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Designing Sustainable Distributed Generation Systems for Rural Communities

An Application of Optimisation Modelling and Decision Analysis to include
Sustainability Concepts and Uncertainty into Design Optimality

A thesis presented in partial fulfilment of the requirements for the degree of
Doctor of Philosophy in Agricultural Engineering (Renewable Energy)
at Massey University, Palmerston North, New Zealand.

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2005

Abstract

The deregulation of the electricity supply industry in New Zealand has led to an increased level of interest in the security of electricity supply to rural communities. This in turn has led to questions about sustainable alternatives to conventional methods of electricity supply. A solution may be the adoption of sustainable community sized renewable energy (RE) based distributed generation systems. However, choosing between the myriad of possibilities requires much data and analysis.

An accurate analysis of electricity load and RE resource matching is normally required. In most cases, this is an expensive and time-consuming assessment. In order to minimise these costs, and yet give due consideration to stakeholder preferences and technical uncertainty, a process incorporating the economic, social, environmental, and technical aspects of sustainable design in a relatively short timeframe will be required.

This study developed such a method through the integrated use of the wind atlas assessment and analysis program (WAsP), the micropower optimisation model (HOMER), and three methods of decision analysis using Logical Decisions for Windows (LDW) software, which formed the decision analysis framework, SPiRAL (Sustainable Power in Rural Areas and Locations).

The efficacy of the integrated use of the software in the SPiRAL framework was tested through two analyses using electricity load and RE resource data from a case study site. The first was an analysis using a full-year of data in a multi-method decision analysis process thus setting the framework in place. A further analysis then tested the minimum monitoring time required to obtain and analyse the data for modelling meaningful results.

In both analyses, the results were ranked based on stakeholder preferences between the economic, social, environmental, and technical aspects of sustainable energy systems. The clear representation of the uncertainty of the electricity loads and the RE resources was paramount in the results. The short-term analysis results differed in small ways from the full-term, but were essentially similar.

This study developed a decision analysis framework that delivered transparent results in a manner likely to instil insight and confidence in them, and this would provide the decision-maker with much valuable information on which to base their decision.

Acknowledgements

Sir Isaac Newton said “If I have seen further, it is by standing on the shoulders of giants”. It is in this same light that I would like to acknowledge the ever ready and willing assistance I received throughout this research and without which, it would not have been as rewarding, fun or as good as it has been. Therefore, my first thanks must go to my research supervisors – Professor Ralph Sims and Dr John Holland – as much for the benefit of their advice and patience, as for their friendship. My life lately has revolved around some of their decisions, knowledge, and wit. I have enjoyed it very much and am a better person for it.

A large portion of my time was in the field gathering data and so I would like to offer special thanks to the residents of Totara Valley, Mike & Prue, Mike, Geoff & Marion, Nick & Jan, and Craig & Pauline; the management and staff of Limestone Downs – Warwick, Alf & Carol, Don, Steve, James and the rest of the crew; the valuable technical assistance from the very able staff at the Institute of Technology and Engineering workshop, Leo, Russell, and Don. Mr Mark Wenborn, Dr Iain Sanders, and Mr Alister Gardner of IRL were also of immense help. The help and advice from Joan, Roanna, Gayle, Trish and Lisa over the years has made my academic life more productive and satisfying and has been much appreciated.

Advice, information and encouragement was received gratefully from: Mr George Horvath, who asked the question that set in motion the curiosity that led to this study; Mr Mark Carter and Mr Laurence Sherriff for their technical advice and encouragement; Dr Steve Reid (NIWA) for the benefit of his extensive knowledge of the wind and modelling it; Dr Tony Bowen (Canterbury University) for his time and advice given on WAsP; and Dr Peter Lilienthal and Mr Tom Lambert (NREL) for their time and energy in tutoring me on the many and varied idiosyncrasies of HOMER. Special thanks to Dr Martin Sullivan for encouragement and friendship, and to the research assistants – Geraldine, Rachael, John, Andrew, and Nihal. To those I have missed or inadvertently omitted, I thank you.

This research would not have been feasible without financial assistance and I hope I have given value for money. Assistance was gratefully received from: Meritec Limited (Jim Fletcher Memorial Scholarship); C. Alma Baker Trust, CentralPower Energy Trust, The Turanga Trust, Massey University for the Massey Doctoral Scholarship; and finally the consortia of electricity distributors – PowerCo, Transpower, Central Hawke Bay Networks, WEL Energy, Mainpower, CentralPower Energy Trust, and Dunedin Lines.

This has been a period of much change and growth for me and at times, it has been hard work and tough for those around me too. Therefore, very special thanks go to my mother and family for their encouragement and support, and my wife Bobbi, who has been there through the good times as well as the difficult times. Lastly, I have thought a lot about my late father while finishing this study, and how his pride and approval would have been expressed in a firm handshake and a comment about the time it took me.

It has taken a quite a while, and it has been done with the help, guidance, and support from many people, for which I am sincerely grateful, thank you.

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1 Introduction

Decision-making about electricity supply in New Zealand has never been more complex than it is now and rational decision-analysis more necessary within a changing electricity industry. New Zealand's electricity demand is increasing. In 1995, 109.6 PJ of electricity was consumed; and in 2002, 123.8 PJ of electricity, an increase of 11.5%. This increasing demand for electricity combined with an aging electricity network, New Zealand's ratification of the Kyoto Protocol and a decreasing share of renewable energy (RE) in the New Zealand electricity generation mix all indicate potential problems ahead for the electricity consumer. One answer to the combined problems may be the increased uptake of distributed generation (DG).

Worldwide, there are evident trends towards renewable energy based distributed energy (DE) systems¹ and distributed generation systems for rural communities. The benefits of such DG systems include an increase in renewable energy generation capacity, retention of the existing customer base (should the grid-supply be economically marginal), and expansion of quality and reliable electricity supply to outlying areas. Additional revenue from renewable energy certificate trading, and increasing the efficiency of the electricity network as a whole could be amongst the benefits to electricity distribution companies should the Government choose to support renewable energy and hence, implement DG.

The electricity industry in New Zealand has been undergoing reforms since the mid 1980s, and to this day, they continue both in legislative modification and in consumer effect. The first of the legislative changes pertinent to the topic of this study is the Electricity Act 1992. A key section of this Act ensures the maintenance of the newly deregulated distribution networks until 2013. On the 1st of April 2013, the Electricity Act 1992 will automatically repeal this section through a sunset clause, and all obligations for the distribution network companies to maintain any conventional form of electricity supply will cease (Appendix A – 13.1). By implication, maintaining the electricity supply lines will only continue should it be economical to do so. Small rural electricity users and rural communities are the most likely to be affected by this. Other legislative and policy changes that are of interest to this study are the Electricity Industry Reform Act 1998, the Electricity Industry Reform Amendment Act 2004 (Appendix A – 13.2), the Energy Efficiency and Conservation Act 2000 (Appendix A – 13.3), and the Resource Management (Energy and Climate Change) Amendment Act 2004 (Appendix A – 13.5).

The Electricity Industry Reform Act 1998 required electricity companies to separate their distribution network business interests from their generation business capacity. The Electricity Industry Reform Amendment Act 2001 moderated the Electricity Industry Reform Act 1998 to some extent and allowed distribution companies to own 'at arms length' a limited fossil

¹ Distributed Energy includes a heating component such as solar water heating. This study will consider distributed generation systems only.

fuel generation capacity or more importantly, an unlimited renewable energy based generation capacity. Passed in conjunction with these Acts coming into force was the Energy Efficiency and Conservation Act 2000 which mandated the formation of a National Energy Efficiency and Conservation Strategy (the Strategy), a policy to promote energy efficiency, energy conservation, and renewable energy in New Zealand. The Strategy was released in September 2001 and aims to improve New Zealand's energy efficiency by 20 percent by 2012 and to increase the amount of renewable energy used by 30 Petajoules (PJ) by the year 2012.

Given the potential effects of the imminent legislative changes and the current status of some of the power line infrastructure in rural areas it is crucial that a process becomes available to enable interested parties to assess and analyse future rural electricity supply issues as they arise.

1.1 Problem Statement

With the electricity supply industry changing, the costs for both electricity supply and its reliability are increasing. Under the current legislation, the assurance of electricity supply to rural communities diminishes after April 2013. Under current policy and legislative initiatives the electricity industry is under review; New Zealand's obligation to meet the *Kyoto Protocol* will require in part, a new look generation mix incorporating more renewable energy, and section 62 of the Electricity Act 1992 will lead towards a reassessment of the viability of the existing supply network by 2013. Hence, a growing number of rural enterprises and communities are looking towards sustainable and renewable energy sources. In addition, there is a growing awareness of the social and environmental impacts associated with energy use and provision.

The problem is that there is currently no transparent, auditable monitoring and decision-analysis method available for electricity consumers or other stakeholders to assess their renewable energy resources and their distributed generation electricity supply options in an accelerated and yet accurate manner. This assessment should be in terms of technical and economic sustainability and with respect to social and environmental benefits and impacts.

1.2 Aim

The aim of this research was to develop an iterative, transparent, and auditable decision analysis framework. An assessment of the data required and an eclectic selection of software will accurately identify within a short-term period of months – rather than years – suitable feasible renewable energy resources and associated energy conversion technologies for use within a rural community to meet a measured or modelled demand and promote a ranked list of viable options. The ranking will consider the comparative (financial) costs, technological merits, social issues, and environmental impacts of the options.

1.3 Objectives

To achieve this aim the research objectives were:

- to identify and use computer modelling software suitable for renewable energy resource modelling (wind), renewable energy based distributed generation system simulation and optimisation, and decision-analysis;

- to monitor and record rural load profiles and renewable energy resources of a selected case study to:
 - provide data on rural electricity load profiles,
 - use in analysing the duration required before short-term duration modelling parameters become apparent, and
 - to provide data to test the efficacy of the software used for resource modelling and renewable energy generation system design,
- to model the decision-analysis process using the previously modelled renewable energy resources and system designs based on case study data to test the efficacy of the decision analysis framework in the provision of both sensitivity and uncertainty information, using both full-term and short-term duration data and using the preferences of multiple stakeholders.

1.4 The Decision Analysis Framework

Extensive community electricity load and renewable energy resource monitoring at the small rural community of Totara Valley led to detailed data sets. These data sets were used in a renewable energy resource modelling, DG system optimisation modelling, and a decision-analysis process. These data were also analysed to ascertain the short-term monitoring duration before modelling parameters required for the aforementioned modelling processes became apparent. The three computer models used were the Wind Atlas Analysis and Application Programme (WAsP – Section 3.1), the Hybrid Optimisation Model for Electric Renewables (HOMER – Section 3.2), and Logical Decisions for Windows (LDW – Section 3.3), and led to the decision-analysis framework, *Sustainable Power in Rural Areas and Locations – SPiRAL*.

For the decision modelling of renewable energy based DG systems, the stakeholder preferences between the decision criteria require noting (Figure 1.1, Box 1). Stakeholders may include system designers, consumers of the electricity, engineers involved in maintenance, local and regional councils and their respective consents officers, electricity distribution-network operators, and anyone else directly involved in the decision-analysis process. Sustainability principles would indicate that such stakeholder preferences might include details relating to cultural, social, environmental, technical, and economic parameters.

Social parameters may include such topics as employment, perceived and actual community well-being, and the appropriateness of some technologies over others. Social impact assessments (SIA) may be a source for such data. Likewise, environmental impact assessments (EIA), environmental mission statements (EMS), resource consent requirements, and individual environmental philosophies may provide material for the decision-analysis. This could also include technical issues such as peak load following, reduction and consistency of supply, and other engineering requirements. Economic factors may involve assessment of the net present cost over the lifetime of the project, the cost of the delivered electricity, local investment levels, and initial capital cost.

