines for higher load applications will be similar to those of the low-load applications and would occur above the range of wind speeds and radiations used in the scenarios.

2.11 Conclusions

Some of the more common hybrid systems have been compared, based on electricity cost per kWh. This was done to determine what the cheapest systems would be as mean wind speed, radiation and load vary. Hybrid systems were varied in configuration-type and not percentage mix of generating sources. An implication is that rough sizing might not have produced optimally designed and lowest cost systems. Had optimally configured hybrid systems been used instead of rough mixes, the effect on the plots (generalised in figure 16) would probably have been a general shift of the boundary lines for the hybrid systems into the diesel-only area. Results obtained are valid when the hybrid configurations and mixes chosen are the available options.

The general relationship for the cheapest of the rough sized hybrid systems, with respect to wind speed and radiation has been identified, but the exact points at which the transition occurs from one system being the cheapest to another is very dependant on the load.

Hybrid systems for low load applications (about 700kWh/year and less) are seen to be cheaper than diesel-only systems for the wind speed and radiation range tested. The type and size of the cheapest hybrid system is dependent on the site resources and load and the optimality of the design.

Hybrid systems for higher load applications (up to about 12MWh/year) were competitive with diesel-only systems within the wind speeds and radiation of the scenarios used. Which system was cheaper depended on the wind and solar resources of the site in question. Diesel-only systems are preferred for sites with a combination of low wind speed and radiation. As the load increased from 1.7 to 12.4MWh/year this combination of low radiation and wind speed increased approximately from 808kWh/m^2/year and 2.1m.s^{-1} (Hypol) to 1 472kWh/m^2/year and 4.5m.s^{-1} (Durban). At about 15MWh/year wind/battery systems were still competitive (at high wind speeds) with diesel-only systems, though at a slightly reduced reliability. PV systems were, however not competitive with diesel-only systems within the radiation limits used.

Hybrid systems for applications with loads higher than about 26MWh/year were not found to be cheaper than diesel-only systems, at least within the wind speeds and radiation considered.

Part 2: CBA for hybrid systems

1 Overview of cost benefit analysis

Cost benefit analysis (CBA) is a tool used to determine the socio-economic feasibility of a project. It is carried out by comparing, using various criteria, the benefits and costs to society of undertaking a project. Costs and benefits are defined relative to their effect on fundamental societal objectives such as:

- maximisation of total income in the country
- the distribution of income between current consumption and saving
- the distribution of consumption between different groups or regions within the society, depending on their initial wealth
- distribution of consumption between private and public sectors.

1.1 Concepts in economic CBA

CBA measures costs and benefits in terms of so called 'efficiency prices'. Costs are defined to reflect their opportunity cost, which is value of the best-foregone opportunity. One way of measuring benefits is in terms of 'willingness to pay', which is what a consumer is willing to pay for an output. Very often, especially in electricity supply projects, what a consumer is willing to pay is more than what he or she is actually charged. This difference is known as the consumers' surplus.

In a perfectly (or reasonably) competitive market, the purchase price is an accurate indication (or at least an initial estimate) of the opportunity cost. However, market imperfections or market failure could mean that purchase price is not the opportunity cost and the opportunity cost would have to be estimated directly. This estimate is then termed the shadow price.

Shadow prices are estimates of economic efficiency prices and as such (should) reflect the value of an input in its best alternative use. Shadow prices are most commonly applied to wages, and to inputs involving foreign exchange or those, whose market price is affected by transfer payments. Transfer payments reflect a transfer of resources from one sector or group to another and as such do not use real resources. Examples are taxes, duties and financial transactions like interest payments.

Inputs which are imported, outputs which are directly exported, and inputs which would have been exported was it not for the project are classified as traded items. The shadow price of a traded item is its world market price, net of any import duties or export taxes but adjusted for international transport costs. Adjustments by the shadow exchange rate will also be necessary.

Decision criteria for the economic analyses are similar to those for the financial analysis, except that economic values, as summarised above, are used in the calculations.

1.2 Financial and economic analyses

The financial analysis is used as the starting point for the economic analysis. The financial analysis is normally in current (or nominal) prices (to reflect the effect of inflation) and the economic analysis in constant (also termed real or fixed) prices and stated for a base year, that is, with the effects of inflation removed. Current prices are converted to constant prices by deflating them using the inflation rate. This would be the first step of the economic analysis.

Certain items used in the financial analysis are either omitted, added or revalued with the intended effect of stating costs and benefits as seen by the national economy as opposed to the implementing institution.

Items that are to be omitted include transfer payments, sunk costs, depreciation and price contingencies. Transfer payments do not have a net effect on real resources, but merely indicate a transfer of resources from one entity to another. Sunk costs refer to costs that have already been incurred and are irrecoverable whether or not the project is undertaken. As such, these costs should not affect the decision. Depreciation, as used in the financial analysis is not an actual cost but merely a way of representing the cost of an item over its intended lifetime. This is done to determine the profit/loss situation for successive time periods (which are shorter than the item's intended life). For the economic analysis the full cost is incurred when the item is acquired. Price contingencies are allowances for future price increases. The economic analysis is done in constant prices and price contingencies are therefore meaningless.

Additional items for the economic analysis represent costs and benefits to society, which are not directly experienced by the implementing agent. One example is the costs that a co-funder has paid for, which are real costs but will not be included in the financial analysis. Other such costs to society but not the agent are environmental costs where the law does not require the agent to pay for the full costs of damage or for protection of the environment. An example of an additional benefit item is increased agricultural production due to irrigation when an area is electrified.

Revaluation of costs and benefits is necessary because market prices (as used in the financial analysis) are not always representative of the costs and benefits to society as a whole. Imperfect market conditions such as subsidies, quotas, monopolies or controls of any kind are the reason for this. Economic efficiency prices as defined earlier should be used in the economic analysis. The cost of an input is the benefit foregone by not using it in its next best use and the value (benefit) of an output is its value in use as measured by the customer's willingness to pay for it.

1.3 Decision criteria

When all the project costs and benefits have been (re)valued, the net benefits for each time interval can be calculated over the entire time frame. From this point, one or more decision criteria are used to determine which, if any, of the projects is the most suitable economically. Some of the decision criteria are described below.

1.3.1 Net present value

Net present value (NPV) reduces the stream of costs and benefits to a single number in which costs and benefits, which are projected to occur in the future, are discounted. The stream of net benefit flows are discounted to their equivalent present value using an appropriate discount rate.

The discount rate to use for the economic analysis is the social discount rate, which is a reflection of the opportunity cost of capital to society as a whole (with respect to the return on investment in alternative projects). The social discount rate has nothing to do with inflation, as these effects have already been removed by expressing all values in real terms. A high discount rate implies that net benefits now have a much higher value than in the future. Although not a fault of the method itself, the principal problem associated with using NPV is the determination of discount rate to use, which is not straightforward or without debate (Pearce 1983). For this reason it is common for a central planning agency to recommend a discount rate to use. For the present Eskom programme, DBSA has stipulated an economic rate of return of 5% for the economic analysis of the projects.

NPV is also used as a decision criterion in the financial analysis but the discount rate used reflects the cost of capital to the implementing organisation. This will be higher than the social discount rate even with the effects of inflation removed (in real terms). The main reason for this is that alternative investments in the private sector have to include a mark-up for taxes, a risk premium and still offer higher returns to attract investors.

1.3.2 Internal rate of return

The internal rate of return (IRR) is defined as the discount rate that equates all future benefits and costs, that is, which results in a NPV of zero. A project with an IRR greater than some predetermined level (referred to as the appropriate discount rate in the discussion of NPV) is deemed acceptable. Two problems are encountered with this criterion. The first is that more than one IRR can result where net benefits change sign more than once during the project's life. Secondly, this criterion implicitly assumes a single discount rate over the life of the project. Assume a project's discount rate is set to 6% for the first *x* years and to 10% for the next *y* years, an IRR of say 8% will be meaningless as far as drawing a conclusion is concerned. IRR can be used for the financial and economic analyses, resulting in a financial and economic internal rate of return (FIRR and EIRR respectively).

1.3.3 Benefit to cost ratio

Benefit to cost ratio (B/C) is defined as the ratio of the present value of benefits to the present value of costs. As with NPV in the economic analysis, the social discount rate is used for the determination of the present values. In effect B/C gives the (discounted) benefit per Rand of (discounted) cost. A flaw when comparing projects is that a smaller project with a higher B/C may yield a smaller net benefit. Another difficulty with B/C is its sensitivity to the definition of costs and benefits. Whereas with NPV a positive benefit could just as well have been a negative cost, in B/C an addition to the numerator will clearly yield a different result to subtraction from the denominator. This problem will most likely surface in the assessment of external effects such as a reduction in pollution which could be defined as a positive benefit or reduction in cost. It is, however, very useful together with NPV in using up capital budgets.

1.3.4 Criteria to use

The following procedure will help determine which criteria to use under different circumstances (Pearce & Nash 1981):

1. Where a project must be accepted or rejected: if the NPV is positive the project should be accepted. If the NPV is negative, the project should be rejected.
2. Ranking – where a series of projects all have positive NPVs: the projects should be ranked in order of their B/C ratios. This is generally required where there are capital constraints.
3. Mutual exclusivity: where the choice is between mutually exclusive projects, the rule is to choose the project with the highest NPV.

1.3.5 Sensitivity analysis

Estimates of costs and benefits are just that – estimates. Uncertainty results because of imprecision in underlying data, modelling assumptions and even measurement of actual events. An economic analysis rests on several assumptions and predictions that lead to estimates which are approximate even for the present. As a starting point, care should be taken that best estimates are used in the first place and that biases are eliminated. No matter how well this is done, there will always be a certain degree of uncertainty. It is therefore important to determine the key sources of uncertainty, the sensitivity of results to these uncertainties and, where possible, probability distributions of benefits, costs and net benefits.

In a situation of uncertainty, a sensitivity analysis is performed. Values for input parameters are varied in magnitude to determine their effects on the results. For some parameters it may be more suitable to determine at what value of the parameter the NPV is zero. This is called its switching value. Sensitivity analysis is easy to implement but does not show the effects of simultaneous changes in more than one parameter.

For the sensitivity analysis, it is important to identify the key parameters. An important one is the discount rate, which will affect the NPV (and not the EIRR). Other key parameters for electricity projects as identified by Davis & Horvei (1995) are initial consumption, consumption growth, the willingness to pay, the technical and non-technical losses and the capital and operating losses. A sensitivity analysis should be performed on these and any other parameters as deemed necessary.

2 Important factors in hybrid system CBA

CBA for hybrid systems does not differ in principle to any other CBA. However, there are several factors that are unique in the implementation of CBA on hybrid systems. These factors are highlighted by means of a set of guidelines developed to aid the implementation of a CBA for hybrid systems. These are largely based on guidelines provided by Davis & Horvei (1995) for energy projects. The guidelines are structured into three distinct categories; initial analysis, estimation of costs and benefits and results.

2.1 Initial analysis

2.1.1 Select a time frame and discount rate

- The time frame for a hybrid project will generally be long – in the region of 15 to 20 years or more. If it is likely that the grid will reach the area before the end of the system's lifetime, the project lifetime should take account of this and a residual value should be attached to assets at the end of the analysis period.
- The social discount rate should be around 5% but adapted to the current social discount rate if it is changing.

2.1.2 Load estimation and system design

The load estimation and system design are the preface to the CBA.

- The electricity load requirements of the site must be carefully determined.
- The system should be designed and carefully examined.

Some of the outputs from the system design which are needed for the financial analysis which in turn precedes the CBA are the sizing parameters and the average daily runtime and capacity factor for diesel gensets.

2.2 Estimation of costs and benefits

2.2.1 Estimating the capital costs

The capital costs should be expressed in fixed prices for each year that they occur. The major items are listed according to the hybrid component they result from. For the specific hybrid system being analysed, they may not all be applicable. Costs that have been covered by grants should be included. Any sunk costs, price contingencies (that is, price escalation) and VAT payments should be excluded. The PV array and wind turbine should be adjusted for their foreign exchange component, as should all other items that have imported components.

- For the diesel genset include the cost of the genset, accessories and storage tanks.
- For the PV component, capital costs should include the cost of the array, regulator, wiring and accessories.
- For the wind turbine generator, include the costs of turbine, tower, rotor and accessories.
- The costs of batteries, chargers and inverters should be included.
- Other costs include the cost of the housing room (if any) and interconnecting cabling and accessories.

- If the hybrid system is to supply a reticulation network the cost of establishing this should be included, as should the costs of street lighting (if any) and connection costs (if customers are going to be connected to this network).
- Installation costs should include costs of labour and transport to site.

Calculate the adjustment factor to convert financial values to their economic equivalents for capital costs. Using this factor convert the financial values to their economic equivalents.

2.2.2 Estimating the operating costs

- The bulk of these will be fuel costs: fuel consumed is most accurately calculated by simulation. During the simulation, fuel consumption in each time interval is determined from the fuel consumption to load factor characteristic of the generator. Total cost of fuel is the product of fuel consumption in all the time intervals and the economic cost of fuel (that is exclude taxes).
- Transport costs of fuel to site should be included (where applicable), as should costs of lubricating oil and the labour involved (appropriately adjusted)

2.2.3 Estimating the maintenance costs

The frequency of servicing and overhaul required will depend on the actual components used, estimated use and the manufacturers recommendations. Regular minor servicing should be scheduled at least once or twice a year. Occasional major servicing and overhauls will be dependent on manufacturer's recommendations and estimated use.

- Estimate the servicing costs and adjust the labour, transport and equipment components appropriately.
- Overhaul costs should be included for the diesel generator

2.2.4 Estimating the replacement costs

Estimate component lifetimes and the present value of their replacement costs.

For the batteries and the genset,

- Calculate the benefits:
    - calculate sales revenues and connection fees, if any
    - calculate the consumer surplus based on willingness to pay
    - calculate other quantifiable benefits, paying particular attention to benefits associated with electricity supply to clinics, schools, street lighting, small business and agriculture
    - include the residual value where applicable of the diesel genset, PV arrays and wind generator.
- Include externalities:
    - include any costs and benefits that can be quantified and valued.

2.2.5 Cash flows and results

- Calculate the total costs and total benefits for each year.
- Calculate the discounted present value of the costs and benefits.
- Calculate the NPV
- Calculate the B/C ratio
- Calculate the EIRR.

2.2.6 Sensitivity analysis

- Identify key parameters.
- Do sensitivity analysis varying the limits of these key parameters.

2.2.7 Non-quantifiable effects

Non-quantifiable effects do not, strictly speaking, form part of the CBA but are mentioned here to note their importance. Where alternative hybrid systems are being considered, it may be difficult to express these effects analytically except if they are a result of electricity being provided to a specific site and not a result of the specific hybrid system design.

Give due consideration to any impacts not reflected in the CBA, if any. These impacts will be specific to each project. Adjust the conclusions based on the numeric analysis where deemed necessary.

3 CBA methodology for hybrid systems

The starting point in performing the CBA for hybrid systems is the output from the financial analysis. The obtained financial costs and benefits are converted to their economic equivalents. This process involves deflating costs and benefits to constant prices if they were in current prices and then addition, omission and revaluation of items as described in section 2.1.2??. Benefits are calculated and included for each year of the analysis, as are externalities that can be quantified and valued. Decision criteria are calculated from the yearly cost and benefit flows and a sensitivity analysis performed. Finally impacts that could not be quantified in the CBA must be described qualitatively.

Stages in the CBA are discussed in more detail and the conversion to economic prices and calculation of decision criteria demonstrated by way of an example.

3.1 Conversion of financial to economic costs

Revaluation of items is necessary where as a result of imperfect market conditions, market prices are not representative of actual costs and benefits to society. Actual prices are replaced by shadow prices, which are their economic equivalents. Shadow factors are the ratio of shadow prices to actual prices.

Revaluation of items is most easily done by calculating an adjustment factor and then multiplying it with the financial cost. As adjustment factors are different for different cost items, financial costs are broken down into categories that could have significantly different adjustment factors as shown in figure 17:

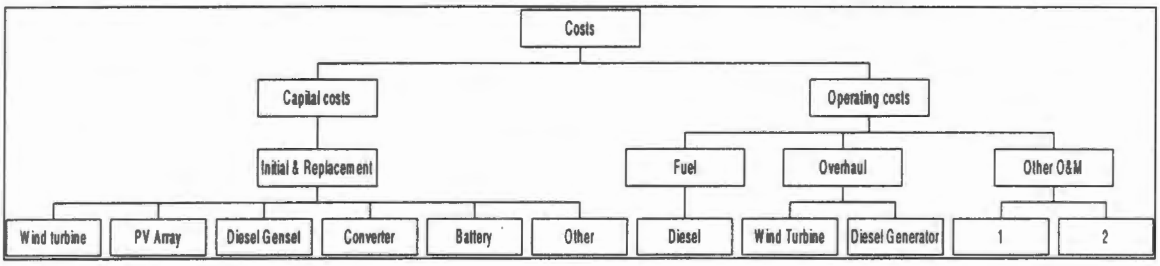


Figure 17: Breakdown of hybrid system costs

The cost of each item to be revalued is further broken down into imported equipment, local equipment, labour, transport, taxes and levies, and other. Each of these items is multiplied by its shadow factor and the total is normalised by the total cost to obtain an overall adjustment factor. This is illustrated in table 12. The shadow factor for imported equipment is the ratio of the shadow exchange rate to the official exchange rate. The shadow factors for taxes and levies will be zero. Where shadow factors for the other items are not readily available, a similar process of breaking costs down further can be employed until the adjustment factor is determinable.

Table 12: Calculation of adjustment factors

Shadow factor		Wind turbine	PV array	Diesel Genset	Conve-rter	Battery	Other	Diesel (fuel)	Wind turbine	Diesel Gen.	Other O&M 1	Other O&M 2
1	Import equip.	90	50	50	40	70		31.83	70	40	10	10
0.95	Local equip.	10	50	50	60	30		16.976	30	60	90	90
0.4	Labour	10	10	10	10	10		4.244	25	25	100	100
0.64	Transport	7	7	7	5	7		13.6	7	7	25	25
0	Taxes, levies	16.5	16.5	26.5	16.5	16.5	0.14	71.4	19	19	33	33
1	Other	1	1	1	1	1	1	25.95	5	5	10	10
	Total	134.5	134.5	144.5	132.5	134.5	1.14	164	156	156	268	268
	Adjustment factor	0.8103	0.7954	0.7403	0.794	0.8028	0.8772	0.5141	0.7563	0.7467	0.6026	0.6026

Multiplication of each (financial) cost component by the relevant adjustment factor yields its economic equivalent. All cost components are added up to obtain the economic costs for each year they occur in.

3.2 Calculation of benefits

Benefits in the financial analysis reflect sales revenue. The economic equivalent is the willingness to pay, which is the sales revenue plus the consumer surplus. Estimating a consumer's willingness to pay for electricity can be difficult and depends on whether the decision to provide electricity (by some means or another) has already been taken or not.

Where electricity must be provided, the willingness to pay will be the cost of the next cheapest electrification option. If the decision to supply electricity has not been taken, the willingness to pay will be at least the cost of the alternative energy sources displaced. The consumer may, in addition, be willing to pay for the added convenience of electricity. An incremental consumer surplus must also be added if energy use is expected to increase as a result of the provision of electricity. This is the additional benefit (consumer surplus) gained by using more electrical energy (over and above the previous energy consumption). These relationships are shown in figure 18, where the total consumer surplus is the savings in alternative energy plus the incremental consumer surplus. Willingness to pay is the consumer surplus plus sales revenue.

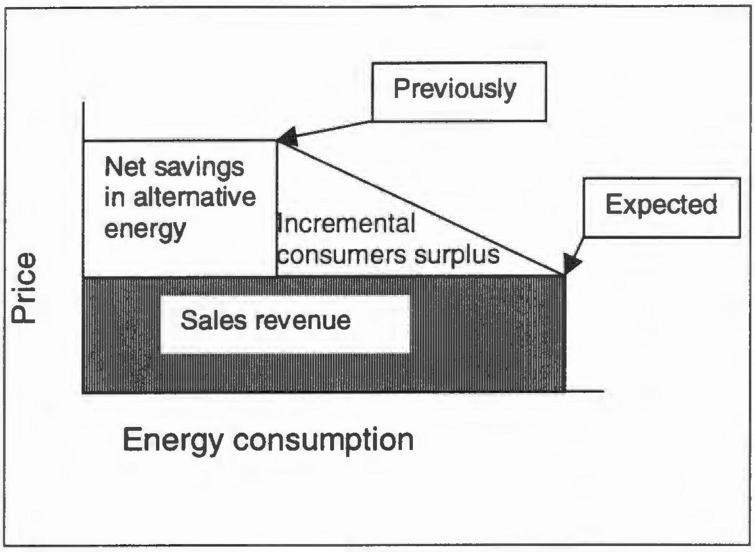


Figure 18: Willingness to pay and consumers surplus (adapted from Davis & Horvei 1995)

3.3 Calculating externalities

Externalities are effects of the project, which are not directly measurable as costs or benefits. It is difficult to associate a monetary value to externalities but where information is available, they should be estimated conservatively. If any doubts exist, externalities should merely be identified and described qualitatively or quantitatively after the CBA. Care should be taken not to double count externalities, which may have been captured in shadow pricing. Some common externalities associated with electrification are listed below (Davis & Horvei 1995) without any quantification whatsoever. The actual impact is dependent on the project to the extent that it may even determine if the impact is a cost or a benefit.

3.3.1 Health and environmental issues

- Air pollution from coal and wood combustion (from domestic, and coal fired power stations in the case of grid connected electricity).
- Noise pollution from diesel generators (and to a smaller extent from wind turbines).
- Accidental ingestion of paraffin by infants.
- Risk of burns and fires associated with candles and paraffin.
- Environmental and social effects of wood collection.
- Improved healthcare in the case of clinic electrification (if not already captured in the estimation of willingness to pay).

3.3.2 Economic growth

- Change in SMME (small medium and micro enterprise) activity.
- Improved working conditions and associated labour productivity.

3.3.3 Training and education

- Access to media.
- Improved quality of working environment for students.
- Training needed for implementation of the project.

3.3.4 Other

- Time savings.
- Convenience and versatility.
- Others.

3.4 Example

A hypothetical diesel battery system is used as an example to demonstrate the method used in the conversion of financial costs to their economic equivalents and the calculation of decision criteria. The financial analysis has been carried out and the yearly system costs for this system are shown in table 13. A lifetime of 10 years has been used and year zero represents the initial costs. Income from revenue is not shown at this stage.

Table 13: Financial yearly system costs

	Capital and replacement						Fuel	O&M and maintenance				
Year	Wind turbine	PV array	Diesel Genset	Conv-erter	Battery	Other	Diesel (fuel)	Wind turbine	Diesel Genset	O&M 1	O&M 2	Total
0	0	0	13800	1594	403	1236	0	0	0	0	0	17033
1	0	0	0	0	0	0	4125	0	5520	2000	19	11664
2	0	0	8052	0	0	0	4125	0	5520	2000	19	19716
3	0	0	0	0	0	0	4125	0	5520	2000	19	11664
4	0	0	8052	0	0	0	4125	0	5520	2000	19	19716
5	0	0	0	0	0	0	4125	0	5520	2000	19	11664
6	0	0	8052	0	0	0	4125	0	5520	2000	19	19716
7	0	0	0	0	378	0	4125	0	5520	2000	19	12042
8	0	0	8052	0	0	0	4125	0	5520	2000	19	19716
9	0	0	0	0	0	0	4125	0	5520	2000	19	11664
10	0	0	8052	0	0	0	4125	0	5520	2000	19	19716

The financial costs in table 13 are then converted to their economic equivalents by multiplying each cost with the relevant adjustment factor from table 12. Table 14 shows the resulting economic yearly system costs.

Table 14: Economic yearly system costs

	Capital and replacement						Fuel	O&M and maintenance				
Year	Wind turbine	PV array	Diesel Genset	Conv-erter	Battery	Other	Diesel (fuel)	Wind turbine	Diesel Genset	O&M 1	O&M 2	Total
0	0	0	10217	1266	324	1084	0	0	0	0	0	12890
1	0	0	0	0	0	0	2121	0	4122	1205	11	7459
2	0	0	5961	0	0	0	2121	0	4122	1205	11	13420
3	0	0	0	0	0	0	2121	0	4122	1205	11	7459
4	0	0	5961	0	0	0	2121	0	4122	1205	11	13420
5	0	0	0	0	0	0	2121	0	4122	1205	11	7459
6	0	0	5961	0	0	0	2121	0	4122	1205	11	13420
7	0	0	0	0	303	0	2121	0	4122	1205	11	7762
8	0	0	5961	0	0	0	2121	0	4122	1205	11	13420
9	0	0	0	0	0	0	2121	0	4122	1205	11	7459
10	0	0	5961	0	0	0	2121	0	4122	1205	11	13420

In the financial analysis, benefits will be the sales revenue and connection fees if any. The equivalent, in the economic analysis is the willingness to pay for electricity, which will depend on each specific electricity user. The assumptions in this example are an annual load of 1 500kWh, no connection fees, a tariff of 30c/kWh and willingness to pay of 40c/kWh. From this the yearly costs and benefits are summarised in Table 15.

Table 15: Financial and economic results

Year	Financial costs	Revenue	Net financial value	Economic costs	Economic benefits	Net econ. value
0	17033		-17033	12890		-12890
1	11664	450	-11214	7459	600	-6859
2	19716	450	-19266	13420	600	-12820
3	11664	450	-11214	7459	600	-6859
4	19716	450	-19266	13420	600	-12820
5	11664	450	-11214	7459	600	-6859
6	19716	450	-19266	13420	600	-12820
7	12042	450	-11592	7762	600	-7162
8	19716	450	-19266	13420	600	-12820
9	11664	450	-11214	7459	600	-6859
10	19716	450	-19266	13420	600	-12820
NPV (discounted at 5%)	R137,697.42	R3,474.78	-R134,222.64	R93,155.30	R4,633.04	-R88,522.26
NPV (discounted at 8%)	R121,495.71	R3,019.54	-R118,476.17	R82,347.68	R4,026.05	-R78,321.63
IRR						
B/C ratio (for discount rate 5%)						0.050
B/C ratio (for discount rate 8%)						0.049

The net present value (NPV) and internal rate of return (IRR) are used as criteria in both the financial and economic analyses. In the economic analysis the benefit to cost (B/C) ratio is also used as an indicator. The discount rates used in the two analyses will, however, generally be different. The discount rate used in the financial analysis represents the cost of capital (required return on capital to the implementing organisation) and the discount rate in the economic analysis represents the opportunity cost of capital (return on alternative projects). These decision criteria have been calculated and are shown in Table 15. The IRRs in this case are non-existent because all the net yearly flows are negative.

4 CBA results for case scenarios

Using the methodology described in the previous section, the financial costs were converted to their economic equivalents. The analysis and results are presented in two parts. The purpose of the first one is to determine the economically cheapest system for each load type. Costs and benefits, which are common to all the systems considered, have not been added to (or subtracted from) the economic equivalents of the financial analysis. The levellised cost of energy (in R/kWh) has been used as the criterion in comparing alternative systems. The reason for this is that benefits (WTP in particular) would be very difficult to estimate for the loads considered. Site and project specific factors play a major part in determining these benefits. The levellised cost of energy is the (discounted) present value of all costs divided by the discounted (to present) quantity of energy supplied. The appendix lists the economic net present costs of all the systems considered.

In the analysis that follows a real economic discount rate of 5% has been used, but in the sensitivity analysis the discount rate has been varied between 2.5% and 15% and the fuel price between 40% and 160% of the base estimate. Results of the sensitivity analysis are plotted in the appendix.

4.1 Clinic load

The clinic has a DC load of 513kWh/year (1.4kWh/day). At the discount rate of 5%, economic costs of each of the systems per kWh are shown in Table 16, together with their load coverage. Systems with load coverage below 95% have their system costs underlined and cheapest systems are in bold. Figure 19 shows the economically cheapest systems.

Table 16: Economic system costs [R/kWh] and load coverage [%] for the clinic

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	36.69	100%	13.32	79%	**14.18**	100%	16.80	56%	14.64	69%
G	36.59	100%	9.49	78%	**13.07**	100%	10.18	87%	9.11	91%
D	36.62	100%	8.49	87%	**12.73**	100%	7.76	93%	7.76	94%
P	36.59	100%	7.92	94%	12.09	100%	7.29	95%	**6.99**	98%
C	36.62	100%	8.21	96%	10.93	100%	6.38	94%	**7.63**	100%
B	36.75	100%	**7.25**	95%	12.00	100%	9.53	79%	9.49	96%
S	36.69	100%	7.04	98%	11.27	100%	**6.10**	97%	6.61	100%
I	36.70	100%	**6.94**	100%	11.28	100%	14.15	92%	10.10	99%
U	36.76	100%	**6.95**	100%	9.89	100%	8.79	91%	7.12	100%

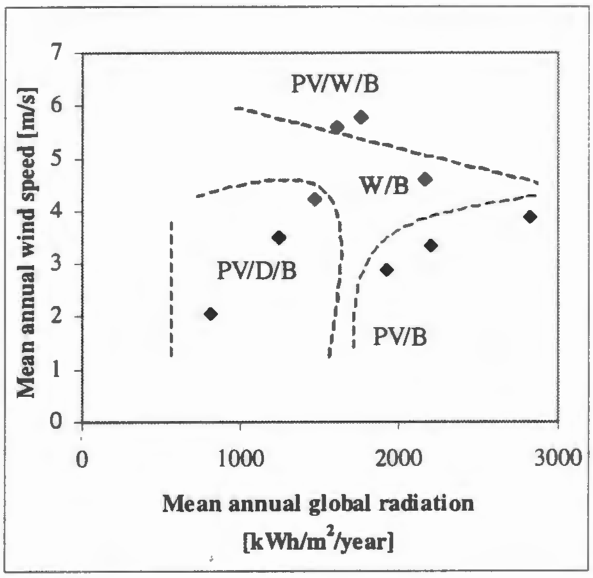


Figure 19: Economically cheapest systems for the clinic load

Significant differences between the financial and economic analysis are the diesel (fuel) price and discount rate. As with the financial analysis, small diesel generators to match the required 105W are not available, resulting in the diesel only systems being very expensive (financially and economically) at all the sites in the simulations. Even the removal of taxes from the fuel price (one of the steps in the economic analysis) did not favour diesel systems over the others.

The financially cheapest (using a discount rate of 8%) systems and the economically cheapest systems at an economic discount rate of 5% are the same.

A sensitivity analysis was performed on two variables: discount rate and fuel price. Discount rates are varied between 2.5% and 15%, and the fuel price between 40% and 160% of the base estimate. The economically cheapest systems remain unchanged for discount rates between 2.5% and 10% and are as shown in figure 19. As the discount rate is increased to 15%, the cost of PV/W/B systems in Upington becomes cheaper than PV/B systems by 6c/kWh.

At a discount rate of 12.5% the costs of PV/W/B and PV/B systems for Upington are equal. The cheapest systems at these discount rates are shown in figures 20a and 20b. Wind systems generally have higher running costs than PV systems. Higher discount rates effectively reduce the present value of future costs, thus favouring wind systems over PV.

Varying fuel price between 40% and 160% of the base estimate had no effect on the cheapest systems for the clinic. Diesel-only systems for the clinic load are very expensive and a reduction in diesel price (to 40%) does not make them competitive. For three sites (Hypo1, George and Durban) where the cheapest systems are PV/D/B, all the non-diesel systems were under-designed (did not cover at least 95% of the required load) and as a result, varying the diesel price only served to compare PV/D/B with diesel-only systems.

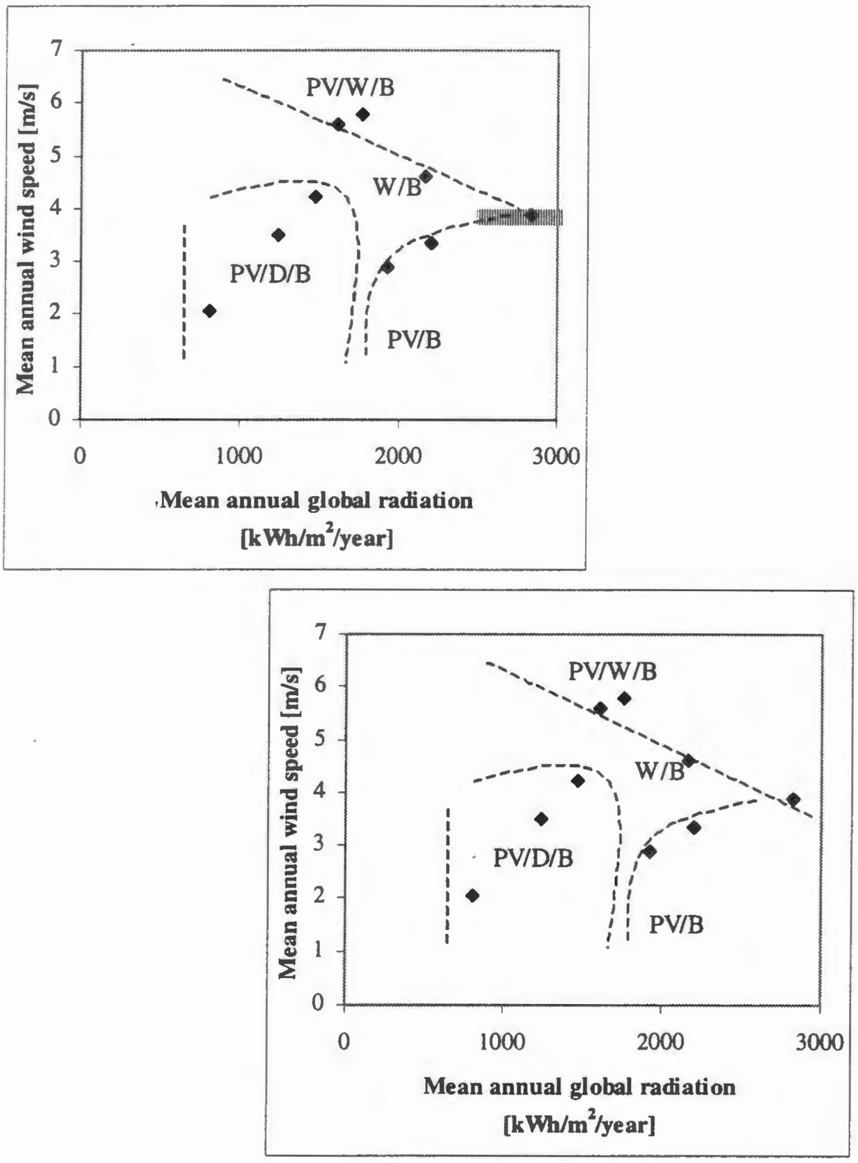


Figure 20: Economically cheapest systems for the clinic load at discount rates of a)12.5% and b)15%

4.2 School load

The school uses both AC and DC loads and has an annual consumption of 716kWh (1.9kWh/day). Table 17 shows the economic costs and load coverage for the school systems.

Table 17: Economic system costs [R/kWh] and load coverage [%] for the school

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	26.67	100%	11.95	75%	**11.01**	100%	23.42	89%	16.06	81%
G	26.57	100%	7.81	76%	**9.65**	100%	22.45	91%	10.90	88%
D	26.59	100%	6.98	86%	9.29	100%	**6.40**	97%	10.31	97%
P	26.55	100%	6.51	91%	9.02	100%	9.29	96%	**7.36**	99%
C	26.59	100%	6.73	93%	8.55	100%	9.36	96%	**6.29**	100%
B	26.77	100%	5.55	95%	9.46	100%	11.38	94%	**8.21**	98%
S	26.67	100%	**5.63**	96%	8.45	100%	9.14	97%	6.71	100%
I	26.73	100%	**5.46**	99%	8.81	100%	22.95	100%	21.60	99%
U	26.73	100%	**5.26**	100%	7.40	100%	7.38	95%	10.06	100%

The economically cheapest systems are shown in figure 21 and are the same as the financially cheapest systems. As with the clinic systems, diesel-only systems are very expensive (financially and economically).

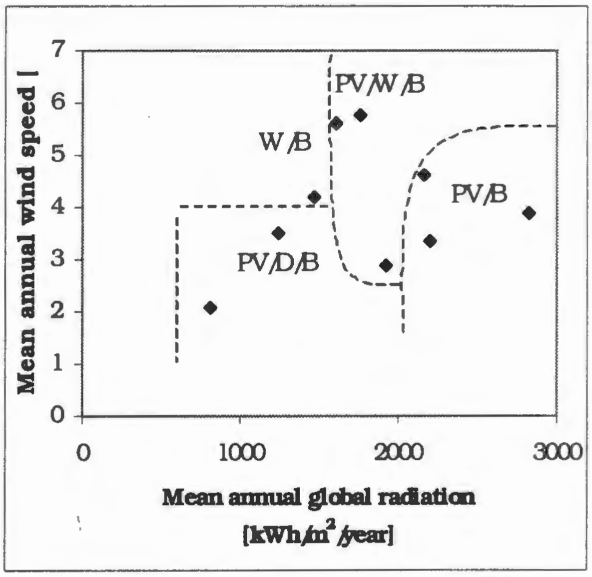
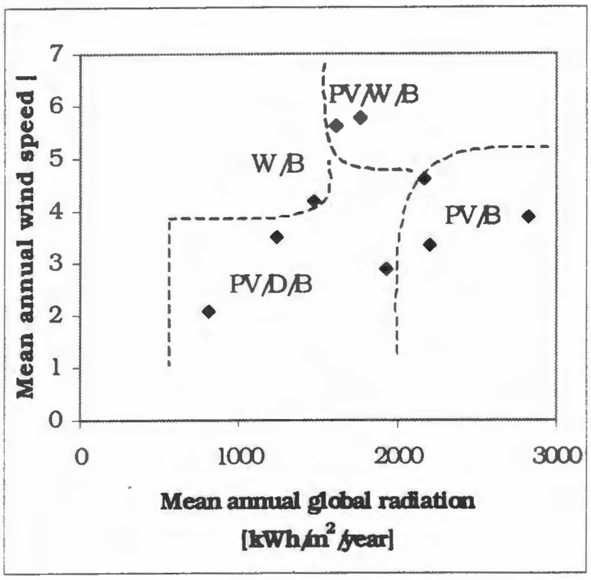


Figure 21: Economically cheapest systems for the school

The economically cheapest systems remain unchanged for discount rates between 2.5% and 10%. At higher discount rates the cheapest systems for Bethlehem and Port Elizabeth become PV/D/B at 12.5% (shown in figure 22a) and 15% (figure 22b) respectively. Varying fuel price between 40% and 160% of the original estimate does not change the cheapest systems. As with the clinic load, diesel-only systems are very expensive and the change in diesel price is not sufficient to make them competitive. Furthermore, the two sites at which PV/D/B systems are the cheapest are unaffected by the change in diesel price as the non-diesel systems were under-designed.

For a small load like the school, even a very high discount rate (of say 15%) would not make diesel-only systems competitive. This high discount rate of 15% does, however, make PV/D/B systems cheaper than PV/W/B at some sites.



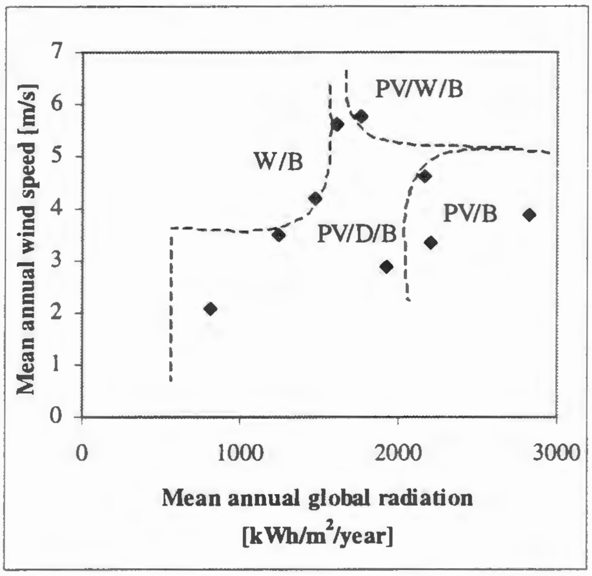


Figure 22: Economically cheapest systems for the school at discount rates of a)12.5% and b)15%

4.3 S1

The S1 is a DC load of 1.7MWh/year (4.7kWh/day). Table 18 shows the economic system costs as well as the load coverage for the S1 load.