Once stakeholder preferences and the weights of these preferences have been assessed (Box 1), full monitoring of the renewable energy resources and the electricity loads is

undertaken, and the data analysed (Box 2a and 2b). The wind energy resource modelling and renewable energy system simulation and optimisation process (Box 3) will utilise the required modelling parameters ascertained in the previous steps (Box 2a and 2b). The results (Box 4) of the energy system modelling are used in the decision-analysis process as alternatives from which to choose (Box 5).

The stakeholder preferences, obtained in the initial stage (Box 1) will be used to assign weights to each of the decision criteria and will then be used to rank the DG systems according to the listed preferences (Box 5). Insight from the results can be gained into potential conflicts by sensitivity analysis between the stakeholders or decision makers (Box 6). The decision-analysis process is to be iterative and the stakeholders can redefine their preferences as the analysis progresses.

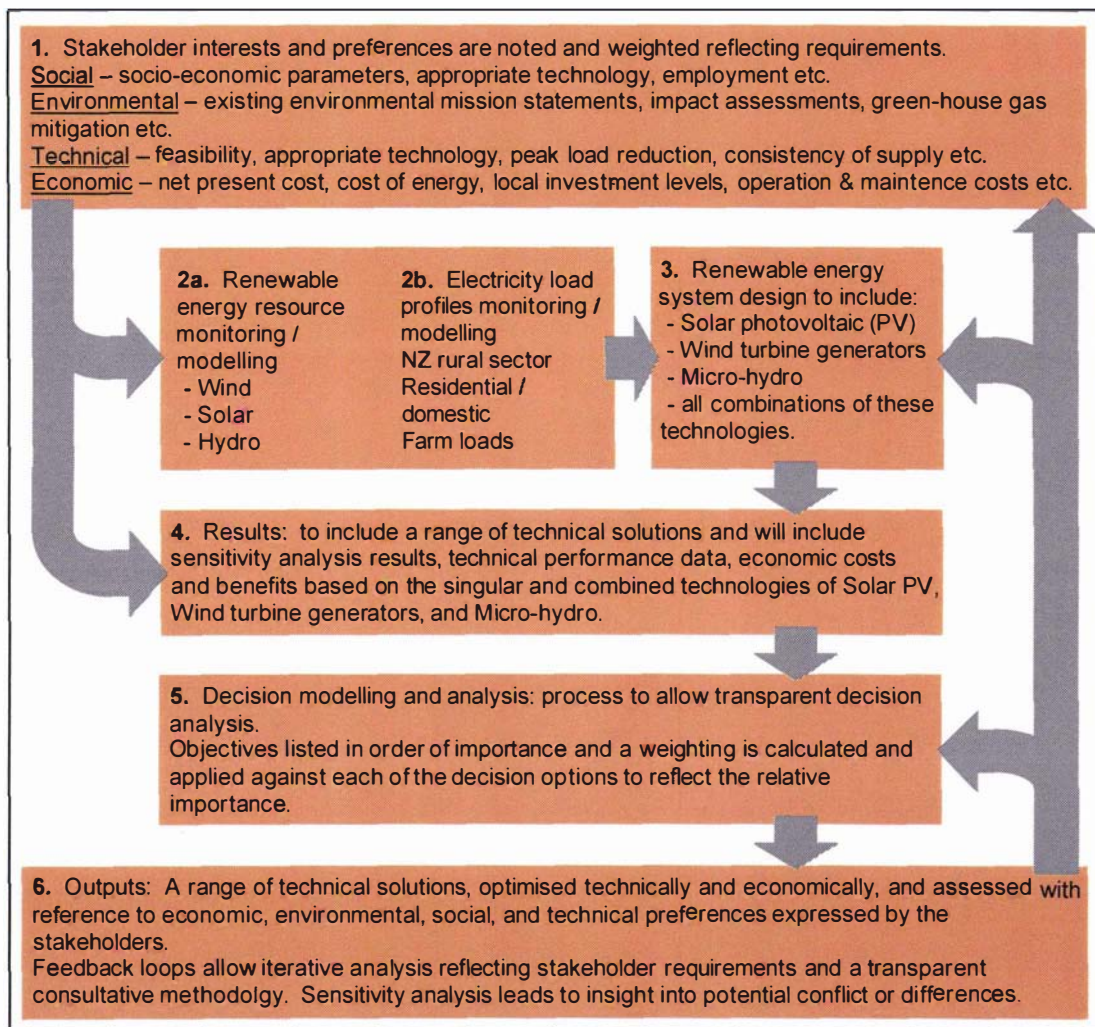


Figure 1.1 An initial schematic diagram of the overall decision analysis framework to be further developed in this study.

This study will lead to the development of a decision-analysis framework that will instil a greater understanding and insight into the optimal design of sustainable renewable energy based distributed generation systems for rural communities. This will involve a decision-analysis process that will assess technical, social, environmental, and economic parameters;

renewable energy resource and electricity load uncertainty; and the effects of stakeholder weightings and preferences on all of these.

Important outputs produced by this study will include:

- capabilities of the individual software and highlighting their suitability to the tasks presented;
- assessment of the collective use of the software;
- electricity load profiles of individual rural residences;
- electricity load profile from a rural community;
- extensive renewable energy resource data from a rural area;
- analysis of requirements for data collection duration regarding a short-term duration project;
- wind energy resource modelling relative to both the full-term and short-term duration;
- renewable energy based distributed generation system design, simulation, and optimisation relative to both the full-term and short-term duration;
- stakeholder-preference elicitation techniques and the difficulties this process poses;
- the composition of a multi-method multiple criteria decision analysis with respect to assessment of the individual methods and the resultant robustness of the combined method;
- the requirements of a decision-analysis process using multiple decision criteria; and
- the overall feasibility of a collective modelling approach as proposed by this study.

Important issues either addressed directly or indirectly included:

- greenhouse gas mitigation and the part that small distributed generation can play;
- a method of implementing a multi-mast wide area wind energy resource monitoring process conducted over a relatively short-term;
- wind energy resource modelling complexities;
- appropriate combinations of renewable energy technologies that can simultaneously:
 - satisfy economic requirements;
 - reduce peak loads,
 - reduce or mitigate environmental, social, and technical impacts;
- the place for sustainability requirements in the design process of an distributed generation system; and
- stakeholder input as a key requirement for the successful design and implementation process of community renewable energy system developments and projects.

1.5 Limitations of Research

This study was limited to an analysis of current software models and their application to rural communities with a case study used to validate the method. Although a process of selection was utilised to choose software, this does not preclude future use of other software.

Irving (2000) initiated the monitoring of wind and solar at one site in February 1999, and the electricity-monitoring programme at Totara Valley in November 1999 in conjunction with Industrial Research Limited (IRL) and the community residents. The installation of the meters in all the reported locations was by IRL staff. Technical limitations of the electricity load monitoring equipment included sample rate, resolution size, and type of data sampled.

The author inherited all monitoring duties from December 1999 whilst undertaking a Master of Applied Science degree and the data consequently used was reported (Murray & Sims, 2001a; Murray & Sims, 2001b; Murray & Sims, 2001c; Murray & Sims, 2002; Sims *et al.*, 2003). All ensuing use and analysis of the data is the author's own work and undertaken for the sole purpose of meeting the aims and objectives of this study.

1.6 Thesis Structure

This thesis comprises five parts, structured into twelve Chapters, and further supplemented with seven appended Chapters. This Chapter introduced the problem, objectives and aims of this study.

Part one outlines the formation and processes of the SPiRAL decision-analysis framework. In Chapter 2, a literature review examines distributed generation; the problems of existing renewable energy systems and methods of design; electricity load profiles; and the use of formal decision analysis in the energy sector. Chapter 3 documents the software selection process and covers the range of software suitable for modelling the wind energy resource, renewable energy based distributed generation system design, and multiple criteria decision analysis. Chapter 4 examines the SPiRAL model formation proposed (Figure 1.1) relative to project duration and short-term duration modelling data requirements. Chapter 5 describes the case study sites, with details of the location of the electricity load and renewable energy resource monitoring.

Part two, Chapter 6 documents the process of data collection through to presentation, and use in short-term duration analysis calculations. The load profiles presented include the community electricity load profiles, collated from all the individual sites. The methods used and the results of the renewable energy resource monitoring are presented in a similar manner in Chapter 7.

Part three presents the modelling of the wind energy resource; renewable energy based distributed generation systems; and the decision-analysis process. Chapter 8 reports on the results of wind energy resource modelling. The renewable energy system modelling makes use of the measured hydrological and solar resource data (Chapter 9). These results are then used in a multiple criteria decision analysis model (Chapter 10).

Part four, in Chapter 11, the overall results of the collective use of the models WAsP, HOMER, and Logical Decisions for Windows are presented and discussed. This includes sections on the overall SPiRAL model, and the short-term project duration analysis, potential users of the method, vulnerabilities of the study, and further research recommendations. A conclusion is given in Chapter 12.

Part five, contains the appended sections on the relevant energy legislation (Appendix A), wind resource modelling (Appendix B), multiple criteria decision analysis software (Appendix C), the Limestone Downs case study site (Appendix D), an aerial photograph of the Totara Valley case study site (Appendix E), the electricity load profiles from the Totara Valley case study site (Appendix F), and the renewable energy resources of Totara Valley (Appendix G).

Part one: the framework design

Review of the literature

Review and selection of the modelling software

The combined SPiRAL decision model

The Totara Valley case study site

2 Review of the Literature

This study develops a decision making process for a sustainable, rural community-sized, renewable energy based distributed generation system design process. To begin with, this topic implies the questions: What is a rural community in New Zealand? Is Totara Valley representative? What are the decisions needing to be made? Why are the decisions necessarily so complex? What will this process achieve that others do not? Why only renewable energy based distributed generation? What is sustainable? What is decision analysis and why should it be used in energy decisions?

Defining what is rural was not straightforward, and is clarified in the New Zealand context in Section 2.1. A summary discussion on the current situation is given in Section 2.2. Distributed generation is gaining support from many aspects of society and the defining attributes of distributed generation are reviewed in Section 2.3. The renewable energy industry has experienced problems with the design and implementation of systems in the past and these are reviewed in Section 2.4. The lack of detailed household electricity use information in New Zealand is reviewed in Section 2.5. The use of rational decision-analysis methods in the electricity industry is examined in Section 2.6. This review is summarised in Section 2.7.

2.1 New Zealand Rural Communities Defined

There is no internationally recognised definition of a 'rural' area. Rural areas in the United States are classified in several ways – population density and size, level of urbanisation, and adjacency to and relationship with an urban centre (RUPRI, 2005; ERS/USDA, 2005). The National Rural Health Association of the United States further defined rural as the "specific to the purposes of the programs in which they are used and that these are referred to as programmatic designations and not as definitions" (NRHA, 2005). The Department for Environment, Food, and Rural Affairs (DEFRA) of the United Kingdom refers to a "scarcity classification" for a measure of population densities at three different scales (DEFRA, 2005). In New Zealand, rural areas have traditionally been residual areas not included in the urban definition. Statistics New Zealand (2005) quoted findings of an earlier study that "identified differences present between rural areas of New Zealand but could not define them, arguing that:

Although it may have been tenable in the past to regard the rural population as homogeneous, recent trends in migration have changed the character of this group. Included under the rural umbrella today are a diversity of groups – farmers and farm workers, forestry workers, 'alternative lifestylers' and craftspeople, among others ... it would be useful to divide the rural population into groups which reflect this diversity.

Statistics New Zealand found from studies of census records (Statistics New Zealand, 2005) that;

There is a huge difference between a rural community based on rural livelihoods and one where a large proportion of the population works in an urban area (particularly a main urban area), but happens to live in a rural area. The urban area provides a significant focus for the latter community. These commuter populations have ready access to urban services: recreational, economic or health. Communities that are rurally focused tend to be further from urban centres, particularly main urban centres, and have poorer access to services. Health services are seen as a crucial resource that is lacking in many rural areas. (Statistics New Zealand, 2005)

Statistics New Zealand (2005) found that the “most suitable measure on which to base the (urban/rural²) classification was found to be a comparison of a person’s usual residence address with their workplace address, using data from the Census of Population and Dwellings”.

The methodology that was used differentiated between urban and rural areas in a rural/urban classification system (Figure 2.1) as follows:

- Main urban area – the main urban centres.
- Satellite urban community – the towns and settlements with strong links to a main urban centre, where 20 percent or more of the usually resident employed population's workplace address is in a main urban area.
- Independent urban community – the towns and settlements without significant dependence on the main urban centres, and where less than 20 percent of the usually resident employed population's workplace addresses are in a main urban area.
- Rural area with high urban influence – includes rural areas that form a transition between the main urban areas and rural areas, where a significant proportion of the resident employed population work in a main urban area.
- Rural area with moderate urban influence – includes rural areas with a significant, but not exclusively, main urban area influence. A large percentage of the resident employed population works in a minor or secondary urban area, or a main urban area.
- Rural area with low urban influence – includes rural areas with a strong rural focus. The majority of the population in these areas works in a rural area, although a number may work in a minor urban area.
- Highly rural/remote area – includes rural areas where there is minimal dependence on urban areas in terms of employment, or where there is a very small employed population.

The urban/rural classification of New Zealand is given in Figure 2.2, and by observing the detailed map of the Totara Valley area (Figure 2.3), Totara Valley is a rural area of low urban influence.

² “urban/rural” inserted by the author.

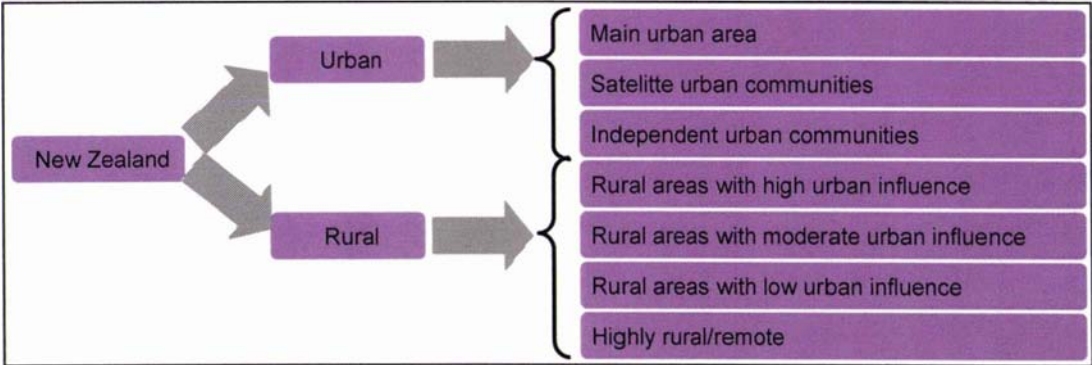


Figure 2.1 Urban rural classification methodology used by Statistics New Zealand (2005).

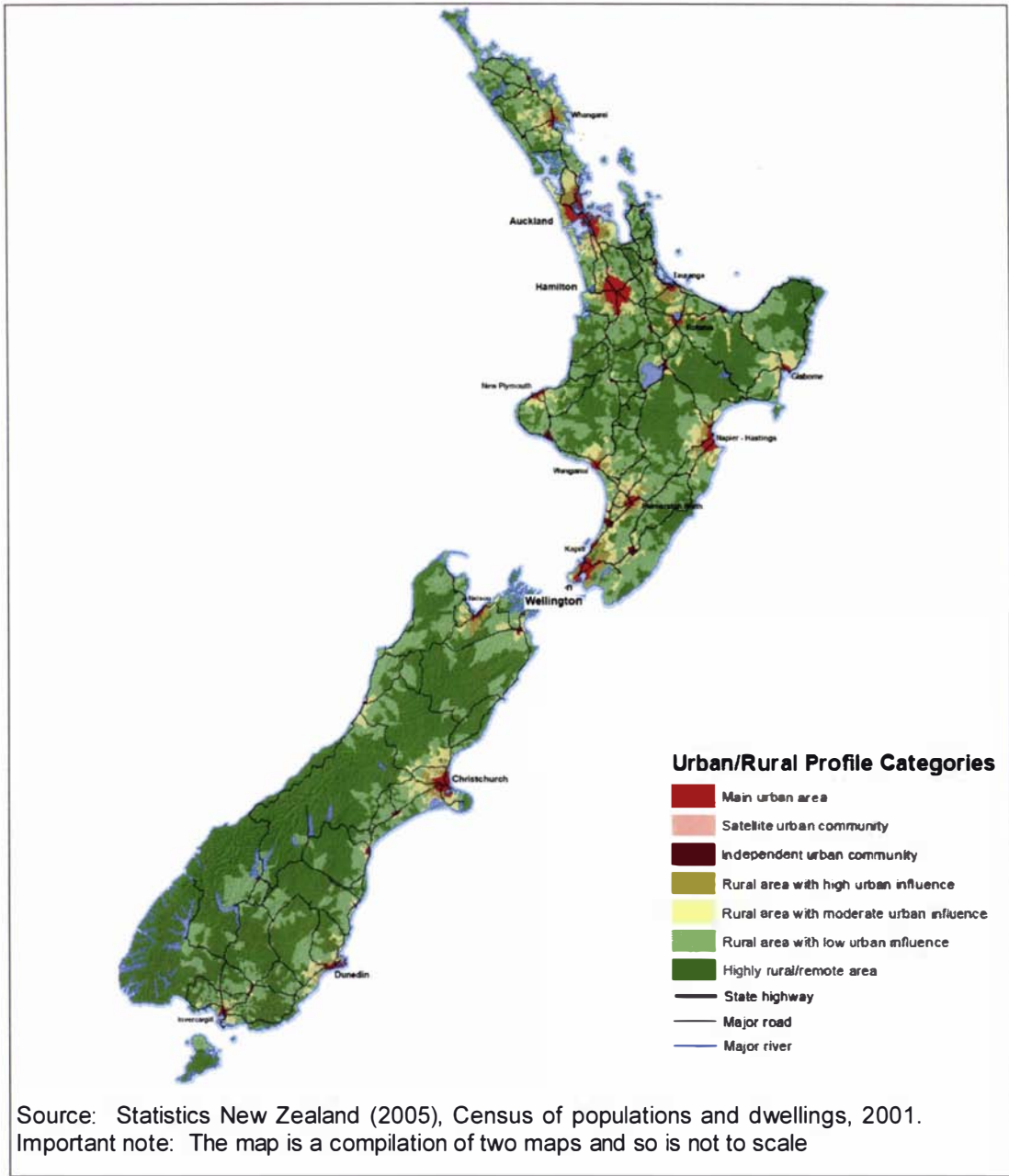


Figure 2.2 The location of the rural/urban areas according to the Statistics New Zealand (2005) classification system.

Such rural areas with low urban influence in New Zealand in 2001 (Figure 2.2):

- covered 87,536 square kilometres or one-third of New Zealand's total land area,
- were second in size only to highly rural and remote areas,
- had only 6% of the NZ census usually resident population count, (224,391 people), and
- had a population density, low by international standards at 2.6 people per square kilometre.
- had an average of 2.7 people per household, (similar to the national average),
- had climates that tend to be less extreme than in highly rural/remote rural areas,
- had more 'traditional' social conditions with a higher proportion of one-family households and married people and fewer families without children.
- had a higher labour force participation rate, at 72.6%, compared with 66.7% nationally.
- had unemployment rates the fourth lowest of the urban/rural profile areas at the time of the 2001 Census (5.5%, compared with 7.5% nationally).
- had an average weekly income of \$547 compared with \$539 nationally,
- had an above average proportion of people earning \$100,001 or more annually (3.3%, compared with 2.4% nationally).
- had a higher-than-average proportion of people earning income from self-employment and a below average proportion of people receiving income from wages and salaries.
- had below average household expenditure (\$41,578, compared with \$43,682 nationally).

2.1.1 Totara Valley – A Rural Community

The similarity of Totara Valley to other locations (Figure 2.2 and Figure 2.3) can be compared between regions by population (Figure 2.4), population density (Figure 2.5), land areas (Figure 2.6), building type (Figure 2.7), household heating method (Figure 2.8), housing occupancy types (Figure 2.9), occupation type (Figure 2.10), and income source (Figure 2.11).

The population of the 'rural areas with low urban influence' within the Manawatu – Wanganui area is 15,237 and ranks sixth among the 15 regions noted (Figure 2.4). This is comparable with Otago (5th) and is slightly more than Southland (7th). When the population density of 1.8 people per square kilometres (9th – Figure 2.5) and the land area of 2.6% (5th – Figure 2.6) of the total national land area are compared with other regions we note that this is comparable with Tasman, Southland, Waikato and Hawke's Bay.

The type of housing is comparable to Otago and Southland (Figure 2.7), and the house-heating methods are similar to Southland and the Bay of Plenty (Figure 2.8). When comparing the number of dwellings by occupancy type (Figure 2.9), the Manawatu – Wanganui region is 5th slightly ahead of Otago, Southland, and Taranaki. Observation of the breakdown of these figures into family type, it can be noted a proportional similarity to most of the comparable regions. An analysis of the occupation type indicates that the predominant occupation is agriculture and fishery (Figure 2.10), similar to the Otago, Bay of Plenty, Southland, and Taranaki regions. The dominant income type is sourced from wages paid to employees and self-employed (Figure 2.11), similar to Bay of Plenty, Otago, and Southland.

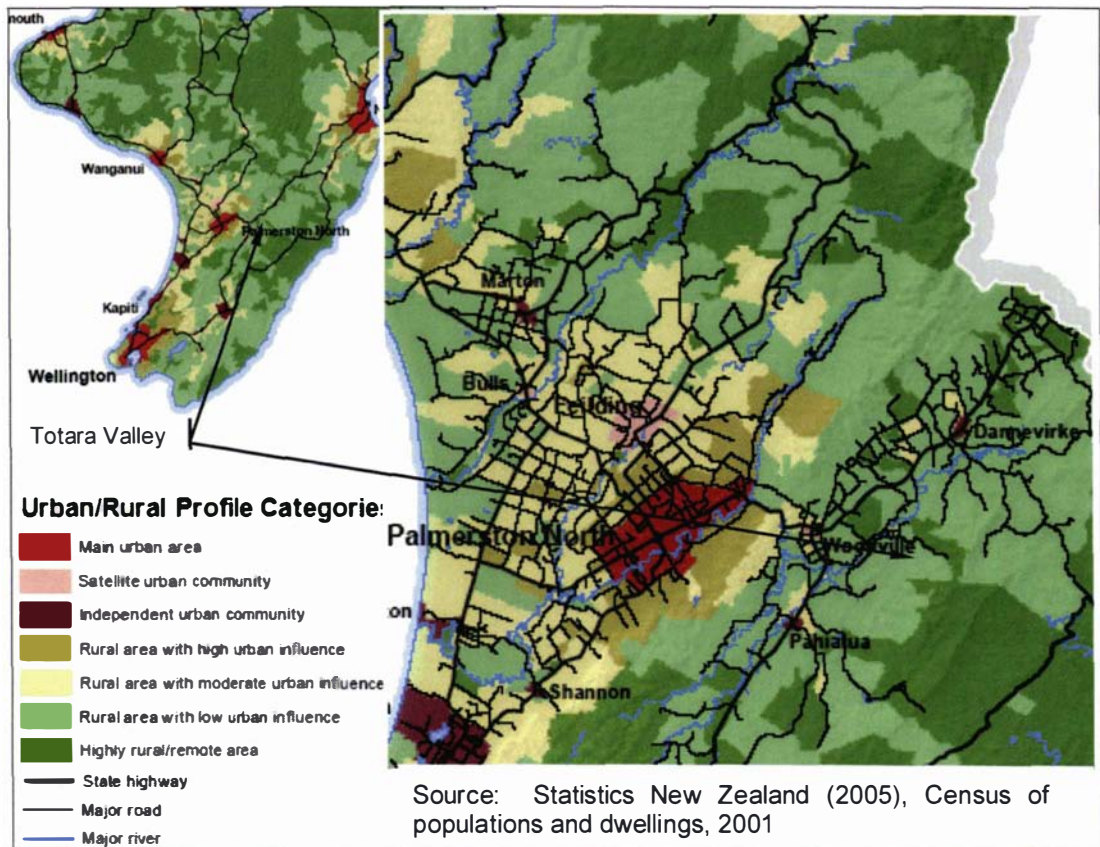


Figure 2.3 The location of Totara Valley in the lower North Island indicating it is rural with low urban influence. The map indicates the rural/urban areas according to the Statistics New Zealand classification system.