Table 18: Electricity costs [R/kWh] and load coverage [%] for the S1 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**12.55**	100%	9.12	83%	12.74	100%	15.78	62%	9.45	80%
G	11.48	100%	5.60	82%	10.97	100%	5.26	94%	**4.91**	97%
D	11.48	100%	4.95	92%	10.38	100%	9.36	99%	**4.68**	100%
P	11.48	100%	4.66	98%	9.68	100%	**3.39**	99%	3.97	100%
C	11.48	100%	5.04	98%	8.79	100%	**3.38**	100%	4.31	100%
B	12.63	100%	**3.91**	99%	10.56	100%	9.80	93%	5.77	100%
S	12.55	100%	4.16	100%	9.23	100%	**3.32**	99%	3.74	100%

I	12.61	100%	**4.16**	100%	9.12	100%	10.45	100%	6.14	100%
U	12.57	100%	**3.95**	100%	7.55	100%	4.92	97%	4.39	100%

Economically cheapest system configurations for the S1 load are shown in figure 23 and are the same as the financially cheapest systems.

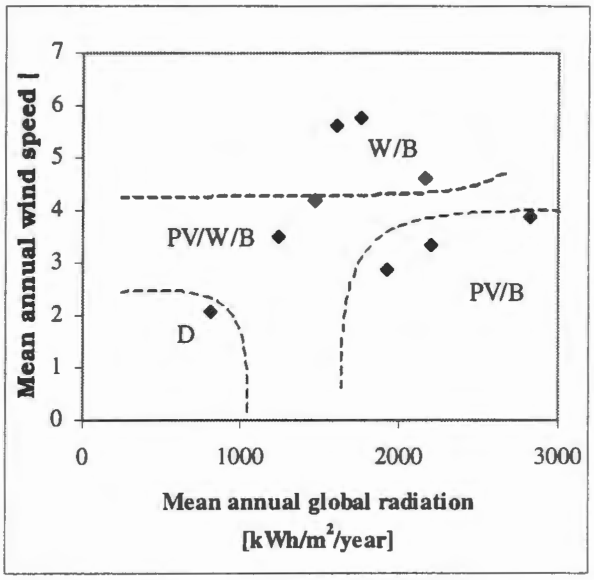


Figure 23: Economically cheapest systems for the S1

The cheapest systems for discount rates between 5% and 15% remain unchanged. At a lower discount rate of 2.5% the cheapest system for Hypo1 is PV/D/B. Fuel price changes between 40% and 130% effect no change in the cheapest system. For fuel prices of 140% to 160% the cheapest system for Hypo1 becomes PV/D/B as was the case with a discount rate of 2.5%. The cheapest systems for this case are shown in figure 24. The difference in cost, between diesel-only and PV/D/B systems at Hypo1, is small and changes in discount rate and/or diesel price could alter which one is cheaper.

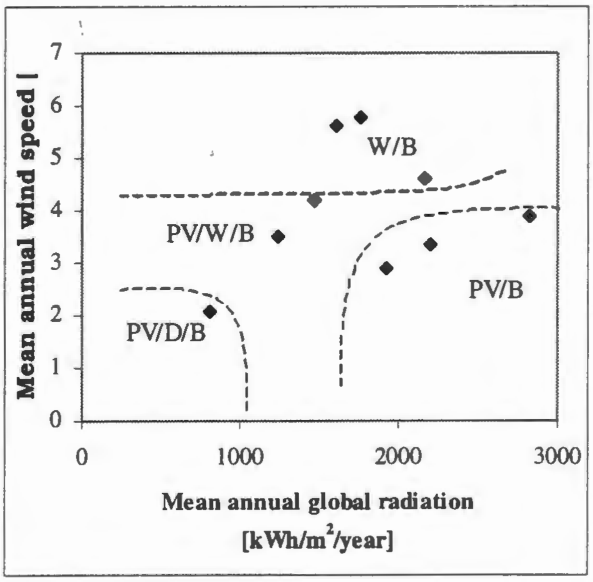


Figure 24: Economically cheapest systems for the S1 load at a discount rate of 2.5% or fuel price of 140% to 160%

4.4 S2

The S2 is a DC load of 3.7MWh/year (10kWh/day). Table 19 shows the economic system costs as well as the load coverage for the S2 load.

Table 19: Electricity costs [R/kWh] and load coverage [%] for the S2 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**7.96**	100%	8.67	83%	9.63	100%	9.32	93%	7.99	96%
G	7.88	100%	5.14	81%	8.53	100%	**5.50**	100%	6.44	97%
D	7.88	100%	4.54	92%	8.35	100%	4.78	100%	**4.23**	100%
P	7.88	100%	4.25	98%	7.94	100%	5.07	99%	**3.52**	100%
C	7.88	100%	4.66	98%	7.58	100%	5.05	100%	**3.72**	100%
B	8.03	100%	**3.53**	99%	7.83	100%	5.42	97%	5.74	100%
S	7.96	100%	3.73	100%	7.55	100%	**2.85**	99%	3.29	100%
I	8.01	100%	**3.74**	100%	7.53	100%	9.55	100%	6.65	100%
U	7.97	100%	**3.57**	100%	6.78	100%	4.81	99%	3.89	100%

Economically cheapest systems for the S2 load are shown in figure 25 and are the same as the financially cheapest systems for the same load.

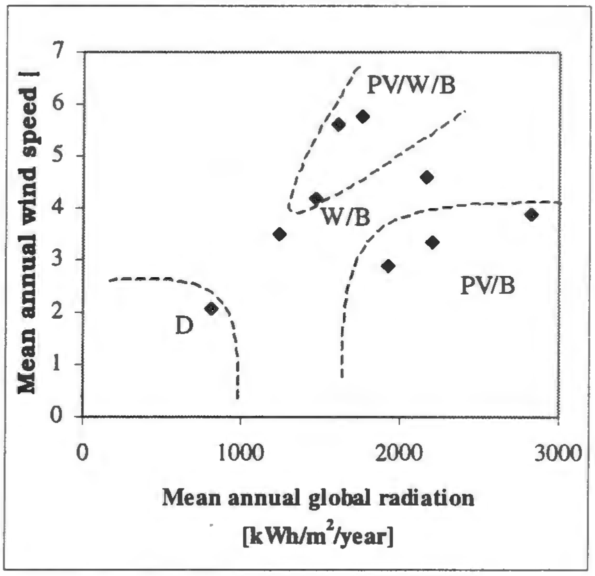


Figure 25: Economically cheapest systems for the S2 load

At a lower discount rate of 2.5% the cheapest system at Hypol is PV/W/B as shown in figure 26a while between 5% and 10% there is no change in the cheapest systems shown in figure 25. At even higher discount rates of 12.5% to 15% (as shown in figure 26b) the cheapest system for George becomes a diesel-only system, previously a wind/battery system.

Reducing fuel price to 40% has no effect on the cheapest systems, while increasing it to between 110% and 160% has the same effect on cheapest systems as a discount rate of 2.5% (figure 26a).

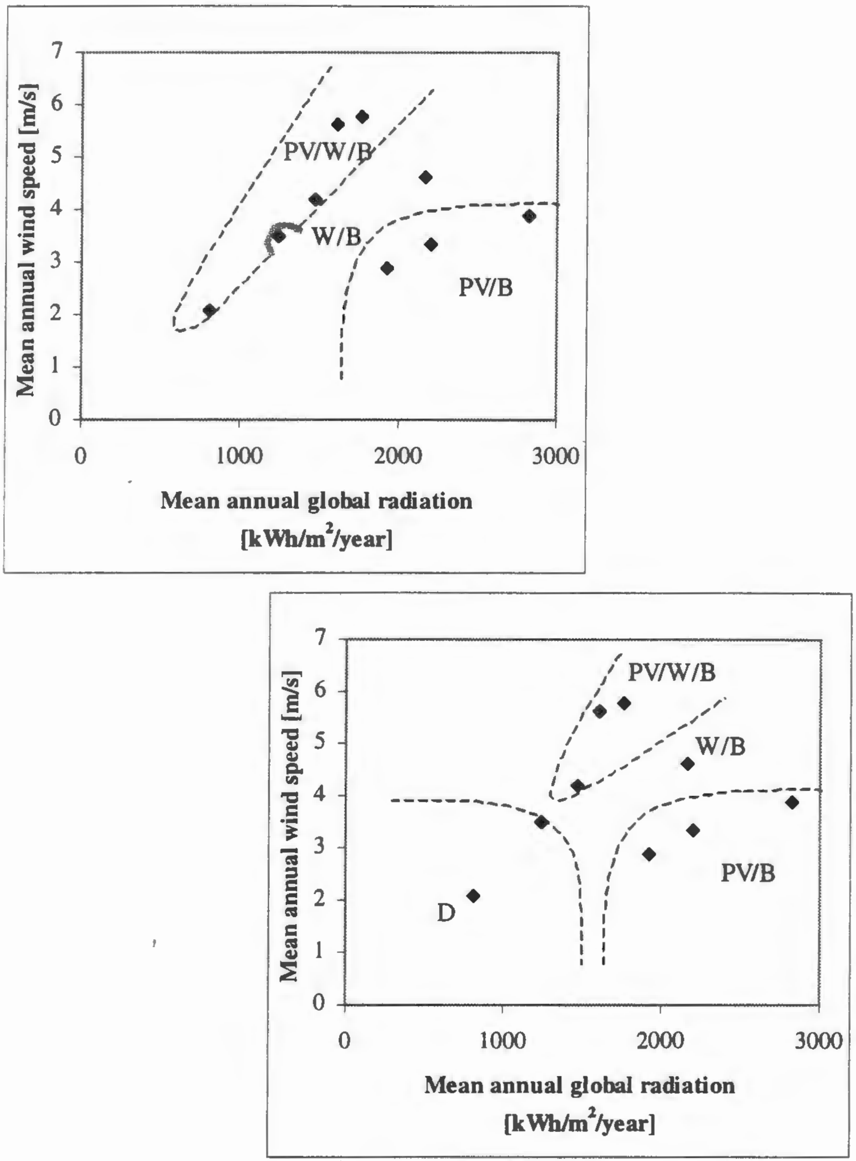


Figure 26: Economically cheapest systems for the S2 load for a)a discount rate of 2.5% or fuel price of 110% to 160% and b)discount rates of 12.5% to 15%

4.5 S3

The S3 is a DC load of 7.3MWh/year (20kWh/day). Table 20 shows the economic cost of electricity as well as the load coverage for the S3 load.

Table 20: Electricity costs [R/kWh] and load coverage [%] for the S3 load

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**4.46**	100%	8.49	83%	6.90	100%	8.27	83%	7.82	96%
G	**4.41**	100%	4.93	81%	5.69	100%	6.13	100%	4.66	100%
D	4.41	100%	4.37	93%	5.62	100%	7.22	100%	**4.36**	100%
P	4.41	100%	4.08	98%	5.41	100%	**3.00**	99%	3.35	100%
C	4.41	100%	4.49	98%	5.18	100%	**3.12**	100%	4.62	100%
B	4.50	100%	**3.36**	99%	5.21	100%	5.24	97%	4.22	99%

S	4.46	100%	3.59	100%	5.06	100%	**2.94**	100%	3.12	100%
I	4.49	100%	**3.60**	100%	5.05	100%	9.38	100%	6.49	100%
U	4.46	100%	**3.40**	100%	4.57	100%	3.43	98%	4.03	100%

Economically cheapest systems for the S3 load are shown in figure 27 and are the same as the financially cheapest systems.

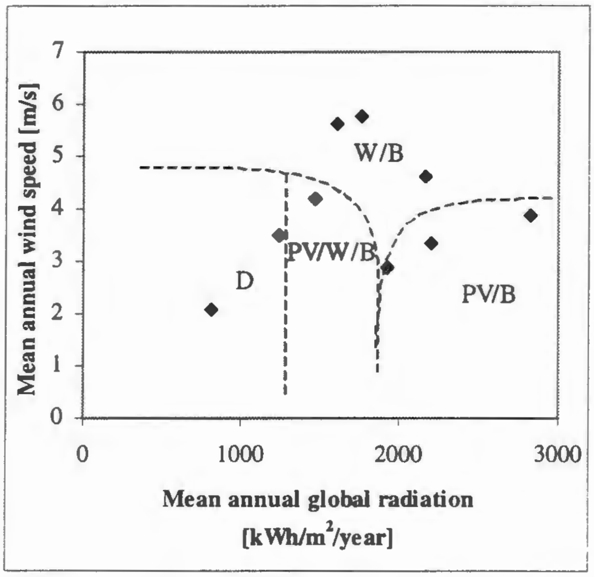
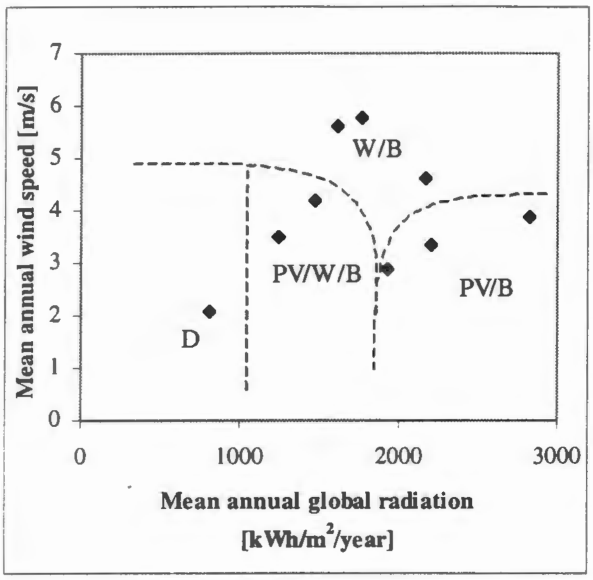


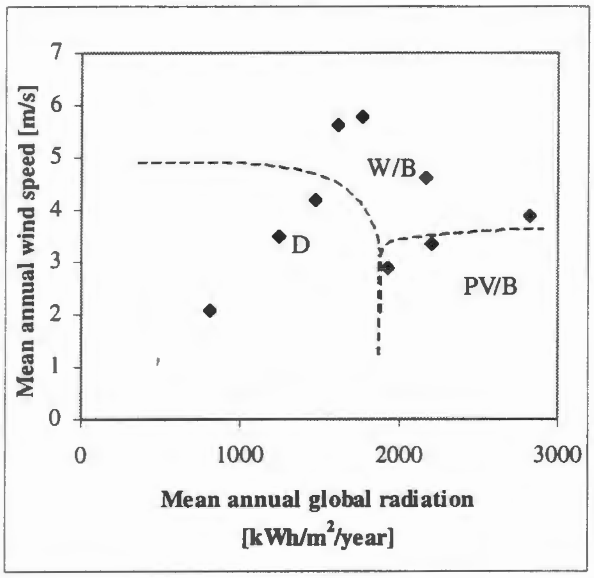
Figure 27: Economically cheapest systems for the S3 load

The effect that varying discount rates have on the economic cost of diesel-only systems is shown in figures 28a to 28d. At lower discount rates PV/W/B is favoured over diesel only (for George at 2.5%). As the discount rate is increased, diesel is favoured over PV/W/B and W/B over PV/B systems. At higher discount rates the future O&M costs of diesel are less weighted as are the O&M costs of wind systems. As the discount rate is further increased, diesel-only systems are seen to be cheaper than PV/B or W/B systems. O&M costs of wind systems are made up of maintenance, overhaul and replacement costs whereas diesel systems have the additional running cost of fuel. A high discount rate therefore favours them more than wind systems. At 15%, the cheapest system at all sites considered is diesel-only and is not shown in figure 28.

If the fuel price is reduced to between 40% and 90% of the base estimate the cheapest system for Durban becomes diesel only. This was also one of the results in Durban of using a discount rate of 7.5%. Fuel price, however, shows no preference between W/B and PV/B, which was the case in Upington for a higher discount rate of 7.5% (figure 28b). Increasing the fuel price to between 130% and 160% results in the cheapest system for George becoming PV/W/B as shown in figure 28a (same effect as a discount rate of 2.5%).

The S3 load is of a size where hybrid systems are competitive with diesel systems and with each other. Changes to either or both of discount rate and diesel price will affect which is the cheapest system for each site.


Mean annual wind speed [m/s]
0
1
2
3
4
5
6
7
W/B
PV/W/B
PV/B
D
0
1000
2000
3000
Mean annual global radiation
[kWh/m²/year]


Mean annual wind speed [m/s]
0
1
2
3
4
5
6
7
W/B
D
PV/B
0
1000
2000
3000
Mean annual global radiation
[kWh/m²/year]

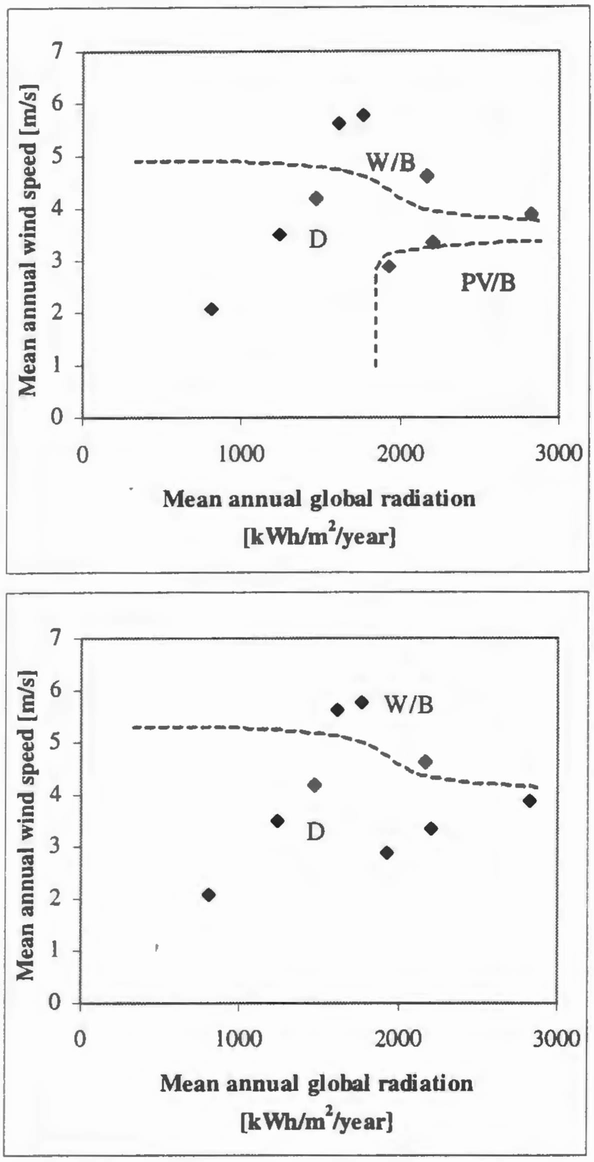


Figure 28: Economically cheapest systems for the S3 load for a) fuel price of 130% to 160% or a discount rate of 2.5%, and discount rates of b)7.5%, c)10% and d)12.5%

4.6 Entrepreneurial development centre

The annual load for the EDC is 12.4MWh (33kWh/day) AC. Table 21 shows the economic systems costs and load coverage. Figure 29 shows the economically cheapest systems for the EDC which are similar to the financially cheapest systems.

Table 21: Economic system costs [R/kWh] and load coverage [%] for the EDC

Site	Diesel only		PV/B		PV/D/B		W/B		PV/W/B	
H	**3.34**	97%	8.48	82%	5.76	100%	8.52	66%	7.79	81%
G	**3.23**	100%	5.01	79%	4.35	100%	3.76	92%	3.91	95%
D	**3.23**	100%	4.43	90%	4.05	100%	3.58	94%	3.81	96%
P	3.23	100%	4.09	96%	3.92	100%	**2.46**	97%	3.03	100%
C	**3.23**	100%	4.46	97%	3.81	100%	3.55	99%	3.24	100%

B	3.60	100%	**3.36**	98%	3.79	100%	4.90	98%	4.47	97%
S	3.34	97%	3.56	100%	3.62	100%	2.59	91%	**2.81**	100%
I	3.59	100%	3.57	99%	**3.52**	100%	5.81	99%	4.66	100%
U	3.32	98%	3.37	100%	**3.24**	100%	3.94	88%	3.43	100%

The EDC load was seen in the financial analysis to be in that region where hybrid and diesel-only systems compete that is at lower loads hybrids were the cheapest, and at higher loads diesel-only was the cheapest. The effects of conversion from financial to economic costs would have been expected to be more visible in the economically cheapest systems for the EDC (figure 29). The only difference is in Irene where the economically cheapest system is PV/D/B whereas the financially cheapest system is diesel only. As mentioned earlier, the effects of removing taxes from diesel, and using a lower discount rate (5% for the economic analysis and 8% for the financial) work against each other. This does however seem to marginally disfavour diesel-only systems.