Every rural location, similar or otherwise to Totara Valley, will each have separate issues unique to the specific situation that will require consideration, and therefore, Totara Valley must be considered unique. High among the unique features of each specific region is the distributed energy resource availability. The solar resource will vary between locations with geographic latitude, prevailing meteorological conditions, and limits imposed by topography. Likewise, both the hydro and wind resources will be particular to the specific location.

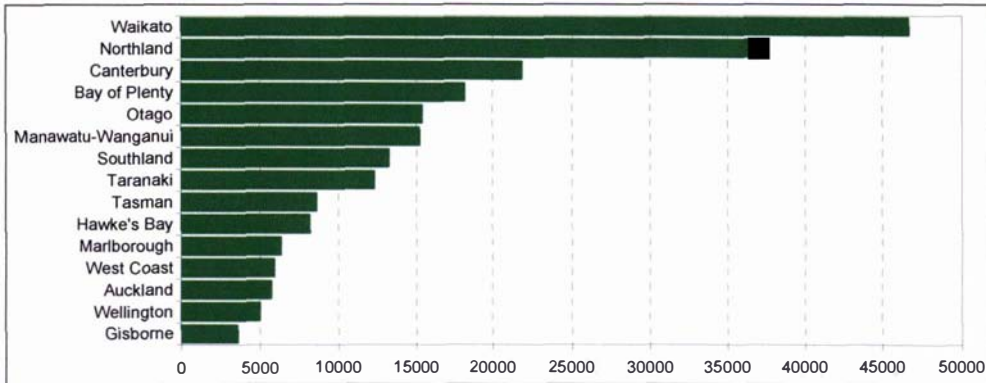


Figure 2.4 Population by region of rural areas with low urban influence (2001 figures).

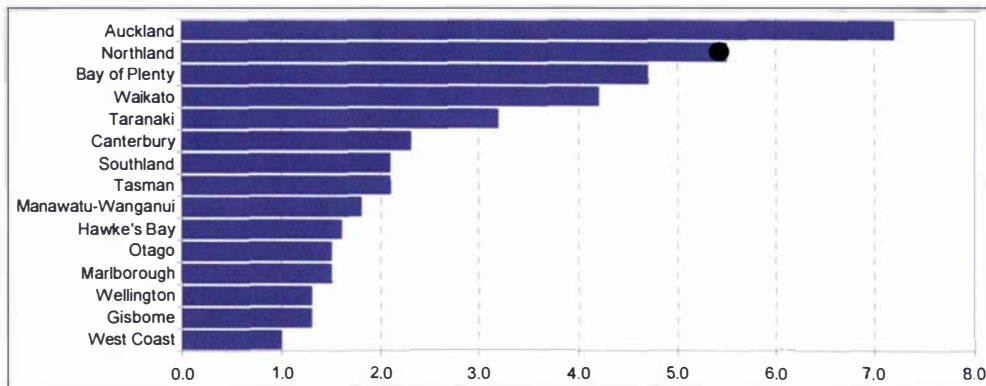


Figure 2.5 Population density (people/km²) by region of rural areas with low urban influence (2001 figures).

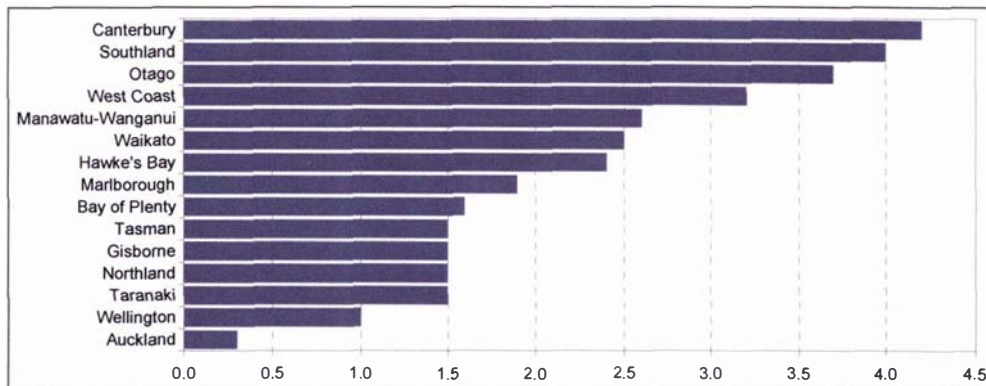


Figure 2.6 Percentage of national land area by region classified as rural with low urban influences (2001 figures).

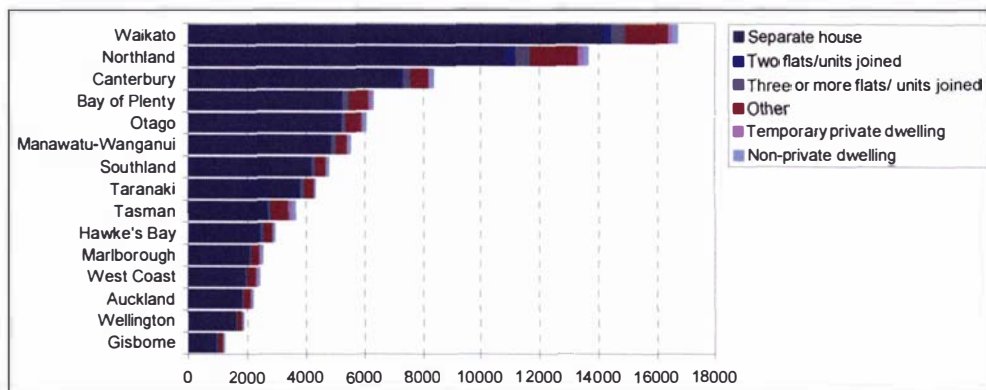


Figure 2.7 Building type by region (2001 figures).

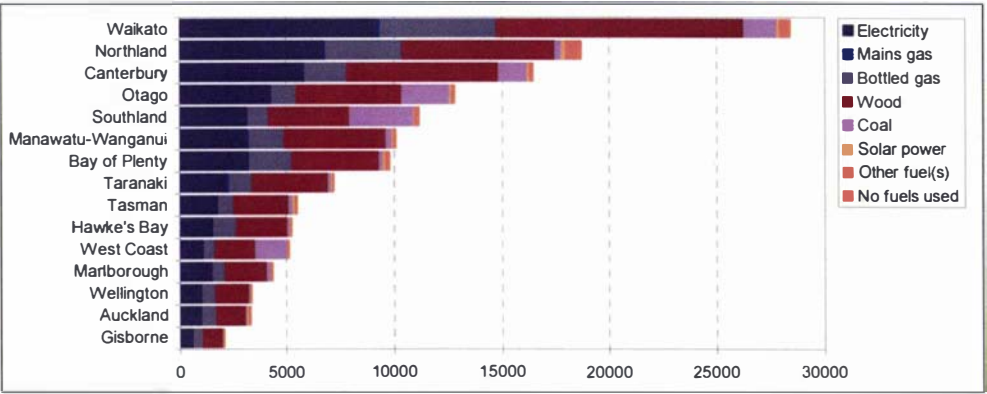


Figure 2.8 Household heating method and fuels by region (2001 figures).

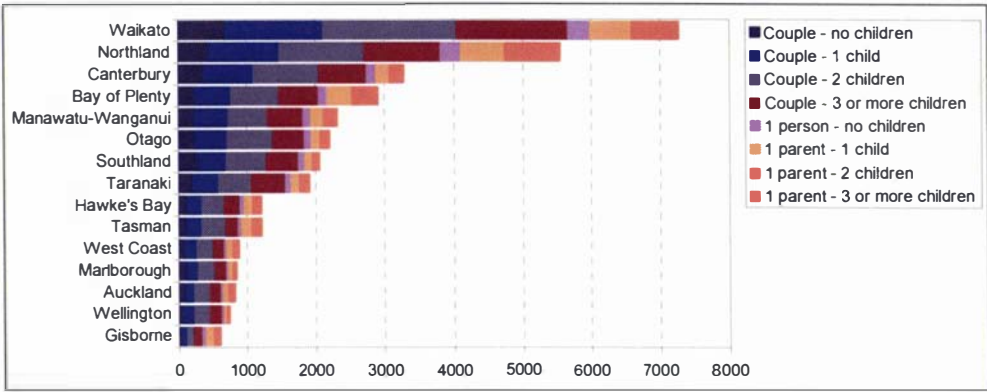


Figure 2.9 Numbers of occupied dwellings by occupancy type and by region (2001 figures).

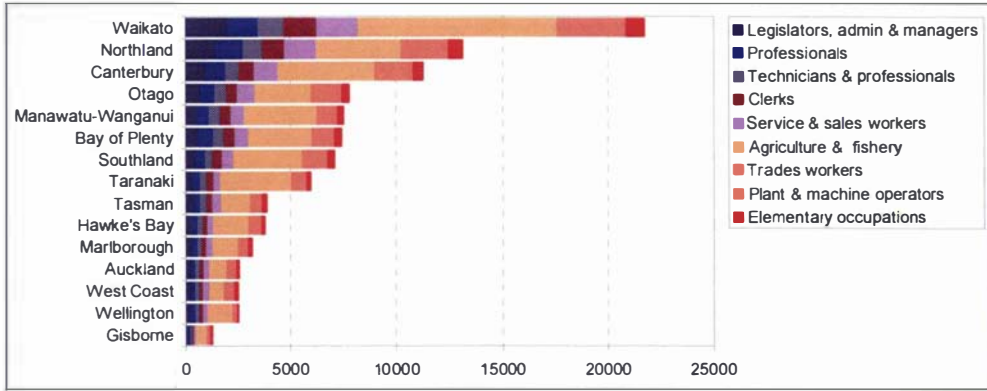


Figure 2.10 Occupation type by region (2001 figures).

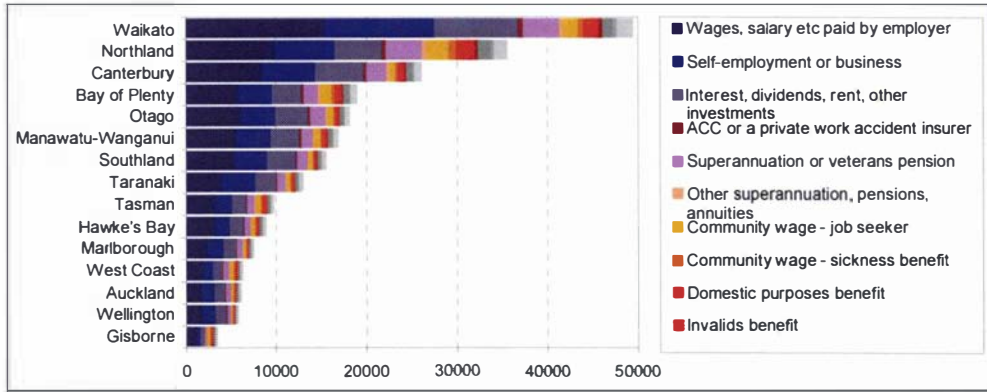


Figure 2.11 Income source by region (2001 figures).

2.2 The Background to the Current Electricity Industry Situation

Since the early 1980s, when a major inter-departmental review of the Crown's role in the electricity industry commenced, New Zealand's electricity sector has undergone many changes, both deregulatory, and subsequently market driven. These changes range from the first Government decisions on electricity reform in 1986; the formation of the Electricity Corporation of New Zealand (ECNZ) in 1987, followed by Transpower as a subsidiary of ECNZ in 1988.

The early 1990s saw the first of many regulatory changes with the culmination of these, the enactment of the Electricity Act 1992³ in 1993. A 'sunset clause' (Section 62, ss 6, Appendix A – 13.1) within this Act removes the legal obligation to maintain a supply of electricity to consumers should the electricity distribution company deem for whatever reason it is no longer in their interest to do so.

Electricity market changes occurred in 1996 with the formation of the wholesale electricity market. The late 1990s saw one of the bigger changes to the electricity sector when electricity retail and lines distribution businesses were separated as business entities. The Government then announced its energy policy framework, which was designed to "...ensure the delivery of energy services to all classes of consumers in an efficient, fair, reliable, and sustainable manner" (MED, 2005). There were electricity shortages in 2001 and 2003. In 2001, the rules governing ownership of generation capacity by distribution companies were relaxed allowing unlimited ownership of renewable generation. The first reports of managed hydro spill appeared in April 2002.

Following concerns about the overall state of the electricity industry, and the apparent lack of benefits to the consumer, the formation of the Electricity Commission was finalised in 2003. This was closely followed by the advent of the oil-fired Whirinaki thermal power station for security of supply with further government decisions regarding reserve supply. The Whirinaki power station was commissioned in 2004. The sustainable energy discussion document was released in 2004 which explored what a sustainable energy system might look like and how New Zealand might achieve it".

Bruckner *et al.* (2005) summarised these changes as requiring a "...shift in thinking in respect of technologies, resources, and architectures". The current generation mix now comprises not only of the conventional hydro, geothermal, and thermal, but also has additional capacity of new renewable energy technologies of wind and biomass.

However, through deregulation, the distribution companies have been left with an aging network that was built up through a subsidised and orchestrated programme of network development. This was through;

...a systematic policy of electrical reticulation to achieve network connection to the majority of the population. Radial supply lines at predominantly 11 kV distribution voltage were pushed through very

³ See Section 62 ss 6 in Appendix A – 13.1.

rugged terrain to a large number of rural and often isolated communities. (Ackermann *et al.*, 1999) (p 206).

Because of this development policy of pushing the network through rugged terrain, and through subsequent aging of distribution components there are now problems with power quality and cost of supply to remote rural networks connected to the 11-kilovolt network. These are big issues to network operators and are now leading to the costs of electricity distribution operation and maintenance being passed on to the consumer. This problem is characterised by Ackermann *et al.* (1999);

Under the deregulated market environment which now exists, the issue of how to maintain and improve grid service to these areas is becoming more important, accentuated by ageing distribution lines and the generally higher expectations from customers for quality power. The demand on many of these weak distribution systems is increasing, often peaking only at certain times of the year, for example during the vacation season, so upgrading is also of concern to power supply companies. Ackermann *et al.* (1999) (p 206).

At this point, key concerns of the consumer appear to be financial cost reduction, climate protection, fossil fuel use displacement, competition failure, supply reliability and security, and various environmental and social impacts (Bruckner *et al.*, 2005). In New Zealand, many of these concerns may be remedied by the implementation of a local renewable energy based distributed generation system. This was the overall finding of Alanne & Saari (2005) who concluded for similar cases in Europe, "...the energy system in the future is going to be a mixture of centralised and distributed generation systems, operating parallel to each other".

2.3 Distributed Generation

Concerns about the worldwide trend of electricity industry deregulation, increasing costs of operation and maintenance, supply reliability and security of long-term supply, the environment and the ongoing emissions from fossil fuel based electricity generation, and advances in renewable and high efficiency technologies, have led to an emphasis on the use of small power generation units in a variety of forms and technological configurations. Distributed generation is a key delivery mechanism of many of these technologies. Ackermann *et al.* (2001) indicated that by 2010, 25% of the new generation in Europe will be delivered in a distributed generation context, however, the definitions for distributed generation (DG) used in the literature were not consistent or unambiguous (Alanne & Saari, 2005).

Electricity generation capacity, when deployed in a distributed context within the electricity grid of an area or location close to end-users is termed distributed generation (DG) (Outhred & Spooner, 2002). Also known as embedded generation, DG was defined by the New Zealand Ministry of Economic Development (MED, 2003) as "any electricity generation facility that either produces electricity for use at the point of location or supplies electricity to other consumers through a local lines distribution network at distribution rather than transmission voltages". Section 3(i) of the Electricity Industry Reform Act 1998 defined distributed generation as "a generator or generators that are connected to a local distribution network or to an end-

user load that is connected to a local distribution network, and not directly connected to the national grid”.

A large range of technologies can be used in distributed generation (IEA, 2002a; Scott *et al.*, 2003; Pepermans *et al.*, 2005). Examples of actual implementation or research of such technologies can be found in the literature for:

- small to medium wind turbines (Forsyth *et al.*, 2000; El-Khattam & Salama, 2004; Divya & Nagendra Rao, 2005; Lund, 2006);
- solar PV (Aly *et al.*, 1999; Wiemken *et al.*, 2001; IEA, 2002 a & b; Conti *et al.*, 2003; El-Khattam & Salama, 2004; Maine & Chapman, 2006; Lund, 2006);
- hydro power (Wijayatunga *et al.*, 2004);
- wave or tidal power systems (Lund, 2006);
- biomass gasification (Jurado *et al.*, 2004; Jurado & Cano, 2005; Banerjee, 2006);
- combined heat and power (CHP) units (Alanne & Saari, 2004; El-Khattam & Salama, 2004; Bischoff, 2005), also known as co-generation utilising reciprocating engines, Stirling engines, fuel cells, and micro turbines can be used in CHP units (Alanne & Saari, 2004; El-Khattam & Salama, 2004; Krumdieck *et al.*, 2004; Bischoff, 2005; Bauen *et al.*, 2003; Bourgeois *et al.*, 2003; Corria *et al.*, 2005; Doyon *et al.*, 2003).and
- DG electricity storage devices such as flywheels, hydrogen generation and storage, advanced batteries, pumped hydro storage, and compressed air (Dell & Rand, 2001; Clark & Isherwood, 2004; El-Khattam & Salama, 2004; Denholm, 2005; Clark & Doughty, 2005; Williams *et al.*, 2005).

Two key benefits of DG that can be realised for network operators are, deferral of network upgrades if the net ‘movement’ of electricity continues in the direction intended, and grid network electricity line losses may also be reduced (Outhred & Spooner, 2002; Dondi *et al.*, 2002). Other benefits (Strachan & Dowlatabadi, 2002; Passey *et al.*, 2002; Dondi *et al.*, 2002; MED, 2003; El-Khattam & Salama, 2004; Raineri *et al.*, 2005; Bruckner *et al.*, 2005; Strachan & Farrell, 2005) of new DG over new centralised energy generators include:

- installation of cost-effective and efficient combined heat and power systems;
- smaller and strategically placed DG may be more cost effective and timely new power sources;
- may allow new business to begin operating in the electricity generation market;
- may allow industries to operate where previously electricity supply would not have been sufficient;
- systems can be placed into distribution networks quicker than centralised systems can be implemented;
- small DG may be easier to finance;
- small DG throughout the supply network may lead to increased security of supply;
- pollution and emissions reduction at local, regional, and global levels;
- improved health status, locally, regionally and nationally;
- peak load matching;

- supply a local level of spinning reserve, and
- improved power quality on weak feeder lines (through voltage support, reactive power compensation and harmonic compensation).

As indicated in the literature, a renewable energy based distributed generation system is usually a cost-effective, energy-efficient, reliable, and environmentally friendly supplement to the traditional centralised generation system (Dincer, 1999, 2000), and the implementation of such technology often seems to be simply a matter of decision-making. However, Alanne & Saari (2005) indicate that the willingness and readiness to make implementation decisions “requires the active promotion of new technology among (the concerned) interest groups”.

Flowers *et al.* (2000) suggested that to date the lack of effective analysis tools that allow “objective, economic comparisons of energy systems for individual buildings and interconnected (isolated mini-grid) facilities to grid extension, using conventional and/or renewable sources” could be “partly responsible for the perpetuation of conventional solutions.” Outhred & Spooner (2002) also indicated “...a need for enhancements to the commercially available network planning tools...” currently in use so that DG modelling can be undertaken ...”in particular, software for modelling generator operation based on various parameters such as weather conditions”. The use of renewable energy sources adds to the complexity of distributed generation system design because their output has often been described as “...intermittent, seasonal, and nondispatchable” (Lambert *et al.*, 2006). One of the key challenges noted in the literature appeared to be related to the documenting and management of the inherent fluctuations in the electricity production from renewable energy sources. Similar barriers to the implementation of DG have been suggested by Painuly (2001); Lund & Münster (2003); Ashby (2004); Chaurey *et al.* (2004); MED (2004b); Reddy & Painuly (2004); MED (2005). The ongoing design and development of HOMER to model grid-connected renewable energy technologies was intended to overcome such barriers (Lambert *et al.*, 2006), and as such has addressed these concerns in part.

2.4 Renewable Energy System Design Problems

The installation of successful, cost-effective, and reliable renewable energy power supply systems has been seen as essential for the initial adoption and continued growth of this technology (Jennings *et al.*, 1996). Lloyd *et al.* (2000) verified this in a series of published case studies of renewable energy systems documenting a number of problems related to aspects of renewable energy system design that could inhibit the uptake of renewable energy technology. Key among the causes of these problems were lack of consultation, no planning for future load increases, inappropriate use of sophisticated technology, renewable energy systems designed and implemented with no back-up, lack of education about system constraints, and rapid technology obsolescence. A general theme from a majority of the responses of the survey was “simple is best” as this was equated with ease of maintenance, durability, cost effectiveness, and reliability. Even with the comment of “simple equates to cost effectiveness”, the high initial capital cost can be a barrier to the uptake of renewable energy, especially with regard to photovoltaics, which is one of the simpler systems to manage. Risk levels should be

considered in system design due to the combined dynamics of load and resource uncertainty. However, often uncertainty was not considered subsequently leading to system failure.

Jennings & Healy (2001) indicated that renewable energy based systems had a poor reputation because of poor “selection and design of the system for the location, clarity in contractor responsibilities, the operator-control equipment interface and/or the level of community involvement or interest in the power station”.