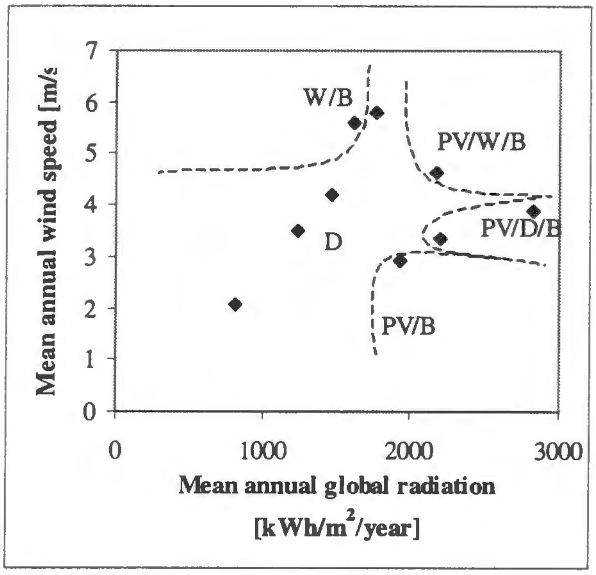


Figure 29: Economically cheapest systems for the EDC

At a lower economic discount rate of 2.5% systems containing diesel (PV/D/B) become less favourable as a result of their higher operating and maintenance costs. As this discount rate is increased, diesel systems become cheaper and above 12.5% are the cheapest within the radiation and wind speed ranges used. Plots for these discount rates are in the appendix.

A decrease in fuel price results in diesel-only systems being preferred over PV/B as well as PV/D/B systems. Increasing fuel price shifts PV/W/B systems in favour of diesel-only systems and PV/B in favour of PV/D/B systems. For Irene and Upington (characterised by high radiation and low wind), optimal systems are PV/D/B systems (at the base fuel price) but an increase in fuel price changes this to PV/B. For these sites (and at this load) PV systems are ideal but should only be complemented with a diesel generator if significant real increases (above inflation) in diesel price are not expected in future. Even at a high diesel price of 160% the base price the cheapest systems for three sites (with low radiation and wind speed) are diesel only. This is also true at a discount rate of 2.5%. Plots for all fuel prices are in the appendix.

4.7 Dairy farm

The annual AC load for the dairy farm is 15.7MWh (43kWh/day). Table 22 shows the economic costs (in R/kWh) and load coverage (%) for all the dairy farm systems. The economically cheapest systems for the dairy farm are shown in figure 30a and are the same as the financially cheapest systems. Diesel-only systems are the cheapest for all but two sites, and the next cheapest systems (excluding diesel-only) were determined and are shown in figure 30b.

Table 22: Economic system costs [R/kWh] and load coverage [%] for the dairy farm

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	**2.71**	100%	8.88	78%	5.19	100%	8.84	72%	7.85	74%
G	**2.86**	100%	5.25	75%	4.14	100%	4.11	94%	4.24	99%
D	**2.86**	100%	4.60	86%	3.70	100%	3.11	97%	3.56	99%
P	2.86	100%	4.19	94%	3.56	100%	**2.20**	98%	3.37	100%
C	2.86	100%	4.51	96%	3.50	100%	**2.84**	99%	3.84	100%
B	**2.74**	100%	3.44	95%	3.27	100%	5.07	94%	4.09	98%
S	**2.71**	100%	3.56	99%	3.15	100%	2.24	94%	3.19	100%
I	**2.73**	100%	3.56	99%	3.15	100%	7.81	100%	5.87	100%
U	**2.71**	100%	3.35	100%	2.83	100%	3.32	95%	3.27	100%

For Springbok the financially second cheapest system is PV/W/B and the economically second cheapest system is PV/D/B. For all other sites financially and economically second cheapest systems are the same. As was the case for the financially cheapest systems, it is seen that at high loads PV systems become less favourable and diesel systems a lot cheaper.

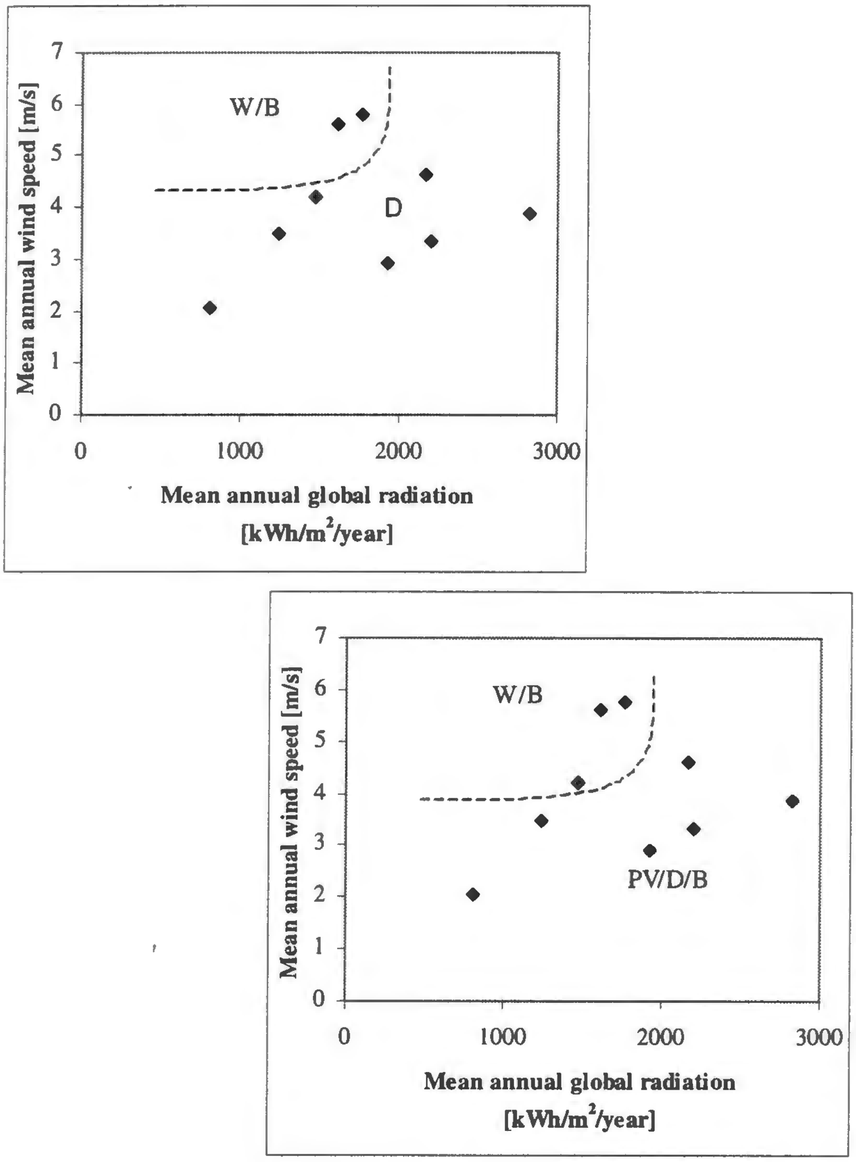


Figure 30: Economically a)cheapest systems and
b)next cheapest systems (excluding diesel-only) for the dairy farm

A lower discount rate shifts cheapest systems from diesel-only to W/B and PV/D/B. Next cheapest systems shift from PV/D/B to PV/W/B and PV/B. A higher discount rate favours diesel-only systems over W/B as the cheapest systems whereas next-cheapest systems are unaffected. Even at a discount rate of 15% there are three sites (with low radiation and high wind resources) where W/B systems are the next cheapest. It was seen earlier that diesel-only systems benefit more from a higher discount rate than wind systems. Here it is seen that PV/D/B systems (with a 40/60 split between PV and diesel) are not favoured over wind systems at higher discount rates (of up to 15%).

A reduction in fuel price results in the cheapest system for Cape Town becoming diesel-only (was W/B at base fuel price). No change occurs to the next-cheapest system. An increase in diesel price favours PV/D/B, W/B and PV/W/B over diesel-only as the cheapest system. As the next-cheapest system, PV/W/B and PV/B systems are favoured over PV/D/B.

4.8 Crop farm

The annual AC load for the crop farm is 26.2MWh (72kWh/day). Table 23 shows the economic system costs (in R/kWh) and load coverage for all the crop farm systems. At all sites the economically cheapest system is a diesel-only system as was the case financially. The economically next cheapest systems are shown in figure 31 and are, with one exception, the same as the financially cheapest systems; for Springbok the financially next cheapest system is PV/W/B, whereas economically PV/W/B and PV/D/B are equal in cost as the next cheapest systems.

Table 23: Economic systems costs [R/kWh] and load coverage [%] for the crop farm

Site	*Diesel only*		*PV/B*		*PV/D/B*		*W/B*		*PV/W/B*	
H	1.90	100%	8.69	80%	**4.46**	100%	8.99	76%	8.16	84%
G	1.86	100%	4.82	77%	**3.23**	100%	4.37	93%	4.17	96%
D	1.86	100%	4.47	87%	**3.15**	100%	3.57	97%	3.71	100%
P	1.86	100%	4.49	86%	**3.13**	100%	2.45	88%	3.21	94%
C	1.86	100%	4.43	96%	3.10	100%	**2.41**	96%	3.31	100%
B	2.45	100%	3.34	96%	**3.10**	100%	5.36	91%	4.47	99%
S	1.90	100%	3.48	99%	**2.83**	100%	2.33	93%	**2.83**	100%
I	2.44	100%	3.49	99%	**3.01**	100%	7.13	97%	5.22	100%
U	1.90	100%	3.37	97%	**2.89**	100%	3.88	85%	3.40	97%

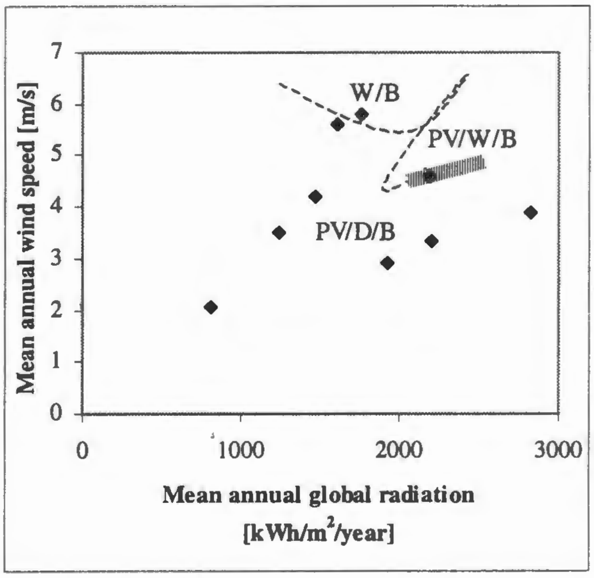


Figure 31: Second cheapest systems after diesel-only for the crop farm

Diesel-only systems are the cheapest at all discount rates between 2.5% and 15% as well as fuel prices between 40% and 160% of the base price. Varying the discount rate shifts the next-cheapest system for Springbok, which was PV/W/B and PV/D/B equally, to PV/W/B at lower discount rates and to PV/D/B at higher discount rates. A reduction in discount rate also shifts the next-cheapest system in Bethlehem in favour of PV/B from PV/D/B.

A reduction in the diesel price results in the next-cheapest system in Springbok becoming PV/D/B and an increase in the fuel price results in it becoming PV/W/B. Increasing the fuel price also favours PV/B systems over PV/D/B in Bethlehem. The complete set of plots for the sensitivity analysis is in Appendix C.

the appendix. The rough-sized hybrid systems are not economically cheaper than diesel-only systems at such high loads and within the radiation limits used.

4.9 Overview of results

The results in terms of the economically cheapest systems do not vary significantly from the financially cheapest systems. The financial and economic costs vary most significantly in diesel price and discount rate. The economic diesel price is about 52% of the financial price, which constitutes a major tax portion. The real discount rate used in the financial analysis is 8% and the real economic discount rate used in the analysis is 5%. Systems consisting of diesel gensets, compared to PV and wind systems, usually have lower initial costs but higher running costs. The effects of the lower economic diesel price and lower economic discount rate work against each other with the result that in general, the financially cheapest systems (at a discount rate of 8%) are the same as the economically cheapest systems at a discount rate of 5%. Exceptions to this are PV/D/B systems being preferred over a diesel-only system (at a load of 12.4MWh/year) and over a PV/W/B system (at a load of 26.2MWh/year), where financially the PV/D/B and PV/W/B systems were equal in cost (for the latter load).

The general shape of the areas where the different hybrid systems were found to be the cheapest (economically) will be the same as that in figure 16 (for the financially cheapest systems) and is repeated in figure 32a. As loads increase there will be a general shift of all the curves to the right and up: diesel systems become more favourable. On the scale used for the plots the shift will be more to the right than up, that is, PV/B systems become more expensive faster than W/B systems.

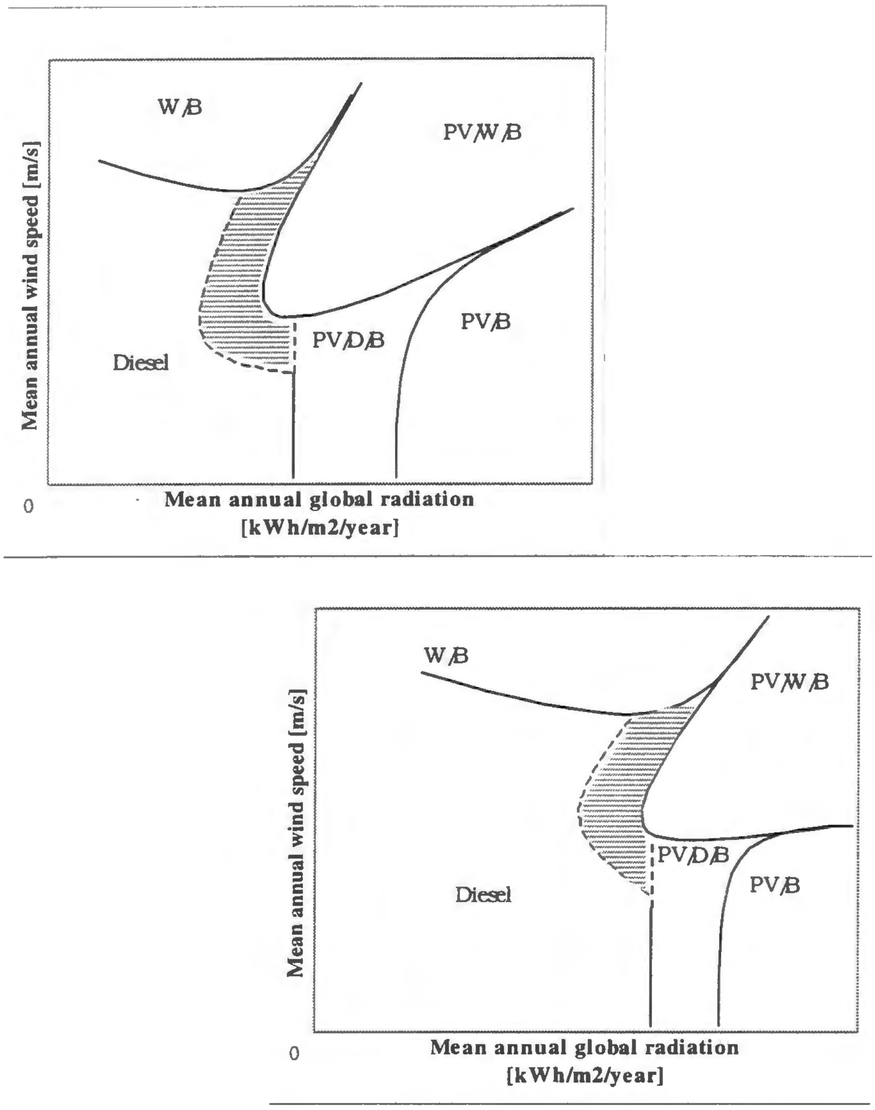


Figure 32: Economically cheapest systems generalised for all loads a)for the base case and b)as discount rates increase

At higher discount rates, systems with diesel generators become economically more favourable than other systems. Systems with wind turbines are favoured over systems with PV at high discount rates. This is a result of wind turbine overhauls and other operating and maintenance costs, compared to almost none associated with PV. Diesel systems benefit more from a higher discount rate than wind systems as they have the additional recurrent cost of fuel. In spite of a 40/60 split (by design) between PV and diesel in PV/D/B systems, an increase in discount rate (of up to 15%) did not favour PV/D/B systems over W/B for any of the cases. As discount rates are increased, there is a rightward and downward shift of all but the W/B and diesel-only systems, which expand right and upward (figure 32b).

For the S3 and EDC loads (7.3MWh/year and 12.4MWh/year) strong competition exists between the hybrid systems and the diesel-only systems. Variations in discount rate significantly affect whether hybrid systems are economically cheaper than diesel-only systems and also which hybrid system is most suited. At lower loads similar competition exists except that for sites with very strong resources, diesel-only systems do not become cheaper even at very high discount rates (of up to 15%). At higher loads diesel-only systems are favoured and variations in discount rate (in both directions) are not enough to significantly reduce the cost difference between hybrid systems and diesel-only systems at many sites.

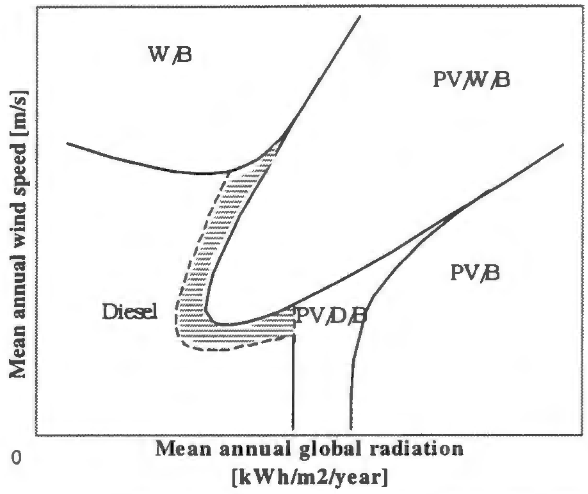


Figure 33: Economically cheapest systems generalised for all loads as fuel price increases

The general result on the plot as fuel price is increased is a left and downward shift of all the regions into the diesel-only area. The area where PV/D/B systems are the cheapest shifts left and downward and narrows. The cheapest systems are not very sensitive to diesel price for loads below 1.7MWh/year or greater than 15.7MWh/year. The S3 and EDC (between 7.3MWh/year and 12.4MWh/year) loads are in a region where diesel price strongly affects whether diesel or hybrid systems are the cheapest economically.

4.10 Conclusions

The economically cheapest systems are very similar to the financially cheapest systems. For the scenarios used they were exactly the same but small differences would have been seen if a broader set of scenarios were used. The reason for such small differences between the financially and economically cheapest systems is the opposing effects of the various steps in the analysis. Of note are the adjustment factors for diesel fuel of 51.4% and the economic discount rate of 5%. Diesel systems when compared to wind and PV systems have low initial costs and high operating costs. The adjustment factor reduces the diesel operating costs but a lower discount rate increases the present value of such future costs.

The general shape of the regions in which each hybrid system was found to be economically the cheapest has been identified and does not differ from that for the financially cheapest systems. Increasing the discount rate showed a shift in most of the boundary lines to the right and down. The W/B and diesel/only areas shifted right and upwards, effectively expanding the region in which diesel only is the cheapest. These shifts were seen to be more into PV than wind systems (on the scale used). Increasing load also showed a rightward and upward shift of the lines.

An increase in diesel price would result in a left and downward shift of all the regions into the diesel-only area as well as a narrowing of the area where PV/D/B systems are the cheapest. Variations in diesel price are seen to significantly affect the cheapest systems for loads between roughly 7.3MWh/year and 12.4MWh/year.