Flowers *et al.* (2000) and Flowers (1998), highlighted “lessons learned” about technical and social requirements for successful implementation of renewable energy projects reflected the findings of both Lloyd *et al.* (2000), and Jennings & Healy (2001). Key among these was the concept of simplicity and robustness of the RE system being better than cost effectiveness, lowest cost, or highest electrical efficiency. The ready availability of maintenance capability and the matching of user needs with system design and development were deemed crucial to the long-term life of the project. Other lessons included the institutional aspects of “partnering with the stakeholders”, the requirement for integrated planning tools for renewable energy projects, and the importance of real economic signals being forwarded to the stakeholders and developers of renewable energy systems.

Operational issues in renewable energy system design included the importance of demand-side energy efficiency implementation on the overall renewable energy system infrastructure and the correct maintenance schedule for each element of the system. Good system sizing and appropriate load to resource matching were vital to the lifecycle economics of the renewable energy system as over-sizing can lead to under utilisation and under-sizing can lead to over use or lack of capacity. The dynamics of a changeable population was found in some cases to lead to under-sized systems much to the detriment of the RE system performance and allowances needed to be made for community dynamics, aspirations, and potential business ventures. Complex RE systems were generally not successful as this complexity tended to ‘disempower’ the energy users because outside help was required for system repair or operational problems. This was a key cause of frustration with some systems in particular and remote renewable energy systems in general. If due consideration was given to such design and implementation issues then renewable energy solutions can indeed be both economical and sustainable (*ibid.*).

Chaurey *et al.* (2004) indicated the lack of information on the techno-economic performance of a hybrid system is often a problem in designing grid connected distributed generation systems. Such uncertainty can be derived from the stochastic nature of renewable sources, and when imposed within a network previously utilised on assumptions of certainty of supply there will be problems (Garcia & Weisser, 2005). This then becomes a major obstacle to the expansion of renewable energy based distributed generation as “today’s electricity grids are designed for generating units of fully controllable output” (*ibid.*). This was also a finding of Mitchell *et al.* (2005) whom “identified unpredictability or reliability of system compared to grid an issue for some”. The economic aspect of uncertainty in resources is often reflected in the

lack of regular predictable income for payment of financial obligations, owner-profit, and operation and maintenance costs (Bhattacharyya, 2006).

This techno-economic uncertainty in turn drives to some extent the acceptance of renewable energy through energy policy. However, Bruckner *et al.* (2005) indicated that;

...the numerical portrayal of distributed technologies is not easy. Nonetheless, public policy energy models need to adequately capture distributed energy technologies if they are to avoid technological discrimination and produce robust conclusions. The task of projecting the potential uptake of distributed technologies and identifying their likely public good contribution (for instance, toward carbon mitigation) is even more difficult (Bruckner *et al.*, 2005).

This too was in findings of Dufo-López & Bernal-Aguistin (2005) who indicated that;

...the design of hybrid systems is complex because of the uncertain renewable energy supplies, load demands and the non-linear characteristics of some components, so the design problem cannot be solved easily by classical optimisation methods (Dufo-López & Bernal-Aguistin, 2005).

Given the complexity of both renewable energy based stand-alone and distributed generation systems, such energy policy formation and execution needs to be underpinned by good data, and robust numerical modelling (Bruckner *et al.*, 2005). System modelling can be used to overcome some of these issues; however, renewable energy system modeling requires reliable energy resource data in order to reproduce the behaviour of a physical system (Gómez-Muñoz & Porta-Gándara, 2002). The concept of 'energy system' commonly refers to the energy chain that can be regarded as an entity consisting of "...energy production, conversion, transmission, distribution, and consumption" (Alanne & Saari, 2005). Absent from this system concept are the important parameters of economic, social, environmental, and technological dimensions, that should be included in the energy system design.

On the supply-side, the distributed energy resources solar, hydro, and biomass are perhaps the easier to model, but wind is often the most difficult to predict due to its spatial and temporal variability, and the applicability of uncertainty of wind data being applied beyond the location of monitoring. On the demand-side, the uncertainty of load profiles and the lack of knowledge of consumer behaviour is an obstacle to the implementation of renewable energy based distributed generation, as it was critical to the design (Aly *et al.*, 1999).

2.5 Electricity Load Profiles

There was little or no current data available directly related to end-use electricity consumption profiles from rural New Zealand. Subsequently there was no data outlining any difference between urban and rural electricity load profiles. Knowledge of electricity use in the form of user load profiles is vital for several key factors of grid-connected renewable energy system design. These factors include the time-of-use pricing within the current competitive retail electricity sector; investment decision-making; and generation and transmission planning. A 1971-72 analysis of electricity profiles in New Zealand (NZ Dept of Statistics, 1973) was until recently, the latest data on New Zealand household electricity consumption. Electricity

appliances, their use, and the means of monitoring this use have advanced much since this first study and only minor re-working of the original data has been undertaken (Wright & Baines, 1986). This is now superseded by the household energy end-use project (HEEP) (Bishop *et al.*, 1998; Camilleri *et al.*, 2002; Camilleri *et al.*, 2000; Isaacs *et al.*, 2002; Pollard *et al.*, 2002; Pollard, 1999; Stoecklein *et al.*, 2002a; Stoecklein *et al.*, 2002b; Stoecklein *et al.*, 2001a; Stoecklein *et al.*, 2001b; Stoecklein *et al.*, 1998), which was started by the Building Research Association of New Zealand (BRANZ) in 1995. The monitoring programme conducted in the Totara Valley since 1998 (Irving, 2000; Murray & Sims, 2001a) also contributes to this body of knowledge.

The HEEP research is set to provide statistically representative data that will see the project extended to include up to 400 houses nationwide, this being the required sample size. Of these 400, 56 will be rural (Isaacs *et al.*, 2002; Stoecklein *et al.*, 2001a & b). To date electricity demand, space heating, and hot water energy usage data have been collected from 66 specifically selected residential houses in Wanganui, Christchurch, and Wellington, with further randomly selected houses in Wellington (43), Hamilton (17), Waikanae (10), Christchurch (37) and Auckland (98) (*ibid.*).

Six classifications of electricity load profile type based on absolute shape (Figure 2.12) have evolved from the HEEP study. Camilleri *et al.*, 2000 and Stoecklein *et al.*, 2001b assessed these as being:

- Class 1: a typical night rate profile: High consumption over night period, followed by flat low day consumption, with a medium evening level of consumption.
- Class 2: the morning and evening peaks are approximately the same height.
- Class 3: a relatively flat profile with a high morning peak.
- Class 4: a sharp mid morning peak, a low midday and high extended evening peak.
- Class 5: no morning peak, a medium afternoon level profile and an early evening peak.
- Class 6: Similar to Class 5, but with a later evening peak and lower overall level.

Figure 2.12 indicates the daily electricity profiles in Watts as classified using an artificial neural network (Camilleri *et al.*, 2000). The thick black line shows the average profile of the class. The inserted pie charts show the proportion of superannuatants (S) and non-superannuatants (nS) included in each class.

These load profile classes will be important in any future modelling of electricity load profiles as the socio-demographic aspect of the HEEP study will enable the profiles to be associated with different types of users. Therefore, if the subject's lifestyle or socio-demographic status is similar to a HEEP user type then an estimation of profile shape can be used and the only aspect of the electricity profile needing to be modelled would be the magnitude of the peak load.

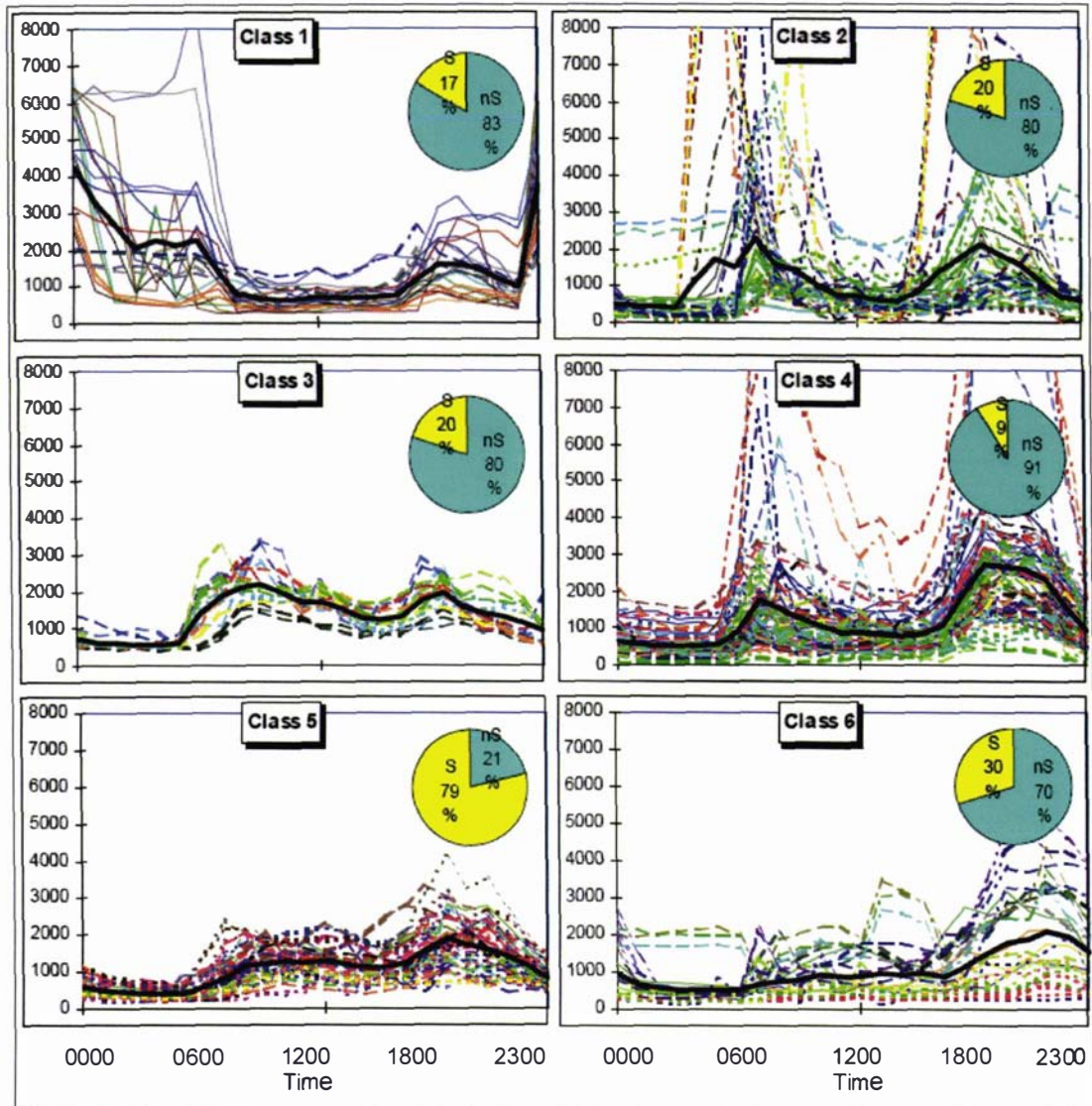


Figure 2.12 The six electricity profile classifications from the household energy end-use project (HEEP) study indicating the mean load profile in each class (Bold black line).

The artificial neural networks (ANN) process used was based on an automatic process that endeavoured to minimise the differences within each of the different profile classes Camilleri *et al.*, (2000). The analysis was conducted on monthly average-day profiles to allow for the variability attributable to seasonal influences. In the analysis of profile classes, 239 profiles were used (*ibid.*). As the classes were assessed from monthly data, each class may be comprised of the monthly profiles of more than one house (Albrecht Stoecklein, 2006. Personal communication).