The hybrid systems used were rough sized and not optimally matched to load size and site resources. If optimal hybrid systems were used and compared to each other and to diesel systems, it is likely that a shift in the regions would have occurred to the left and downwards, effectively reducing the size of the area, where diesel-only systems are the cheapest.

Hybrid systems are economically cheaper than diesel only systems at low loads (roughly 700kWh/year and less). The reverse is true at very high loads of 26MWh/year. In between

700kWh/year and roughly 4MWh/year, diesel-only systems are cheapest for sites with very poor resources. For loads between roughly 7MWh/year and 12MWh/year hybrid and diesel systems compete. The cheapest systems in this load range are also the most sensitive to economic parameter changes. Between 12 and 26MWh/year the competitiveness of hybrid systems to diesel systems is progressively reduced. At about 12MWh/year, all five hybrid configurations were found to be the cheapest at some radiation-wind speed combination. At 15MWh/year wind systems were the cheapest when wind speeds were high and diesel systems otherwise. At 26MWh (and above) diesel only systems are the cheapest for all systems within the wind and radiation limits used.

Other than a shift, it is expected that the general shape of the cheapest systems (figure 32a) will be the maintained at all loads. For the wind speed and radiation range used and plotted, the 7MWh/year to 12MWh/year load range showed the closest costs between all the systems.

Key decision criteria to complete the cost-benefit analysis were not calculated. This was because estimates for benefits, WTP in particular would be inaccurate if not done for a specific project. The economic net present costs (appendix) can be used as an indication of the present value of indirect benefits needed to make the system economically feasible.

5 CBA implementation in *Hybrid Designer*

Hybrid Designer is a hybrid system optimisation and simulation program developed by the Energy & Development Research Centre (EDRC). Hybrid designer optimises the hybrid system configuration using genetic algorithms and one step in the genetic algorithm is to determine the life cycle costs of each system in order to weight it. Life-cycle costs are calculated in one of two ways, depending on the mode the simulation is run. The difference between the 'quick' and 'in-depth' costing is that in quick costing costs like replacement costs are evenly distributed over the replacement period, whereas in the in-depth costing a replacement cost is incurred at the end of each replacement period (Kuik & Seeling-Hochmuth 1998).

A method is presented here for implementing CBA into Hybrid Designer. This could be done to either optimise the hybrid system configuration based on economic costs and benefits (as opposed to financial) or to determine the economic impact of a manually designed or optimised hybrid system.

5.1 Conversion of financial costs to economic costs

Financial costs used in Hybrid Designer are listed in Table 24 below.

Table 24: Cost items used in Hybrid Designer

Diesel generator	*Battery*	*Wind turbine*	*PV panel*	*Converter*
Cost of genset	Cost of battery	Cost of wind turbine	Cost of PV panel	Cost of converter
Installation cost	Installation cost	Installation cost	Installation cost	Installation cost
BOS cost	BOS cost	BOS cost	BOS cost	BOS cost
Fuel price (/l)				
Overhaul cost		Overhaul cost		
Maintenance cost	Maintenance cost	Maintenance cost	Maintenance cost	Maintenance cost
Diesel tank cost				

For each of these costs an adjustment factor must be calculated to determine its shadow price. This can be done in one of two ways:

1. If the user knows the adjustment factor for each item, it may be entered directly.

2. If the user does not know each adjustment factor, the cost of the item must be broken down (by user input) into six categories (as a fraction or as actual costs), namely imported equipment, local equipment, labour, transport, taxes/levies and other. Also needed as input are adjustment factors for the last six categories but those are generally readily available. The adjustment factor for each cost item is then calculated as

$$Adjustment\_factor = \frac{\sum_{all\_categories} adjustment\_factor_{category} \times \cos t_{category}}{\sum_{all\_categories} \cos t_{category}}$$

It is recommended that these adjustment factors be calculated for the system as a whole (for each component type) and maintain them as default values. In the component description, the user must then be given the option to specify adjustment factors that are different to the default ones. This will be important when, say, local and imported equipment are available as choices and tariffs exist on some equipment. To reduce the number of inputs, only one adjustment factor need be used for installation costs (for all component types). Furthermore, the adjustment factors for each component cost can be grouped with its BOS cost.

The adjustment factors that are needed are for the following costs:

1. Diesel generator and associated BOS
2. Diesel generator maintenance
3. Diesel generator overhaul
4. Diesel tank
5. Battery and associated BOS
6. Battery maintenance
7. Wind turbine and associated BOS
8. Wind turbine maintenance
9. Wind turbine maintenance
10. PV panel and associated BOS
11. PV panel maintenance
12. Converter and associated BOS
13. Converter maintenance
14. Diesel fuel

These adjustment factors will be default factors, with the option of changing factors 1 to 13 to component specific ones.

Using the same method used in Hybrid Designer for (financial) in-depth costing, the economic costs are recorded as they are incurred. These economic costs will be the financial costs multiplied by their relevant adjustment factors: the component specific ones if they exist or the default ones otherwise. The same procedure and operating variables (to determine maintenance, overhaul and replacement requirements as well as fuel consumption) used to calculate the financial costs could be used to determine the economic costs, to allow for easier implementation. The economic costs must be added up, to determine the total costs incurred in each year of the analysis. Call this $Economic\_costs_{y}$, where the subscript denotes the year y.

5.2 Adding in the benefits and other costs

The largest portion of the benefits will usually be the 'willingness to pay'. This will have to be input by the user and will be dependent on the application being served. Guidelines for estimating this can be found in 'Handbook for the economic analysis of energy projects' (Davis & Horvei, 1995). The willingness to pay must be stated as the benefit per kWh of electricity supplied ($=WTP_{kWh}$)

There will be specific costs and benefits associated with each specific hybrid system and its location. These will have to be specified either per kWh of energy produced by each component or as an amount per installed capacity of each component for each year the component is in existence. Possible inputs are then:

Benefit of diesel generator (R/kWh) $=B_{dg\_kWh}$

Benefit of wind turbine (R/kWh) $=B_{wt\_kWh}$

Benefit of PV panel (R/kWh) $=B_{pv\_kWh}$

Benefit of diesel generator (R/kWpeak/year) $=B_{dg\_kWp}$

Benefit of wind turbine (R/kWpeak/year) $=B_{wt\_kWp}$

Benefit of PV panel (R/kWpeak/year) $=B_{pv\_kWp}$

Additional cost of diesel generator (R/kWh) $=C_{dg\_kWh}$

Additional cost of wind turbine (R/kWh) $=C_{wt\_kWh}$

Additional cost of PV panel (R/kWh) $=C_{pv\_kWh}$

Additional cost of diesel generator (R/kWpeak/year) $=C_{dg\_kWp}$

Additional cost of wind turbine (R/kWpeak/year) $=C_{wt\_kWp}$

Additional cost of PV panel (R/kWpeak/year) $=C_{pv\_kWp}$

If the installed capacity of diesel generator, wind turbine and PV are CAP_{dg}, CAP_{wt} and CAP_{pv} respectively, their energy produced $ELEC_{dg}$, $ELEC_{wt}$ and $ELEC_{pv}$ and the energy delivered to the load $ELEC_{del}$ the benefits and additional costs incurred in each year of operation are:

$$\begin{aligned}\mathit{Benefit} = {} & (WTP_{kWh} \times ELEC_{del}) + (B_{dg\_kWh} \times ELEC_{dg}) + (B_{wt\_kWh} \times ELEC_{wt}) + (B_{pv\_kWh} \times ELEC_{pv}) \\ & + (B_{dg\_kWp} \times CAP_{dg}) + (B_{wt\_kWp} \times CAP_{wt}) + (B_{pv\_kWp} \times CAP_{pv})\end{aligned}$$

$$\begin{aligned}\mathit{Additional\_cost} = {} & (C_{dg\_kWh} \times ELEC_{dg}) + (C_{wt\_kWh} \times ELEC_{wt}) + (C_{pv\_kWh} \times ELEC_{pv}) \\ & + (C_{dg\_kWp} \times CAP_{dg}) + (C_{wt\_kWp} \times CAP_{wt}) + (C_{pv\_kWp} \times CAP_{pv})\end{aligned}$$

These benefits and additional costs must be calculated for each year of the selected time frame. The benefits and additional costs for the year y can be denoted as $\mathit{Benefit}_y$ and $\mathit{Additional\_cost}_y$.

Two more inputs needed before the decision criteria are calculated are the real economic discount rate (*redr*) and the time frame (*tf*) in years.

The Economic net present value, B/C (benefit to cost ratio) can be calculated as (year zero denotes costs and benefits incurred at time of implementation):

$$Economic\_NPV = \sum_{y=0}^{tf} \frac{Benefits_y - Cost_y - Additional\_\cos t_y}{(1+redr)^y}$$

The economic internal rate of return (EIRR) must also be calculated as one of the decision criteria in CBA. This is the discount rate at which NPV=0. EIRR is calculated iteratively by improving on guesses of EIRR until the NVP is close enough to zero. Details of how to implement this are not provided, as it is assumed that the software on which this is being implemented has a function to estimate *redr* for which *Economic_NPV* will be zero.

$$B/C = \frac{\sum_{y=0}^{tf} \frac{Benefits_y}{(1+redr)^y}}{\sum_{y=0}^{tf} \frac{Cost_y + Additional\_\cos t_y}{(1+redr)^y}}$$

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Appendix: logsheets, economic net present costs and graphs

Rural clinic

						Summer weekday				Summer weekend				Winter weekday				Winter weekend				
Equipment	Power (W)	% use within hour	Quantity	Total Power	Average power	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	AC/ DC
Lights	15	40%	4	60	24	5	19	24	120	5	19	24	120	5	19	24	120	5	19	24	120	DC
	15	40%	4	60	24	5	0	5	120	5	0	5	120	5	0	5	120	5	0	5	120	DC
Lights (consulting room)	15	100%	4	60	60	0	0	0	0	0	0	0	0	8	8	16	480	0	0	0	0	DC
Fridge (vaccine)	60	38%	1	60	22.5	24	0	24	540	24	0	24	540	0			0	0			0	DC
	60	50%	1	60	30	0			0	0			0	24	0	24	720	24	0	24	720	DC
Freezer (vaccine)	60	25%	1	60	15	24	0	24	360	24	0	24	360	24	0	24	360	24	0	24	360	DC
									1140				1140				1800				1320	

Rural school						Summer weekday				Summer weekend				Winter weekday				Winter weekend				
Equipment	Power (W)	% use within hour	Quantity	Total Power	Average power	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	AC/DC
Lights	40	100%	8	320	320	3	19	22	960	0	0	0	0	3	18	21	960	0	0	0	0	DC
	40	67%	8	320	213.3	0	0	0	0	0	0	0	0	6	8	14	1280	0	0	0	0	DC
Lights	11	100%	1	11	11	3	19	22	33	0	0	0	0	3	18	21	33	0	0	0	0	DC
TV	80	50%	1	80	40	6	8	14	240	0	0	0	0	6	8	14	240	0	0	0	0	AC
	80	25%	1	80	20	0	0	0	0	6	8	14	120	0	0	0	0	6	8	14	120	AC
VCR	15	50%	1	15	7.5	6	8	14	45	0	0	0	0	6	8	14	45	0	0	0	0	AC
	15	25%	1	15	3.75	0	0	0	0	6	8	14	22.5	0	0	0	0	6	8	14	22.5	AC
PC	150	50%	1	150	75	6	8	14	450	0	0	0	0	6	8	14	450	0	0	0	0	AC
	150	25%	1	150	37.5	0	0	0	0	6	8	14	225	0	0	0	0	6	8	14	225	AC
OHP	150	25%	1	150	37.5	6	8	14	225	0	0	0	0	6	8	14	225	0	0	0	0	AC
									1953				367.5				3233				367.5	

Ld=logged data, S1=Ld/8.5, S2=Ld/4, S3=Ld/2

Hour	Ld	S1	S2	S3
1	990	116	248	495
2	990	116	248	495
3	990	116	248	495
4	990	116	248	495
5	990	116	248	495
6	990	116	248	495
7	990	116	248	495
8	2430	286	608	1215
9	1980	233	495	990
10	1620	191	405	810
11	1890	222	473	945
12	1980	233	495	990
13	2700	318	675	1350
14	2430	286	608	1215
15	2250	265	563	1125
16	2070	244	518	1035
17	2070	244	518	1035
18	1980	233	495	990
19	1350	159	338	675
20	990	116	248	495
21	990	116	248	495
22	990	116	248	495
23	990	116	248	495
24	990	116	248	495
25	990	116	248	495
26	990	116	248	495
27	990	116	248	495
28	990	116	248	495
29	990	116	248	495
30	990	116	248	495
31	990	116	248	495
32	1440	169	360	720
33	1530	180	383	765
34	1620	191	405	810
35	2205	259	551	1103
36	2970	349	743	1485
37	4050	476	1013	2025
38	2970	349	743	1485
39	1800	212	450	900
40	1530	180	383	765
41	1620	191	405	810

Hour	Ld	S1	S2	S3
57	1170	138	293	585
58	1260	148	315	630
59	1710	201	428	855
60	2250	265	563	1125
61	2700	318	675	1350
62	2520	296	630	1260
63	2250	265	563	1125
64	1485	175	371	743
65	1980	233	495	990
66	2025	238	506	1013
67	2070	244	518	1035
68	2115	249	529	1058
69	1890	222	473	945
70	1350	159	338	675
71	990	116	248	495
72	990	116	248	495
73	990	116	248	495
74	990	116	248	495
75	990	116	248	495
76	990	116	248	495
77	990	116	248	495
78	990	116	248	495
79	990	116	248	495
80	1890	222	473	945
81	1620	191	405	810
82	1800	212	450	900
83	1980	233	495	990
84	2070	244	518	1035
85	1980	233	495	990
86	2250	265	563	1125
87	2160	254	540	1080
88	2520	296	630	1260
89	3060	360	765	1530
90	3150	371	788	1575
91	2700	318	675	1350
92	2250	265	563	1125
93	2070	244	518	1035
94	1620	191	405	810
95	1170	138	293	585
96	1170	138	293	585
97	1170	138	293	585

Hour	Ld	S1	S2	S3
113	3870	455	968	1935
114	4950	582	1238	2475
115	1530	180	383	765
116	1170	138	293	585
117	1170	138	293	585
118	1170	138	293	585
119	1170	138	293	585
120	1170	138	293	585
121	1440	169	360	720
122	1440	169	360	720
123	1440	169	360	720
124	1440	169	360	720
125	1440	169	360	720
126	1440	169	360	720
127	1440	169	360	720
128	1440	169	360	720
129	1440	169	360	720
130	1350	159	338	675
131	1440	169	360	720
132	2250	265	563	1125
133	2430	286	608	1215
134	2250	265	563	1125
135	1980	233	495	990
136	1800	212	450	900
137	1440	169	360	720
138	1170	138	293	585
139	1170	138	293	585
140	720	85	180	360
141	1170	138	293	585
142	1170	138	293	585
143	1170	138	293	585
144	1170	138	293	585
145	1350	159	338	675
146	1350	159	338	675
147	1350	159	338	675
148	1350	159	338	675
149	1350	159	338	675
150	1350	159	338	675
151	1350	159	338	675
152	1350	159	338	675
153	1350	159	338	675

43	1890	222	473	945
44	2025	238	506	1013
45	2520	296	630	1260
46	1890	222	473	945
47	990	116	248	495
48	990	116	248	495
49	990	116	248	495
50	990	116	248	495
51	990	116	248	495
52	990	116	248	495
53	990	116	248	495
54	990	116	248	495
55	990	116	248	495
56	1080	127	270	540

99	1170	138	293	585
100	1170	138	293	585
101	1170	138	293	585
102	1170	138	293	585
103	1170	138	293	585
104	1800	212	450	900
105	2250	265	563	1125
106	3150	371	788	1575
107	3330	392	833	1665
108	3510	413	878	1755
109	1800	212	450	900
110	1170	138	293	585
111	1530	180	383	765
112	1800	212	450	900

155	1350	159	338	675
156	1980	233	495	990
157	3150	371	788	1575
158	2070	244	518	1035
159	1980	233	495	990
160	2430	286	608	1215
161	2700	318	675	1350
162	2700	318	675	1350
163	2790	328	698	1395
164	2340	275	585	1170
165	2250	265	563	1125
166	1980	233	495	990
167	990	116	248	495
168	990	116	248	495

Weekly load [Wh/week]	280215	32960	70111	140110
Daily load [kWh/day]	40.03	4.71	10.02	20.02
Peak load [W]	4950	582	1238	2475
Annual load [kWh/year]	14651	1723	3666	7326

Entrepreneurial development centre

						Summer weekday				Summer weekend				Winter weekday				Winter weekend				
Equipment	Power (W)	% use within hour	Quantity	Total Power	Average power	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	AC/ DC
Lights	40	100%	15	600	600	9	8	17	5400	9	8	17	5400	9	8	17	5400	9	8	17	5400	AC
Lights	40	100%	4	160	160	7	17	24	1120	7	17	24	1120	7	17	24	1120	7	17	24	1120	AC
(night)	40	100%	4	160	160	8	0	8	1280	8	0	8	1280	8	0	8	1280	8	0	8	1280	AC
Radio	10	100%	3	30	30	9	8	17	270	9	8	17	270	9	8	17	270	9	8	17	270	AC
Fridge	300	100%	1	300	300	24	0	24	7200	24	0	24	7200	24	0	24	7200	24	0	24	7200	AC
Kettle	2000	5%	1	2000	100	9	8	17	900	9	8	17	900	9	8	17	900	9	8	17	900	AC
	2000	50%	1	2000	1000	1	13	14	1000	1	13	14	1000	1	13	14	1000	1	13	14	1000	AC
Fan	100	100%	1	100	100	9	8	17	900	9	8	17	900	9	8	17	900	9	8	17	900	AC
Solder	250	50%	1	250	125	5	8	13	625	5	8	13	625	5	8	13	625	5	8	13	625	AC
Iron	250	50%	1	250	125	3	14	17	375	3	14	17	375	3	14	17	375	3	14	17	375	AC
Welder	2000	50%	1	2000	1000	5	8	13	5000	5	8	13	5000	5	8	13	5000	5	8	13	5000	AC
(SP)	2000	50%	1	2000	1000	3	14	17	3000	3	14	17	3000	3	14	17	3000	3	14	17	3000	AC
Drill	250	30%	1	250	75	5	8	13	375	5	8	13	375	5	8	13	375	5	8	13	375	AC
Press	250	30%	1	250	75	3	14	17	225	3	14	17	225	3	14	17	225	3	14	17	225	AC
Electric	450	30%	1	450	135	5	8	13	675	5	8	13	675	5	8	13	675	5	8	13	675	AC
Drill	450	30%	1	450	135	3	14	17	405	3	14	17	405	3	14	17	405	3	14	17	405	AC
Angle	600	40%	1	600	240	5	8	13	1200	5	8	13	1200	5	8	13	1200	5	8	13	1200	AC
Grinder	600	40%	1	600	240	3	14	17	720	3	14	17	720	3	14	17	720	3	14	17	720	AC
Sander	550	40%	1	550	220	5	8	13	1100	5	8	13	1100	5	8	13	1100	5	8	13	1100	AC
	550	40%	1	550	220	3	14	17	660	3	14	17	660	3	14	17	660	3	14	17	660	AC
Lathe	380	50%	1	380	190	5	8	13	950	5	8	13	950	5	8	13	950	5	8	13	950	AC
(wood)	380	50%	1	380	190	3	14	17	570	3	14	17	570	3	14	17	570	3	14	17	570	AC
									33950				33950				33950				33950	