Work got under way in 2004 to monitor randomly selected houses in the locations of Foxton Beach, Rotorua, Taupo, Tauranga, Oamaru, Dunedin, Wairoa, Gisborne, Napier, and Invercargill and in the regions of Northland, Waikato, Tasman, Marlborough, Franklin, Rodney, and Thames (Isaacs *et al.*, 2002; Stoecklein *et al.*, 2001 a & b). As electricity load monitoring to date has occurred in urban settings there was no clear indication of rural household energy end use, their load profiles, or whether differences existed between rural and urban electricity use. The proposed monitoring of households in rural regions may achieve this. When completed,

the HEEP data and model can be utilised in a detailed load modelling process to negate the need for future large scale monitoring programmes.

2.6 Decision Analysis

Thompson (1982) formally defines decision analysis as “the rational determination of those actions best serving the interests of the decision makers”, and in this regard, Bond (1995) outlined the history of decision-analysis philosophy:

The roots of decision theory trace back to Daniel Bernouilli (1738), where the concept of utility was first introduced to explain people's non-linear value of money. This was revived in the 1920s by Frank Ramsey and subsequently by von Neumann & Morgenstern (1944). It was formalised into the set of decision theory axioms by Savage (1954). This normative theory has since remained unchanged (albeit with some controversy). Bond, 1995. (p 2).

Wallace (2000) ascribed to the ideal that all decisions were made under uncertainty and were constructed from the need to choose from alternatives based on criterion to meet an objective or goal (Belton & Stewart, 2002; Clemen, 1996; Hobbs, 2000; Kirkwood, 1992). Decisions are made based on ‘criteria’, defined in the Chambers twentieth century dictionary as “...a means or standard of judging; a test; a rule.” The range and variety of criteria for deciding amongst alternatives can be many and hence the complexity inherent in many decisions involving multiple criteria.

Multiple criteria decision analysis (MCDA) is a term used by Belton & Stewart (2002) as “...an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter”. The concept of MCDA is also called multiple criteria decision aid, multiple criteria decision making (MCDM) and multiple criteria analysis (MCA) (Belton & Stewart, 2002; Clemen, 1996). MCDA methods appear to have developed rapidly over the last 20 to 25 years given the growth in published literature (Urli & Nadeau, 1999; Morton *et al.*, 2001; Belton & Stewart, 2002) and the applications of the various methods (Belton & Stewart, 2002; Morton *et al.*, 2001; Clemen, 1996). However, Clark & Scott (1999) surveyed the level of MCDA usage in New Zealand and found that from 177 useful responses (out of 297 received) 70% of respondents had used CBA, 22% had used some form of formal decision analysis but only 12% had used MCDA. All respondents had heard of CBA but 29% had not heard of any of the methods used in MCDA.

MCDA has been commonly used where decisions are complex (Borison, 1995) and Belton & Stewart (2002) described the practice of MCDA data processing as being “...through complexity to simplicity.” MCDA methods have been applied where cost-benefit analysis (CBA) is seen as inadequate due to a lack of good cost data or when cost is not a good measure of performance (Butler *et al.*, 2001). Hill (1968) wrote a good critique of the CBA approach to decision-making and Dorfman (1996) indicated that CBA as currently practised has three distinct shortcomings. It does not specifically identify the population segment to which the benefits or costs accrue, it attempts to reduce all comparisons to a single dimension (typically monetary), and it conceals the degree of uncertainty or inaccuracy in the estimates calculated.

The contingent valuation method of CBA has been criticised for relative inflexibility because of the requirement for expression in dollar terms (Ananda & Herath, 2003). MCDA techniques are now considered favourably for evaluation of complex problems since they have the potential to take into account the many "conflictual, multi-dimensional, incommensurable and uncertain effects of decisions explicitly" (*ibid.*) while using the "more subjective methods of decision analysis to capture preferences for intangibles, such as 'quality of the environment' and 'intergenerational equity'" (French & Geldermann, 2005).

However, MCDA processes are not perfect either and Belton & Stewart (2002) indicated that some myths surround the concept of MCDA at times. Such myths include the belief that MCDA will give an objective analysis that will relieve decision-makers for the responsibility of making difficult decisions or that MCDA will take the 'pain' out of decision-making and will give the right answer. Belton & Stewart (2002) were emphatic in their response that there is no such thing as "the right answer" (even within the model being used) and further indicated that the concept of optimisation in MCDA is non-existent as well.

Buchanan *et al.* (1998) have a very good commentary on subjectivity and objectivity in decision-making and indicated "...decisions are made by decision makers, not by a model. The decision maker(s) stands in the center of the decision making process". MCDA is designed to be an aid to decision-making – "a process that seeks to integrate objective measurement with value judgement – make explicit and manage subjectivity" (Belton & Stewart, 2002). Such subjectivity contributes to decision complexity and is inherent in all decision-making especially in criteria choice on which decisions are based, and the relative weight given to the criteria (Belton & Stewart, 2002).

Beroggi (2000) refers to the two components of decision making as behavioural and mechanical. Behavioural is where the decision makers inherent subjectivity (and inconsistency) is documented, and the mechanical is where this subjectivity (and inconsistency) is dealt with in the model. Sadeghi & Hosseini (2006) indicated that the complexities of natural, social, and human behaviours in decisions...

...is ever rooted in the incompatible nature of subjectivity and objectivity, accuracy and inaccuracy, simplicity and complexity, certainty and uncertainty, etc. Trying to analyze the subjectivity, inaccuracy and uncertainty of natural, social and human systems had never led to satisfactory conclusions. (p 996).

Further to this it was added that "...under certain and random circumstances, mathematical and stochastic methods have been used successfully in the simulation of natural and human behaviors, respectively, these methods could not describe reality perfectly" (*ibid.*).

Indeed, MCDA does not dispel this subjectivity but rather it makes the results of subjective judgments explicit and the processes in which they are calculated, transparent (Belton & Stewart, 2002). French *et al.* (2001) indicated that some of the main problems perceived in the use of MCDA methods were the inherent subjectivity of the problem structure and weightings used, an apparent difficulty trading off very diverse attributes, and the consistency of these from one decision to another. Subjectivity is not an uncommon topic of

discussion in the literature (Buchanan *et al.*, 1998; Beroggi, 2000; French *et al.*, 2001; Belton & Stewart, 2002; Hyde *et al.*, 2003; Keefer *et al.*, 2004; Munda, 2004; Kim, 2005; Nigem *et al.*, 2004).

However, through the transparent manner of the portrayal of subjectivity (Belton & Stewart, 2002), both Munksgaard & Larsen (1998) and van den Broek & Lemmens (1997) showed the strength of MCDA processes to assure the sustainability of decisions in order to deal with socio-economic objectives alongside financial and macro-economic objectives⁴. Scott *et al.* (2000) maintained that sustainability includes social considerations alongside environment and economic considerations and places sustainability into the New Zealand context.

Analysis of the notion of sustainable rural communities has particular relevance to New Zealand, where a commitment to the concept of sustainability has been signalled, particularly through the Resource Management Act 1991. Scott *et al.* (2000). (P 433).

For clarity, the purpose, and principles of the Resource Management Act 1991 (Appendix A – 13.4) is to promote the sustainable management of natural and physical resources where sustainable management means:

...managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic and cultural wellbeing and for their health and safety while... ...avoiding, remedying or mitigating any adverse effects of activities on the environment. (Resource Management Act, 1991).

The terms 'sustainable' 'sustainability' and 'sustainable development' have many meanings and interpretations in the literature with most being similar to the definition of "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The three main threads of sustainability appear to be the ability of a community to live within the limits and means of the environment, the equitable distribution of resources between present and future generations and understanding the linkages between environment, society, and economy.

Jefferson (2006) indicated that the 1987 Brundtland Commission's Report provided four key elements of sustainable energy. These were listed as requiring;

- sufficient growth of energy supplies to meet human needs (including accommodating relatively rapid growth in developing countries);
- energy efficiency and conservation measures, in order to minimise waste of primary resources;
- the addressing public health and safety issues where they arise in the use of energy resources; and
- protection of the biosphere and prevention of more localised forms of pollution.

⁴ Many further such examples exist in the literature, of which, some are indicated the bibliography section of this study.

Indeed on the last point listed, Carlson, (2002) indicated where several studies have shown that the externalities due to energy conversion can be considerable, and that it was "cost-effective for society to take these externality costs into consideration in order to avoid damages instead of paying for them at a later stage".

Outhred *et al.* (2002) further defined the dimensions of sustainability in the energy sector as being economic, environmental, social and technical sustainability, further noting that "these dimensions are not fully independent and that they may involve concepts of community at household, local community, state, national or global levels". This implies sustainability issues within renewable energy sector decision-making must be considered in the catchment wide or regional and community scale context, and must therefore include the cumulative effects of multiple renewable energy projects within the catchment or region. These 'effects' can appear sustainable on an individual basis, but when such projects occur on a wider scale within a confined area (valley, or catchment), the environmental, economic, social, or technical sustainability of the individual projects could be jeopardised.

Sustainable development by the definitions above requires a sustainable supply of energy. In this regard, the tangible linkage between renewable energy sources and sustainable development becomes clear (Dincer 2000). Furthermore, the energy sector, because of its contribution to the greenhouse effect should play a major role in any policy formulation for sustainable environmental development. This concept was formally introduced into international politics in the Framework Convention on Climate Change signed by 155 nations at the UN Conference in Rio de Janeiro in 1992 (Meyer, 2003).

It must be accepted that energy provision be a key factor in any discussions or study of the economic, social, and environmental dimensions of sustainable development. Alanne & Saari (2005) indicated "...a sustainable energy system has been commonly defined in terms of its energy efficiency, its reliability, and its environmental impacts" but also add that "Sustainable development does not make the world 'ready' for the future generations, but it establishes a basis on which the future world can be built".

The definition of sustainability put forth by Brundtland (1987), implies that the effects of the preferences of present-day stakeholders need to be considered beyond the present generation. Any decision-making method therefore must be able to be used by the present generation to attain a sustainable decision leading to a durable outcome for the sake of future generations, especially considering energy related decisions as these are characterised by intergenerational issues. By default, this must be done by assuming what future generations needs will be based on current needs. This begs the question; does the MCDA methodology allow such input to be assumed? The current decision-making methods such as CBA are used in such a manner and MCDA should be no different. In the past, decision makers using MCDA methodologies have utilised a Delphi approach to forming assumptions based on current knowledge, trends, and indirect elicitation methods (Lotov, 2003).

Indeed, weight preference information can be difficult to obtain from stakeholders unfamiliar with the MCDA method employed (Kim & Ahn, 1999; Lahdelma *et al.*, 2000; Lotov,

2003). Lam *et al.* (1997) indicate the uncertainty of preferences elicited directly from stakeholders in such circumstances. This uncertainty is partly derived from the manner in which the preference values were assessed, and the number of attributes the problem has been decomposed into. Ambiguity of interpretations and imprecision of communicating their preferences result in a level of uncertainty in allocating preference values.

Therefore, conducting MCDA analyses with incomplete, imprecise, or partial information is often required and has been documented in the past (Azondekon & Martel, 1995; Kim & Ahn, 1997; Kim & Ahn, 1999; Kim *et al.*, 1999; Ngwenyama & Bryson, 1999; Ahn *et al.*, 2000; Dias & Clímaco, 2000; Vetschera, 2000; Hämäläinen, 2003; Mateos *et al.*, 2003; Mateos *et al.*, 2005; Mustajoki *et al.*, 2005). It was indicated that even with incomplete, imprecise, or partial information or knowledge of the stakeholders preferences, results close to the final stakeholder preferences were possible (Vetschera, 2000).