Dairy farm

						Summer weekday				Summer weekend				Winter weekday				Winter weekend				
Equipment	Power (W)	% use within hour	Quantity	Total Power	Average power	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	Duration hrs/day	Start time	Stop time	Daily energy Wh/day	AC/ DC
Fridge	2000	100%	1	2000	2000	4	12	16	8000	4	12	16	8000	4	12	16	8000	4	12	16	8000	AC
Freezer	2000	100%	1	2000	2000	4	8	12	8000	4	8	12	8000	4	8	12	8000	4	8	12	8000	AC
Computer	200	100%	1	200	200	6	10	16	1200	6	10	16	1200	6	10	16	1200	6	10	16	1200	AC
VCR	30	100%	1	30	30	3	17	20	90	3	17	20	90	3	17	20	90	3	17	20	90	AC
TV	70	100%	1	70	70	5	17	22	350	5	17	22	350	5	17	22	350	5	17	22	350	AC
Radio	10	100%	2	20	20	7	10	17	140	7	10	17	140	7	10	17	140	7	10	17	140	AC
Fan	100	100%	1	100	100	4	11	15	400	4	11	15	400	4	11	15	400	4	11	15	400	AC
Lights (maintenance)	40	100%	7	280	280	2	6	8	560	2	6	8	560	2	6	8	560	2	6	8	560	AC
	40	100%	7	280	280	3	19	22	840	3	19	22	840	3	19	22	840	3	19	22	840	AC
Tools (repair)	750	100%	1	750	750	3	17	20	2250	3	17	20	2250	3	17	20	2250	3	17	20	2250	AC
Cow unit	400	100%	1	400	400	11	6	17	4400	11	6	17	4400	11	6	17	4400	11	6	17	4400	AC
Water pump	2000	100%	1	2000	2000	4	6	10	8000	4	6	10	8000	4	6	10	8000	4	6	10	8000	AC
Cooling (milk)	250	100%	1	250	250	24	0	24	6000	24	0	24	6000	24	0	24	6000	24	0	24	6000	AC
Geyser	3000	100%	1	3000	3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	AC
Lights	40	100%	10	400	400	6	0	6	2400	6	0	6	2400	6	0	6	2400	6	0	6	2400	AC
	40	100%	10	400	400	1	23	24	400	1	23	24	400	1	23	24	400	1	23	24	400	AC
									43030				43030				43030				43030	

Crop farm

						Summer weekday				Summer weekend				Winter weekday				Winter weekend				
Equipment	Power (W)	% use within hour	Quantity	Total Power	Average power	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	Duration (hrs/day)	Start time	Stop time	Daily energy Wh/day	AC/ DC
Fridge	2000	100%	1	2000	2000	4	14	18	8000	4	14	18	8000	4	14	18	8000	4	14	18	8000	AC
Freezer	2000	100%	1	2000	2000	4	8	12	8000	4	8	12	8000	4	8	12	8000	4	8	12	8000	AC
Computer	200	100%	1	200	200	6	10	16	1200	6	10	16	1200	6	10	16	1200	6	10	16	1200	AC
VCR	30	100%	1	30	30	3	17	20	90	3	17	20	90	3	17	20	90	3	17	20	90	AC
TV	70	100%	1	70	70	5	17	22	350	5	17	22	350	5	17	22	350	5	17	22	350	AC
Radio	10	100%	2	20	20	7	10	17	140	7	10	17	140	7	10	17	140	7	10	17	140	AC
Fan	100	100%	1	100	100	4	11	15	400	4	11	15	400	4	11	15	400	4	11	15	400	AC
Lights (maintenance)	40	100%	7	280	280	2	6	8	560	2	6	8	560	2	6	8	560	2	6	8	560	AC
	40	100%	7	280	280	3	19	22	840	3	19	22	840	3	19	22	840	3	19	22	840	AC
Tools (repair)	750	100%	1	750	750	3	17	20	2250	3	17	20	2250	3	17	20	2250	3	17	20	2250	AC
Milling	4000	100%	1	4000	4000	8	8	16	32000	8	8	16	32000	8	8	16	32000	8	8	16	32000	AC
Water pump	2500	100%	1	2500	2500	6	4	10	15000	6	4	10	15000	6	4	10	15000	6	4	10	15000	AC
Lights	40	100%	10	400	400	6	0	6	2400	6	0	6	2400	6	0	6	2400	6	0	6	2400	AC
	40	100%	10	400	400	1	23	24	400	1	23	24	400	1	23	24	400	1	23	24	400	AC
									71630				71630				71630				71630	

Economic net present costs [Rands] of systems supplying the clinic load

	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	234599	66974	90648	59955	64992
George	233971	47380	83602	56363	53233
Durban	234176	47380	81427	46329	46854
Port Elizabeth	233971	47380	77319	44085	43808
Cape Town	234176	50395	69871	38484	48772
Bethlehem	234990	44187	76752	48425	58411
Springbok	234599	44365	72036	37900	42139
Irene	234682	44365	72134	83301	63852
Upington	234522	44365	63114	51035	45409

Economic net present costs [Rands] of systems supplying the school load

	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	238453	80066	98433	187250	115767
George	237606	53364	86317	181997	86017
Durban	237774	53364	83040	55310	89633
Port Elizabeth	237403	52935	80687	80101	65346
Cape Town	237774	55949	76501	80139	56072
Bethlehem	239011	47045	84528	95631	72003
Springbok	238453	48413	75553	79517	59812
Irene	238793	48413	78740	204364	192180
Upington	238347	46906	66020	62235	89663

Economic net present costs [Rands] of systems supplying the S1 load

	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	269280	162933	273370	210585	162460
George	245529	98121	234968	106687	102409
Durban	245529	98121	222522	199545	100419
Port Elizabeth	245529	98121	207530	72083	85296
Cape Town	245529	105657	188433	72215	92628
Bethlehem	270549	83048	226680	196482	123253
Springbok	269280	89077	198206	70764	80322
Irene	270229	89077	195797	224306	131783
Upington	269005	84555	161688	102049	94060

Economic net present costs [Rands] of systems supplying the S2 load

	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	362670	328479	439131	397175	351636
George	359729	189810	389460	250949	285864
Durban	359729	191318	381243	217707	192844
Port Elizabeth	359729	189810	362731	229948	160759
Cape Town	359729	207898	346095	230316	169925
Bethlehem	365098	159665	357076	239119	261438
Springbok	362670	170216	344509	129068	150396
Irene	364489	170216	343673	436181	303938
Upington	362151	162680	308693	216717	177158

Economic net present costs [Rands] of systems supplying the S3 load

	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	406702	641116	629816	624339	687383
George	402692	363780	519562	558980	424918
Durban	402692	369809	512987	659098	397705
Port Elizabeth	402692	363780	493798	271833	305676
Cape Town	402692	399954	472515	284739	421620
Bethlehem	410033	303489	475583	462425	382934
Springbok	406702	327605	462145	266753	284941
Irene	409194	327605	460843	856521	592063
Upington	405991	309518	416051	305976	366570

Economic net present costs [Rands] of systems supplying the EDC load

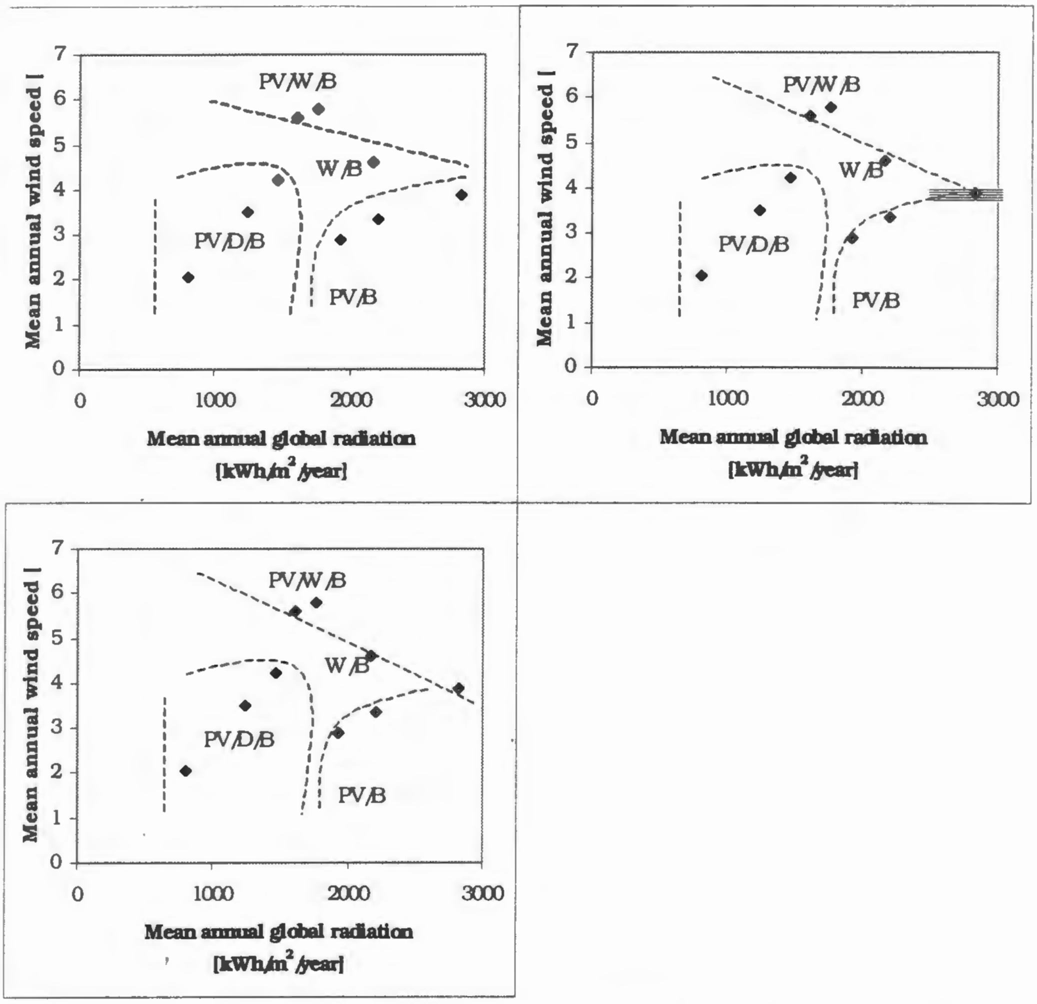
	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	502913	1080759	891400	867462	977144
George	498466	610492	673888	538018	577289
Durban	498466	616521	626711	518617	567593
Port Elizabeth	498466	610731	607080	370622	467982
Cape Town	498466	670783	589555	543771	500373
Bethlehem	557244	507998	587278	740604	674380
Springbok	502913	550202	560337	365344	435198
Irene	556225	550202	545339	886416	721319
Upington	502246	520057	500826	538458	529276

Economic net present costs [Rands] of systems supplying the dairy farm load

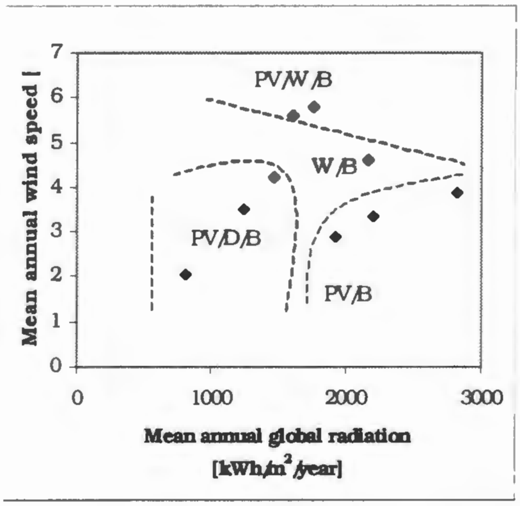
	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	532560	1367662	1018230	1255739	1143466
George	560384	770786	813309	761563	822041
Durban	560384	776815	726031	593863	688353
Port Elizabeth	560384	770786	698772	422788	660751
Cape Town	560384	849163	686557	551961	751303
Bethlehem	538191	644175	641066	931865	791053
Springbok	532560	692408	617290	414193	626499
Irene	536749	692408	618363	1533579	1151507
Upington	531394	656233	554320	619014	640634

Economic net present costs [Rands] of systems supplying the crop farm load

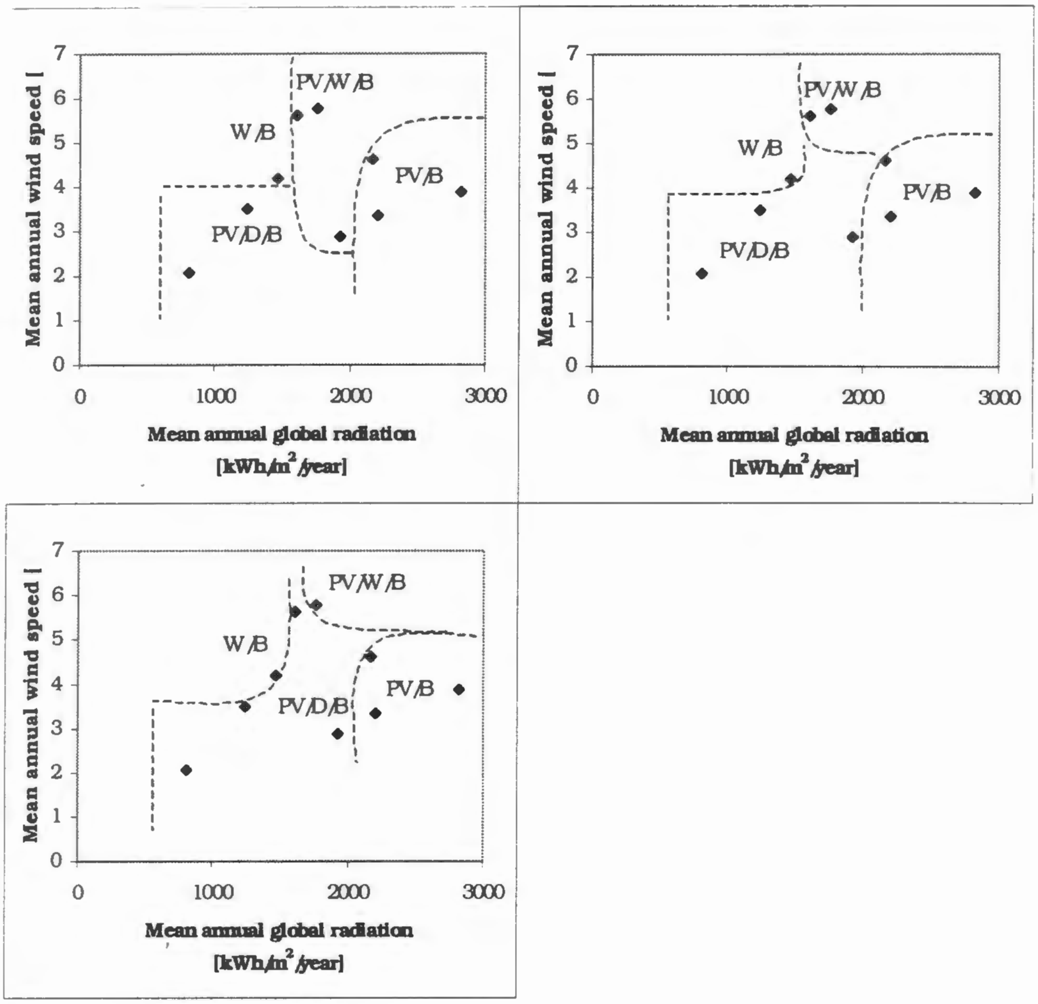
	Diesel only	*PV/battery*	*PV/diesel/ battery*	*Wind/ battery*	*PV/Wind/ battery*
Hypo1	617761	2257842	1456133	2218524	2238171
George	607690	1204650	1056562	1326337	1314190
Durban	607690	1275105	1028901	1134128	1207631
Port Elizabeth	607690	1269076	1024070	705520	987298
Cape Town	607690	1395686	1013150	756055	1078909
Bethlehem	799362	1052030	1012948	1596197	1452601
Springbok	617761	1130408	925755	711543	923995
Irene	796877	1130408	982580	2269466	1702951
Upington	616038	1070117	942191	1068412	1072307



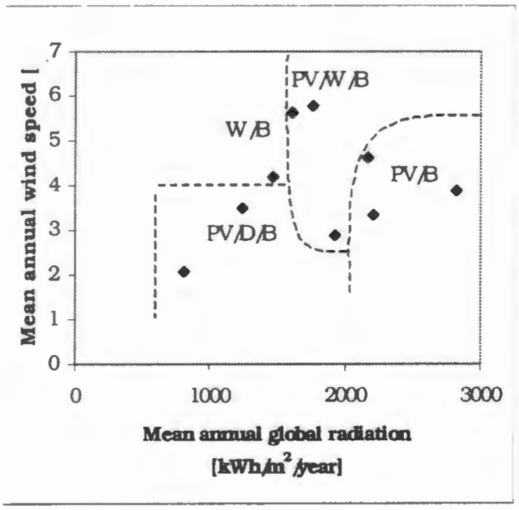
Economically cheapest systems for the clinic for discount rates of a)2.5% to 10%, b)12.5% and c)15%



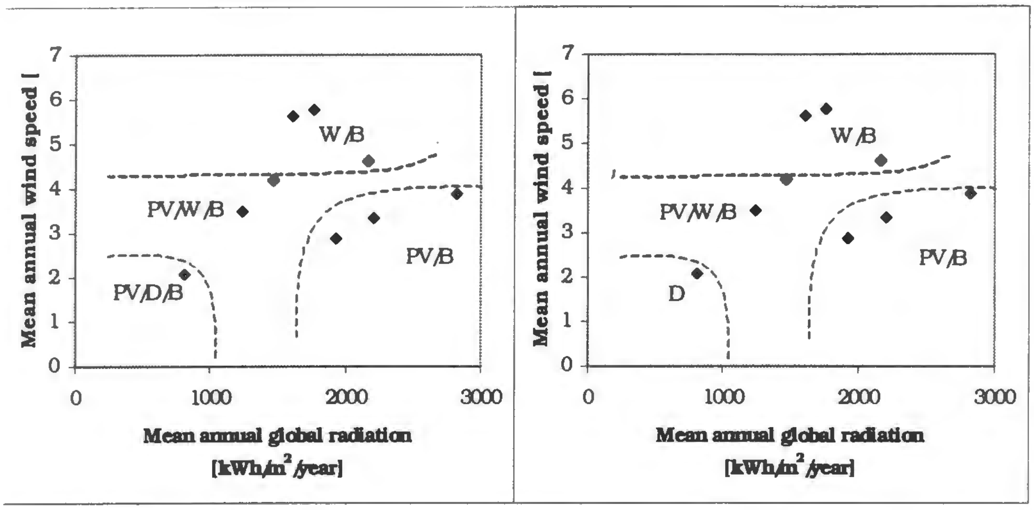
Economically cheapest systems for the clinic for fuel price between 40% and 160%



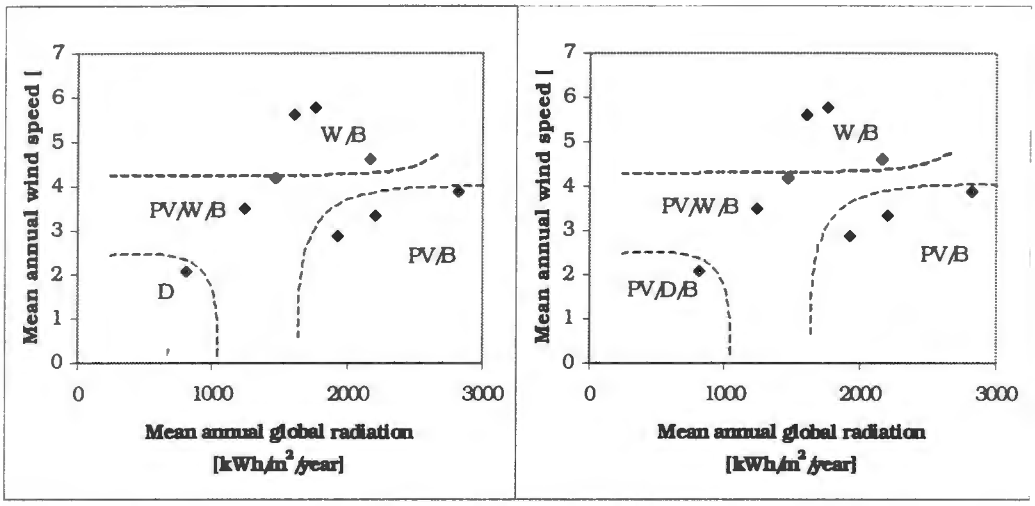
Economically cheapest systems for the school for discount rates of a)2.5% to 10%, b)12.5% and c)15%



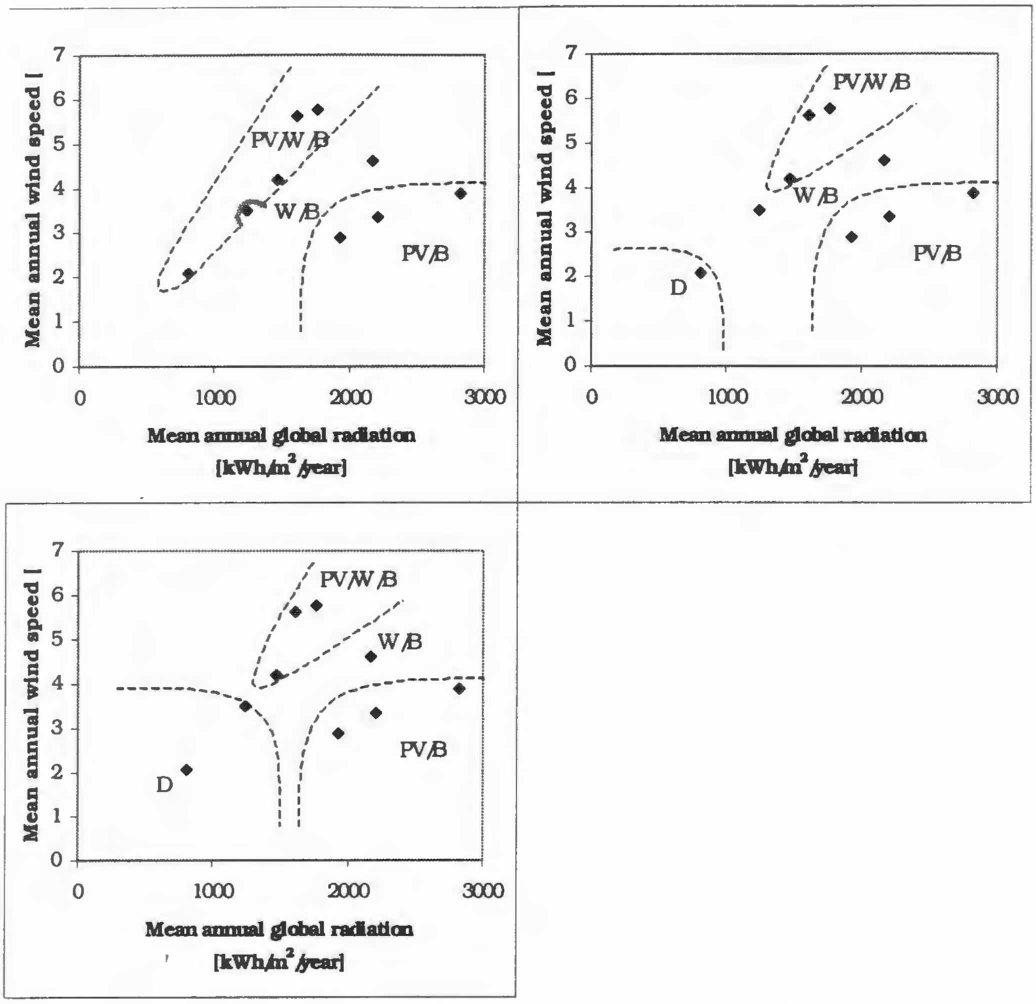
Economically cheapest systems for the school for fuel prices between 40% and 160%



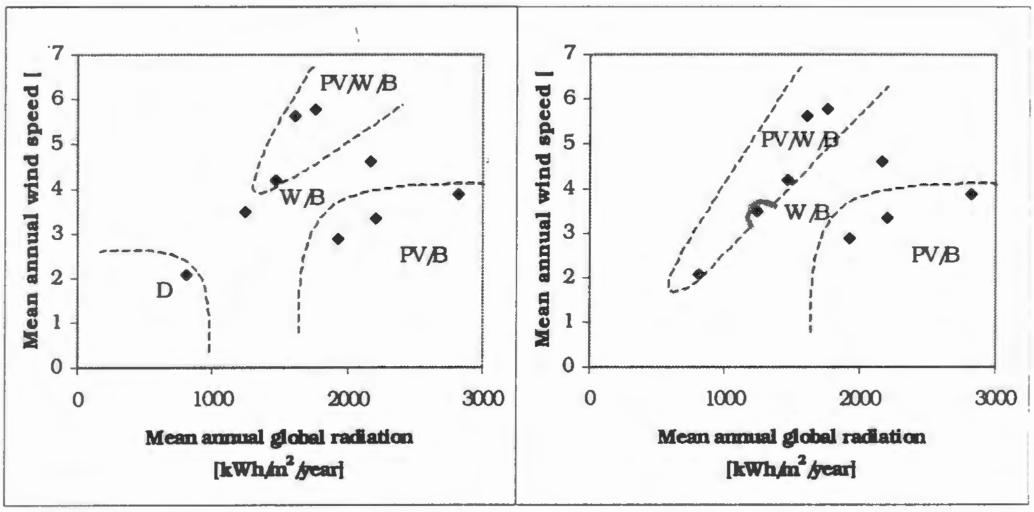
Economically cheapest systems for the S1 load for discount rates of a)2.5% and b)5% to 15%



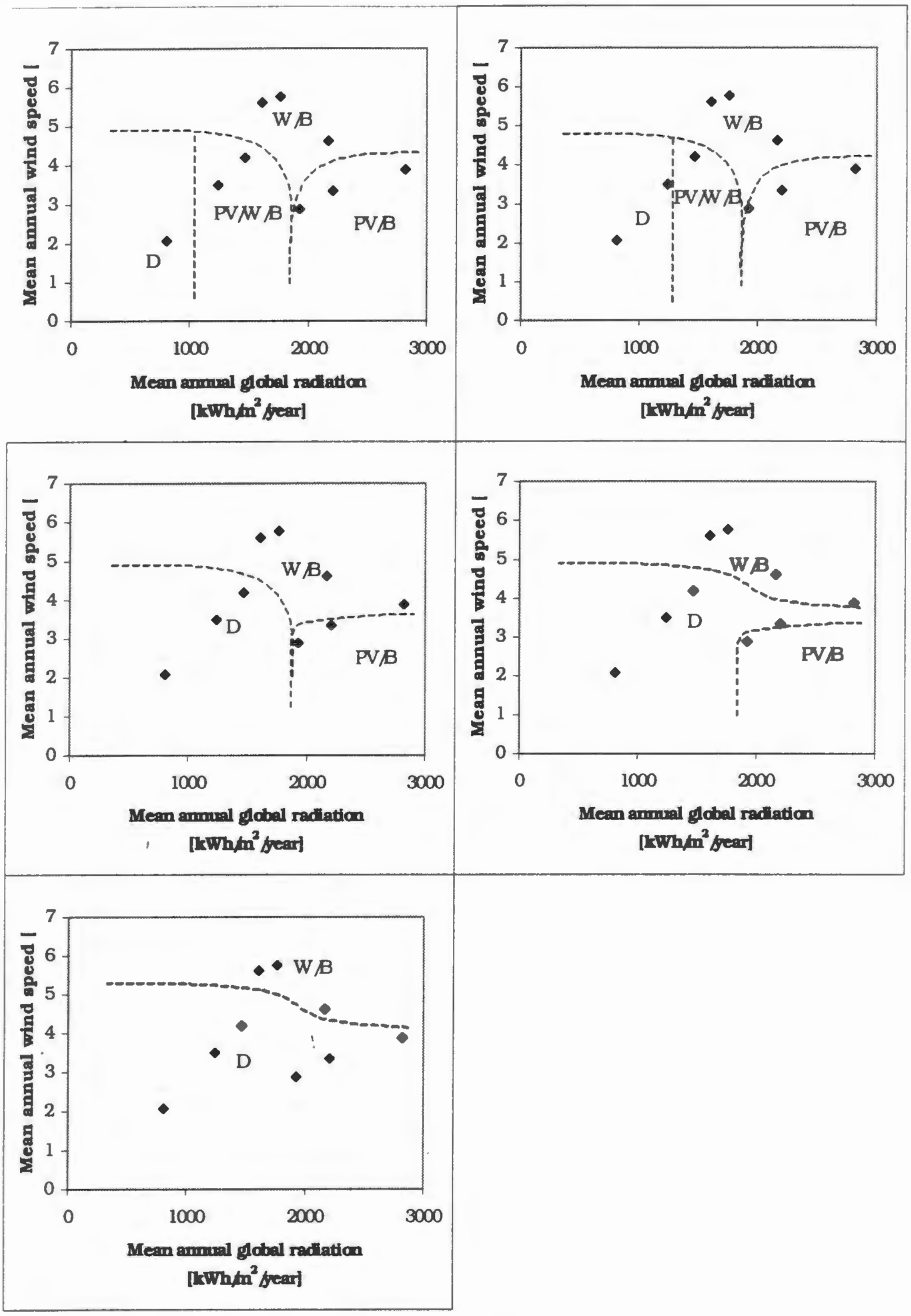
Economically cheapest systems for the S1 load for fuel prices of a)40% to 130% and b)140% to 160%



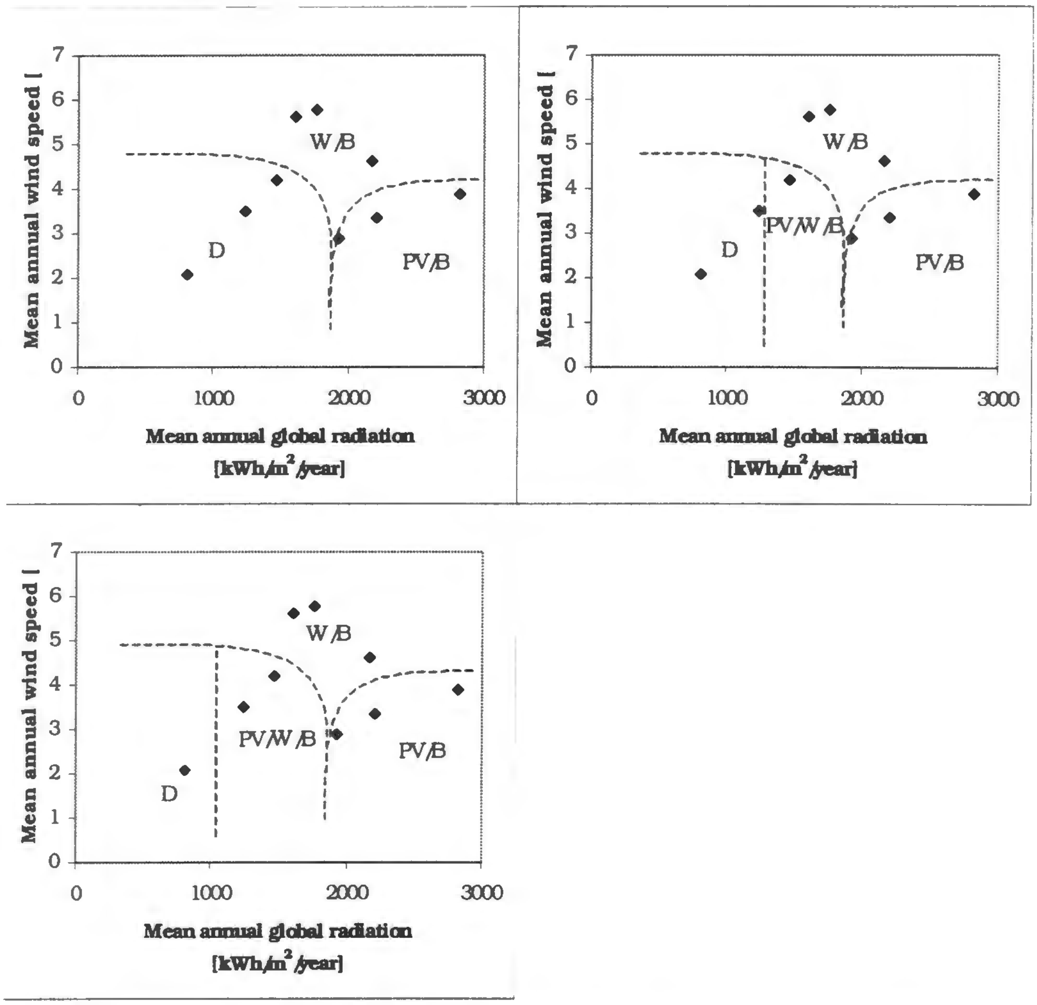
Economically cheapest systems for the S2 load for discount rates of a)2.5%, b)5% to 10% and c)12.5% to 15%



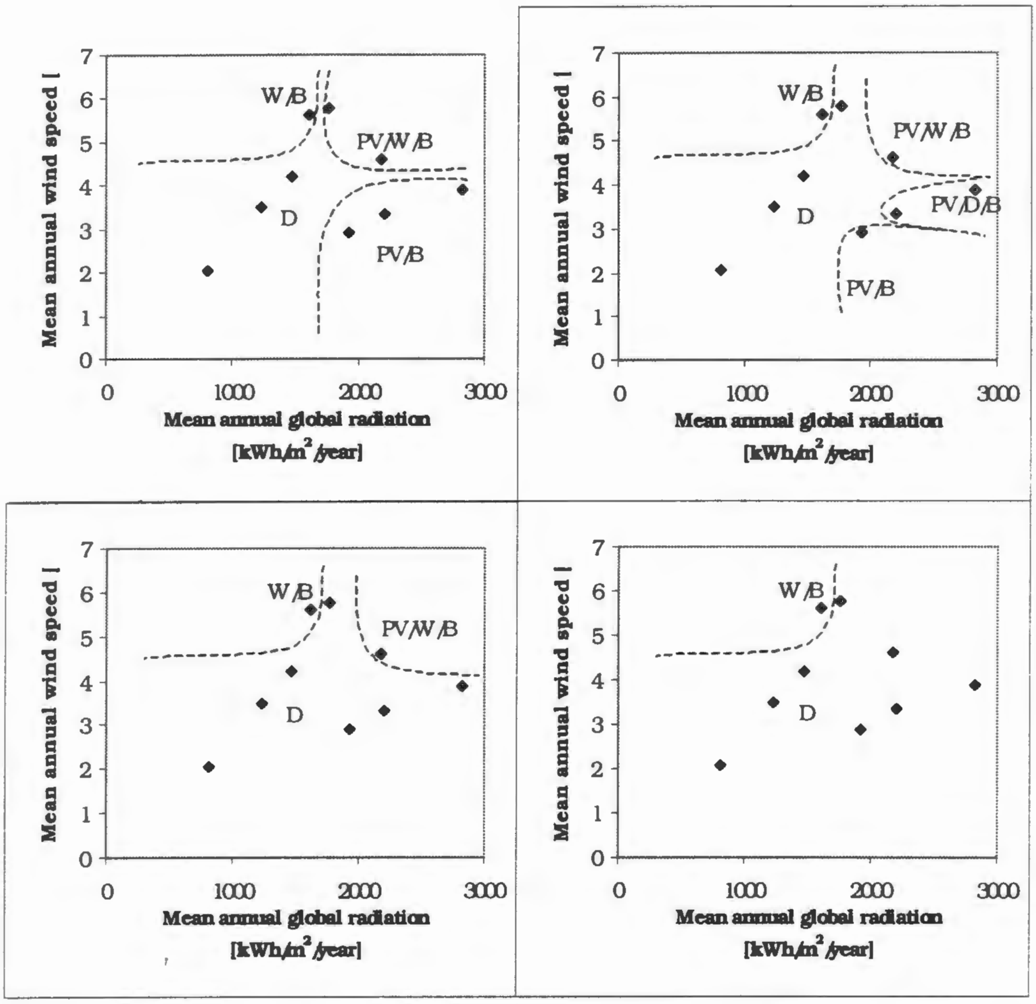
Economically cheapest systems for the S2 load for fuel prices of a)40% to 100% and b)110% to 160%



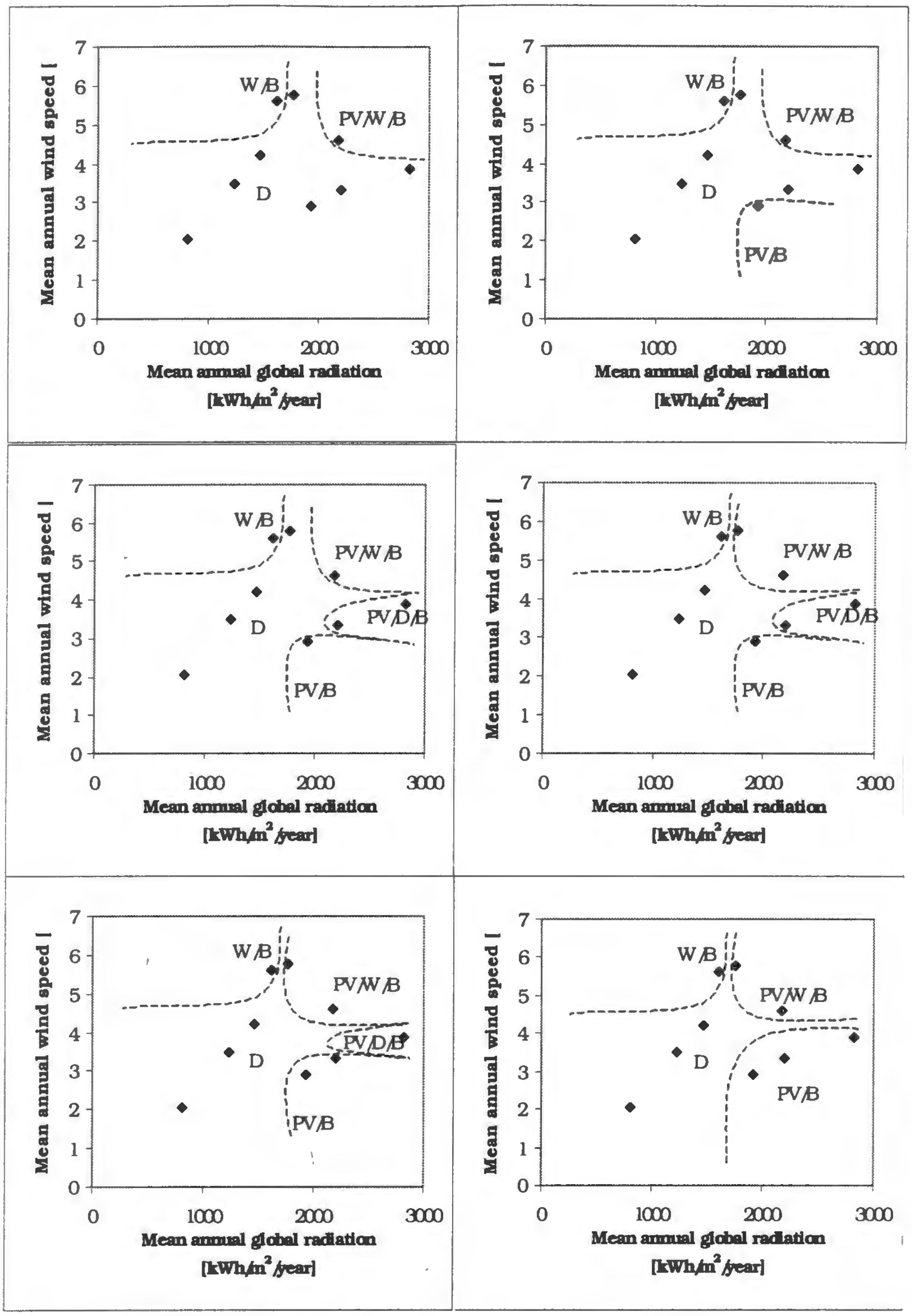
Economically cheapest systems for the S3 load for discount rates of a)2.5%, b)5%, c)7.5%, d)10% and e)12.5%



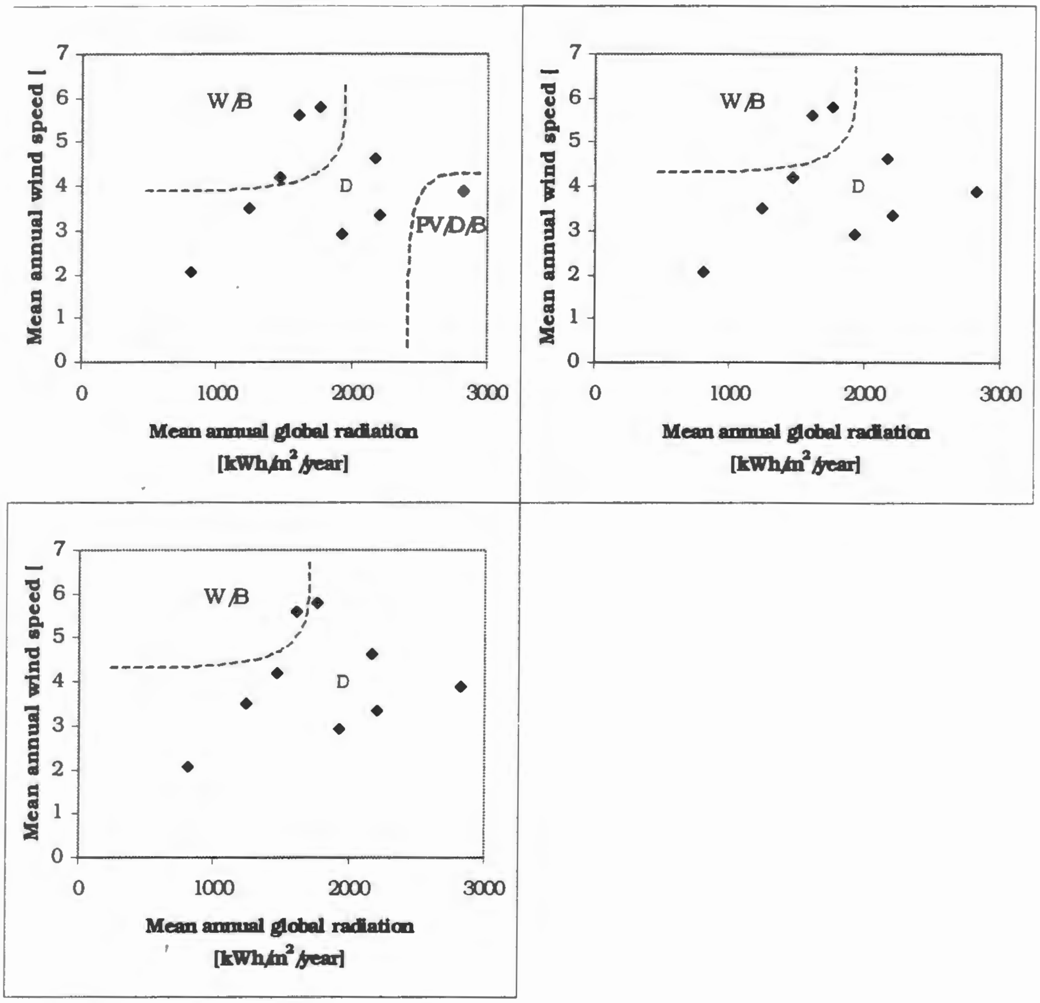
Economically cheapest systems for the S3 load for fuel prices of a)40% to 90%, b)100% to 120% and c)130% to 160%



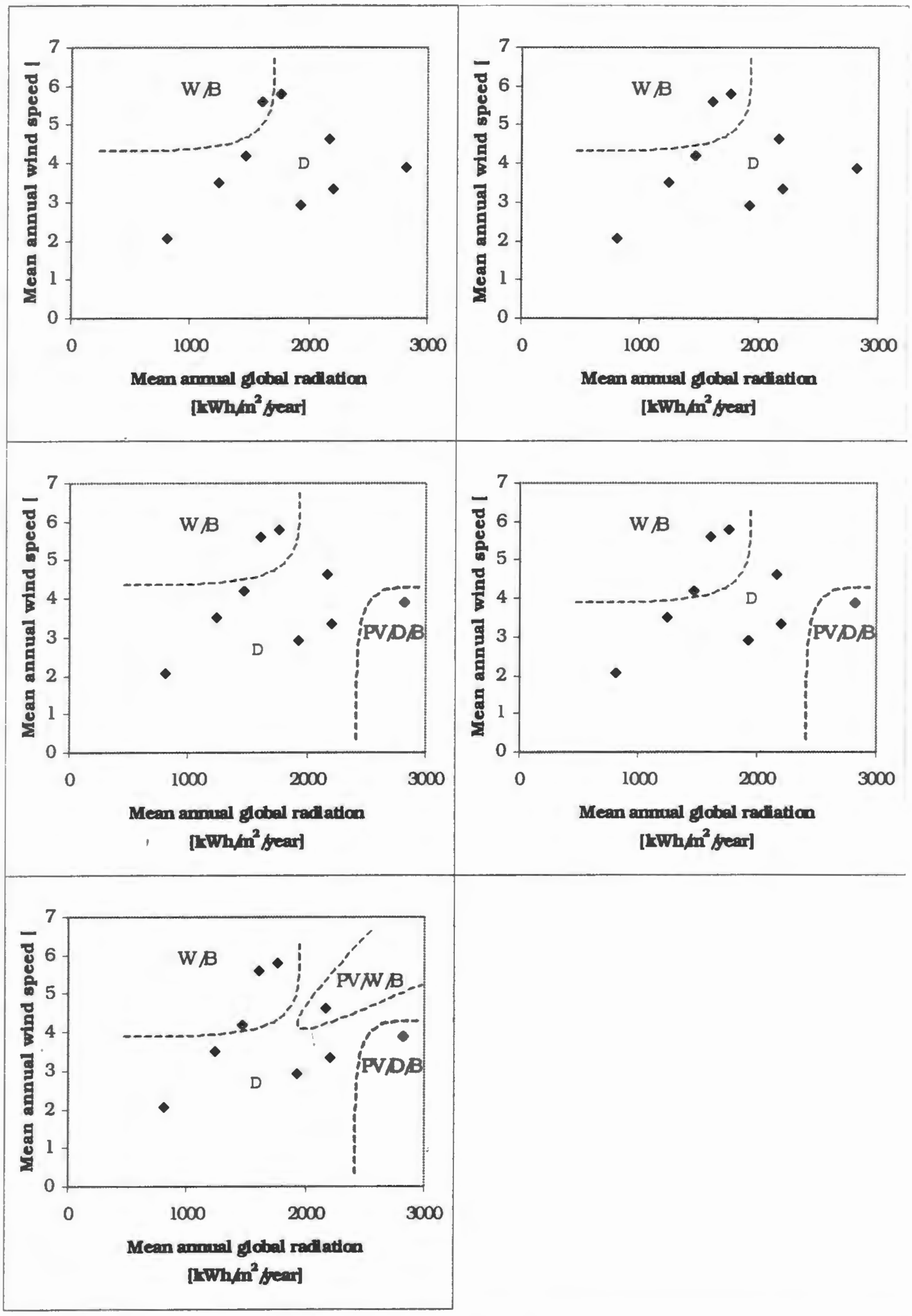
Economically cheapest systems for the EDC for discount rates of a)2.5%, b)5%, c)7.5%, d)10% to 12.5%



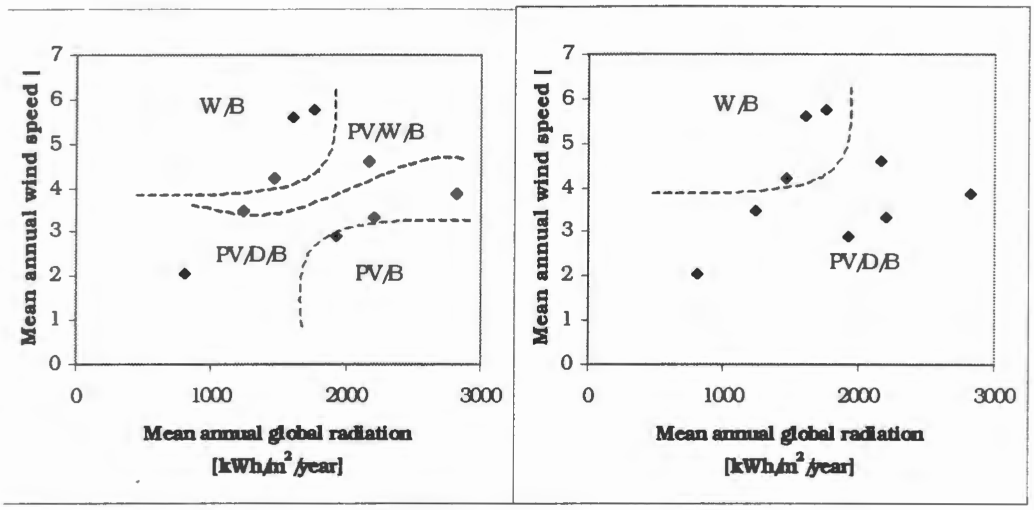
Economically cheapest systems for the EDC load for fuel prices of a)40% to 70%, b)80%, c)90% to 100%, d)110%, e)120% to 130% and f)140% to 160%



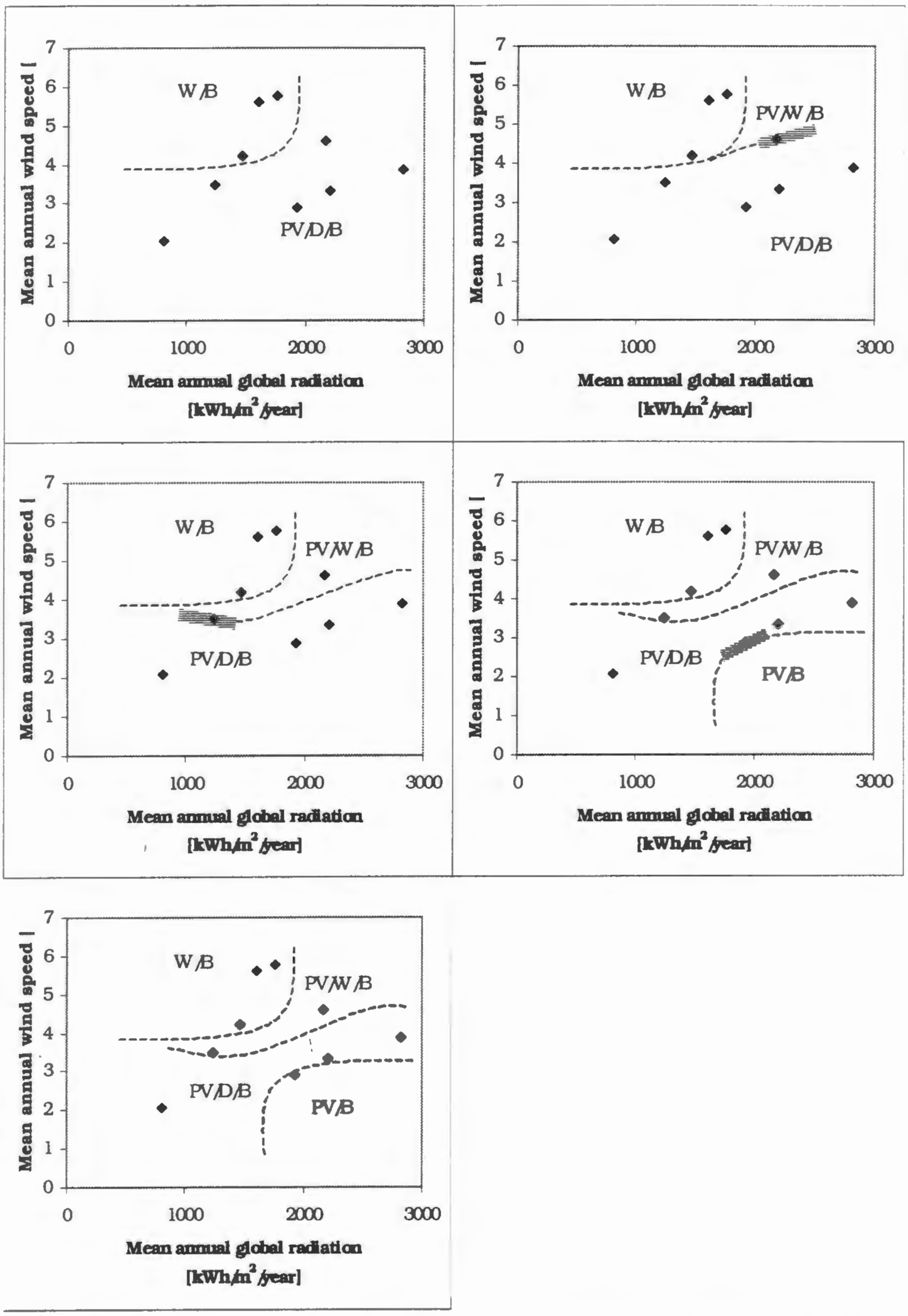
Economically cheapest systems for the Dairy farm for discount rates of a)2.5%, b)5% and c)7.5% to 10%



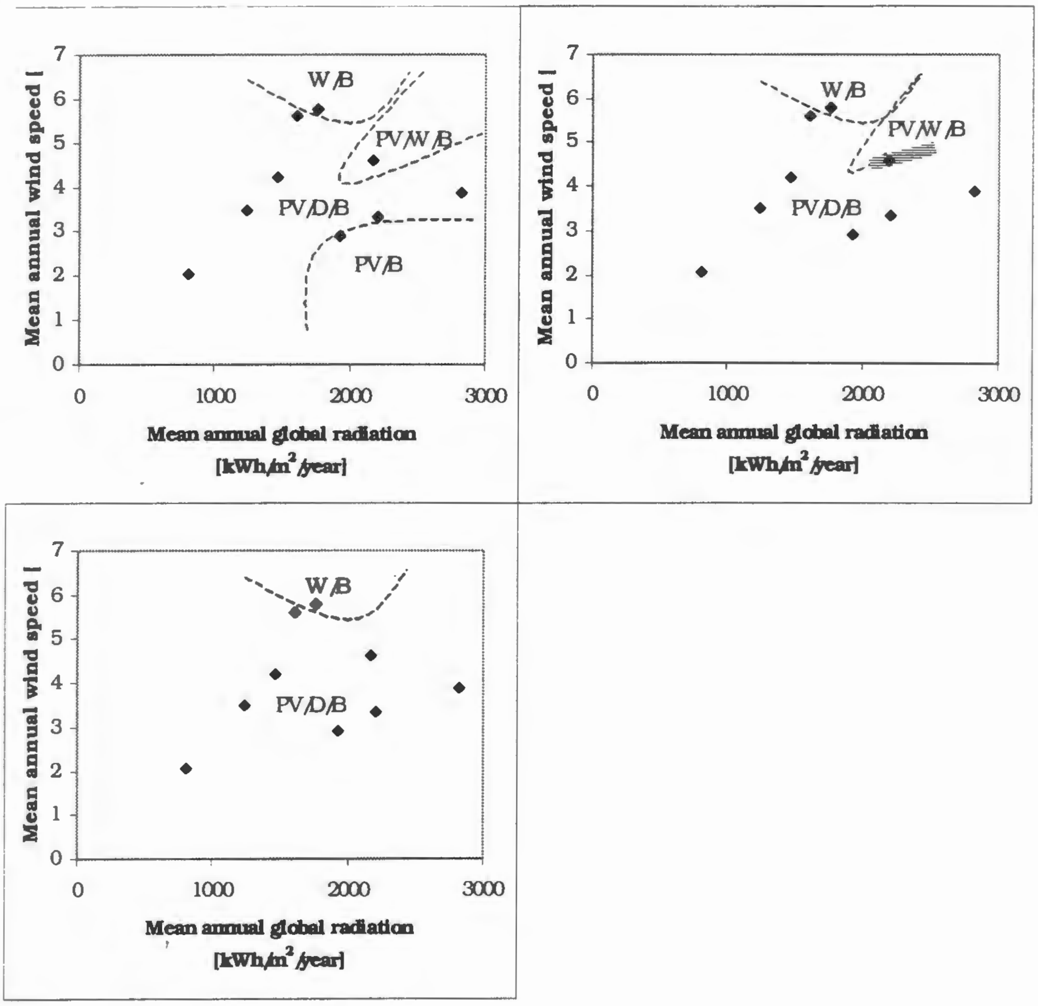
Economically cheapest systems for the dairy farm for fuel prices of a)40% to 90%, b)100% to 110%, c)120% to 130%, d)140% to 150% and e)160%



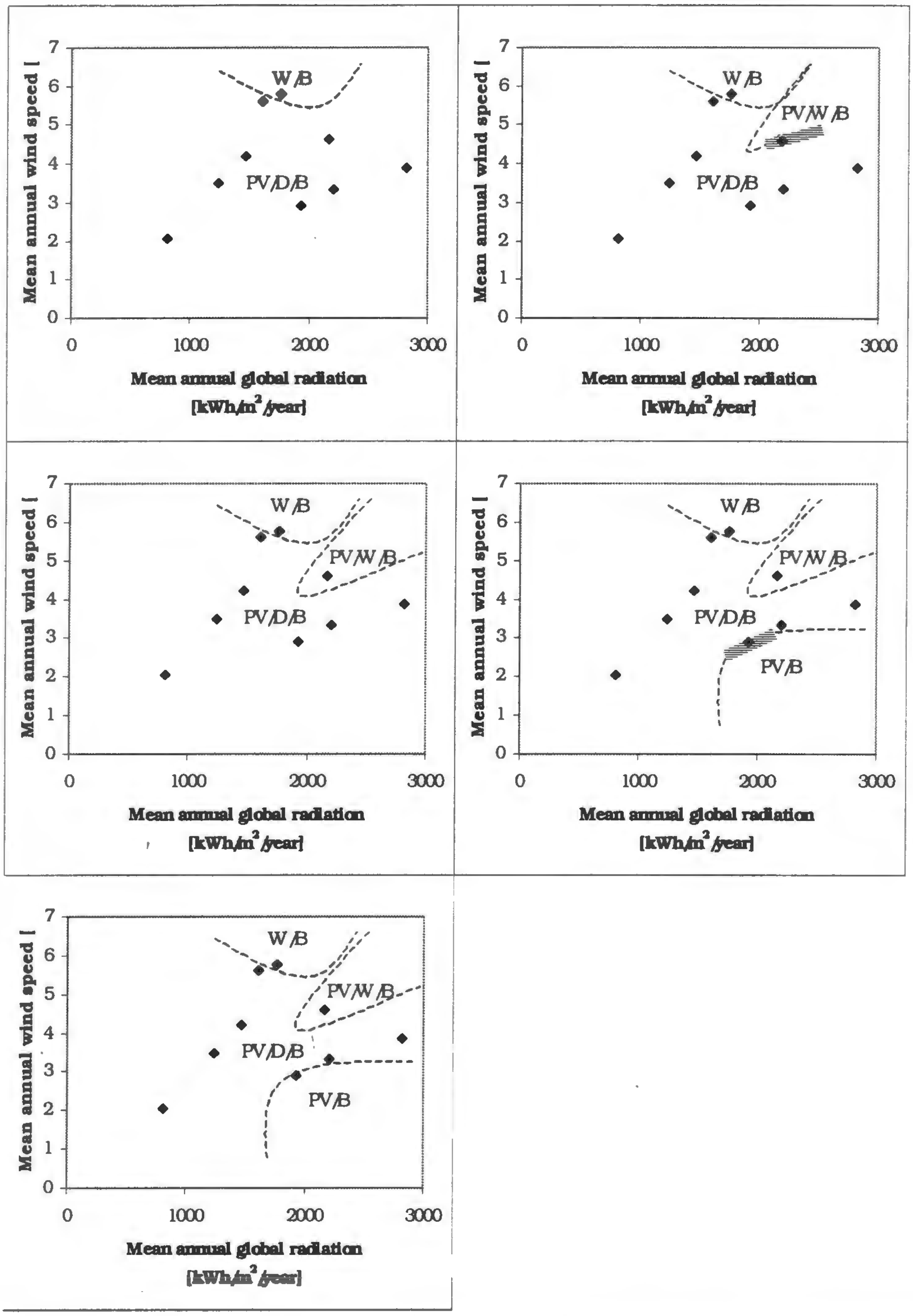
Economically next-cheapest (after diesel-only) systems for the Dairy farm for discount rates of a)2.5% and b)5% to 15%



Economically next-cheapest (after diesel-only) systems for the dairy farm for fuel prices of a)40% to 100%, b) 110%, c)120%, d)130% and e)140% to 160%



Economically next-cheapest (after diesel-only) systems for the Crop farm for discount rates of a)2.5%, b)5% and c)7.5% to 15%



Economically next-cheapest (after diesel-only) systems for the crop farm for fuel prices of a)40% to 90%, b)100%, c)110% to 130%, d)140% and e)150% to 160%