However, in some cases where previously MCDA was utilised within a Delphi-group approach without direct stakeholder involvement, the internet is now making such applications of MCDA accessible to lay stakeholder involvement much easier (Lotov, 2003; Hämäläinen, 2003). It is thus allowing a shift from the technocratic paradigm to a more democratic one (Lotov, 2003).

2.6.1 Decision Analysis in the Electricity Industry

Electricity generation and transmission by its very nature has both environmental and social impacts and Balson *et al.* (1992) further qualified this to include specific impacts such as personal and community health impacts, environmental and economic risks. To answer some of these inherent problems will require the participation of the varied stakeholder groups.

Stakeholder involvement, in this context include all people directly affected, is seen as a precursor to successful sustainable development of a renewable energy project. A sustainable energy system must therefore be able to supply energy services, while also minimising the impacts on society, local communities, climate, biodiversity, and local and national pollution levels. In its lifecycle/lifetime, it would use materials, land, and energy efficiently and in a manner that emphasised re-use, sometimes called cradle-to-cradle design (*ibid.*). It would create or promote further employment; be affordable and least-cost (economically, socially, and environmentally) to society and the planet; and at the very least not increase social inequity (*ibid.*). The concept of 'perfect sustainability' was not seen as a practical goal, neither was full unconditional consensus between all stakeholders, but rather, realistic trade-offs must be made that allow communities to improve all aspects of sustainability through time (*ibid.*). The sustainability of the renewable energy sector involves many more attributes other than merely economic in the decision-making stage of project design and subsequent implementation, and thus, consideration of sustainability must involve communal issues as well those that were solely the province of a project developer (*ibid.*).

Hobbs (2000) indicated in an editorial statement that;

Solving environmental and natural resources problems is difficult because they often involve multiple objectives and stakeholders, great

uncertainty, and large systems that ignore political boundaries...as an example, the energy industries.

Many of these problems arise from the simultaneous increase in public environmental concerns at the same time that the market restructuring has sharpened competition and increased market uncertainties. (p 5).

Some of the earliest applications of MCDA methods have been within the energy sector (Hobbs, 2000; Golabi *et al.*, 1981). Other such applications included transmission line extension (Borison, 1995); integrated resource planning at British Columbia Gas (Keeney & McDaniel, 1999); demand uncertainty planning (Gardner & Rogers, 1999); hydro planning (Keeney & McDaniel, 1992; Keeney *et al.*, 1995); power system expansion planning (McCutcheon, 1988); and socio-economics of wind energy systems (Munksgaard & Larsen, 1998; Connors, 1996). Borison (1995) stated that formal decision analysis had been used in such areas as capacity planning, environmental compliance, fuel procurement, and plant operations. Munksgaard & Larsen (1998) showed that using a socio-economic basis for their MCDA calculation, the environmental benefits of wind energy placed this technology equal to natural gas, and showed that wind power is more advantageous than a coal-fired power plant. Still within the wind energy sector, Connors (1996) reported on a multi-attribute trade-off analysis in wind power that further identified market opportunities for power generation capacity.

Gardner & Rogers (1999) and Wallace (2000) also highlighted demand uncertainty as a key concern for electric utility planners and indicated that increased competition may cause even greater uncertainty. Spinney & Watkins (1996) indicated that technology changes, fuel costs, load growth, economic trends, and environmental concerns are all basic risks and increase the uncertainty of decision-making.

Kirkwood (1992) and Keeney & Raiffa (1976 & 1993) provided a good assessment of methods for applied decision-analysis in the early computer days. With the large improvements in commercially available software, this has allowed decision analysis to be undertaken rapidly and effectively.

Keeney & McDaniel (1999) reported on an instance where multi-attribute utility theory (MAUT) was used where contingent valuation had been usually employed in an integrated resource-planning programme within British Columbia Gas. It was used to consider the multiple objectives of supply and demand within a framework for evaluating alternative plans with direct involvement of stakeholders (ratepayers and investors), representing a wide range of societal perspectives (environmental protection and service reliability). By using this method, they endeavoured to forge a consensus between stakeholders regarding the preferred plan.

Many further examples of the application of MCDA methodology to energy sector decision-making problems are indicated in the literature (Greening & Bernow, 2004; Pohekar & Ramachandran, 2004a; Zhou *et al.*, 2005). Some of which and others are included in Table 2.1.

Table 2.1 Selected references to energy related MCDA applications or research in the literature.

Author	Topic of literature	DA method
Aras <i>et al.</i> (2004)	An applicaion to wind monitoring site selection in Turkey.	AHP
Agrawal & Singh, (2001)	Research into energy allocation for cooking purposes in India.	Fuzzy set
Akash <i>et al.</i> (1999)	An application to electrical power plant selection in Jordon.	AHP
Borges & Antunes (2003)	Energy policy research regarding national economy plans in Portugal.	Linear programming
Brand <i>et al.</i> (2002)	Transport energy & environment decision support in Europe.	Pairwise comparison
Beccali <i>et al.</i> (1998, 2003)	Renewable energy planning at the regional level in Sardinia.	ELECTRE III
Cavallaro & Ciraolo (2005)	A preliminary analysis to aid in the selection of wind turbines in Italy.	Pairwise comparison
Diakoulaki & Karangelis, (2005)	An application of MCDA in Greek electricity system expansion planning.	PROMETHEE
Goumas & Lygerou, (2000)	An application to geothermal field power expansion planning.	PROMETHEE
Georgopoulou <i>et al.</i> (1997)	Decision support system for renewable energy planning in Europe.	ELECTRE III
Georgopoulou <i>et al.</i> (1998)	Group decision support system for renewable energy planning in Europe.	PROMETHEE
Georgopoulou <i>et al.</i> (2003)	Defining national priorities in GHG reduction in the Greek energy sector.	ELECTRE Tri
Goletsis <i>et al.</i> (2003)	Group decision support for eletricity system project ranking in Armenia.	ELECTRE III PROMETHEE
Elkarmi & Mustafa, (1993)	Renewable energy planning research in Jordan.	AHP
Haralambopoulos & Polatidis, (2003)	Group decision support for renewable energy implemetation in Greece.	PROMETHEE
Kablan (2004)	Application to energy conservation measures assessment in Jordan.	AHP
Kim <i>et al.</i> (1998)	Korean electricity utility planning application with consideration to the environment.	MAUT
Mills <i>et al.</i> (1996)	Improving electricity planning in the IRP context.	MAUT
McDaniels (1997)	Implementing sustainability principles in electricity planning.	Trade-off
Mavrotas <i>et al.</i> (2003)	Wind energy project ranking research in Greece.	ELECTRE III
Nigim <i>et al.</i> (2004)	Renewable energy resource prioritisation research for development.	AHP & Linear programming
Poh & Ang (1999)	Transport fuel policy development application.	AHP
Pohekar & Ramachandran (2004b)	Cooking method assessment research in India.	PROMETHEE
Ramanathan & Ganesh (1995a)	Evaluation of lighting alternatives research.	AHP
Ramanathan & Ganesh (1995b)	Energy resource allocation research.	AHP
Winebrake & Creswick (2003)	An assessment of the future of hydrogen fuelling systems for transport.	AHP
Wijayatunga <i>et al.</i> (2005)	Assessment of strategies to overcome barriers for energy options.	AHP
Tzeng <i>et al.</i> (2005)	An application to assess alternative fuelled buses for public transport in Taiwan.	AHP

2.7 Summary

From the literature, one can surmise that the case study site of Totara Valley, if not a typical rural location, is at least within a rural area similarly classified as a large geographic portion of New Zealand. The Totara Valley is located in the Manawatu-Wanganui regions (Statistics New Zealand, 2005), and by the measures used in this section (Figure 2.4 to Figure 2.11) appears comparable to Waikato, Bay of Plenty, Hawke's Bay, and Taranaki in the North Island; and Tasman, Otago, and Southland in the South Island. This would imply that indeed, any electricity load data obtained from this study would be representative of this type of rural setting.

Renewable energy based distributed generation figured prominently in the literature as a potential solution to many of the problems associated with emissions from large centralised systems, and had many benefits, locally, nationally, and globally. However, one can conclude from the literature that there were problems in some renewable energy systems. Such problems either were systemic design problems or were inherent in a design process catering for dynamic and site-specific mix of energy resources. Many such problems may be mitigated through the application of alternative design methodology.

Such methodologies are required as the techno-economic performance and social acceptance of many renewable energy based distributed generation technologies were site specific. Bruckner *et al.* (2005) summarised this as being "...defined by the adjoining infrastructure and unit commitment practices, the existing and likely future commercial settings, and the prevailing environmental and institutional circumstances" They further indicated that "This often means that the system-oriented benefits of distributed technologies can only materialize where suitable integration, coordination, and benefit sharing mechanisms prevail".

In this context, the need for suitable decision-support models has greatly increased for both electricity generators and regulatory policy setting bodies (Ventosa *et al.*, 2005). One such method, decision-analysis, does not appear to have been tried to any significant extent in New Zealand. There are very few reported applications of MCDA in New Zealand, and indeed, only a small percentage of potential New Zealand users have heard of the practice of MCDA techniques. Yet, certain sectors of the overseas electricity industry have benefited from the application of decision analysis.

Documentation of electricity load profiles was found to be lacking and so further study of rural electricity load profiles would not only add to our knowledge of electricity use in the New Zealand rural sector, but would provide pertinent data for the objectives of this study.

Further exploration of the application of decision analysis methods to the distributed generation of electricity in the context of the New Zealand rural sector would realise many benefits as reported for overseas applications. Such benefits include a greater understanding of the sustainability issues affecting energy supply, stakeholder values expressed as formal preferences, load and resource uncertainty and the inherent effect on choices, and the definition of the appropriate application of technology relative to sustainability and stakeholder preferences.

3 Review and Selection of Modelling Software

In order to develop the decision-analysis framework (Figure 1.1), the topics of wind energy resource modelling, renewable energy based distributed generation system modelling, and multiple criteria decision analysis modelling software were reviewed to assess the most suitable. Reviews of software capability were undertaken using both evaluation titles where available, and reports of software use in the literature. Where there were many software titles to choose from, as was the case with decision analysis software, a set of capability-criteria identified software that would not meet these. Therefore, the choice of software was based on capability, cost, and suitability for the decision-analysis framework.

3.1 Wind Resource Modelling Software

The identification and subsequent assessment of potential wind turbine generator (WTG) sites normally requires some extent of feasibility study based around a wind-monitoring programme at the subject site. Wind energy resource monitoring programmes of necessity can be both long in duration and expensive relative to the cost of a small to medium sized WTG⁵ installation project, with much of the expense being incurred in the installation and maintenance of monitoring equipment and on the subsequent analysis of the data generated. For this reason, many potential investors sometimes either postpone or drop altogether the project (Simões *et al.*, 1999).

To ensure optimal site choice while also retaining a reasonable level of cost when assessing a number of potential WTG sites, especially in complex terrain, models need to be used that can estimate the wind energy potential of the respective sites. Van Lieshout (2000), Rohatgi & Nelson (1994), Beljaars *et al.* (1987), Tammelin & Hyvönen (1999), Watson & Landberg (1999), Ayotte (1997), Focken *et al.* (1999), Heinemann *et al.* (1999), and Reid (1997) all indicated that several computer models have been developed specifically to calculate and predict wind flows over a given area and that one or two strategically placed anemometers within the area of interest may be all that is necessary to provide the required input (Van Lieshout, 2000).

Computer modelling has rapidly evolved from the early mathematical models and much written regarding this evolution, especially for wind flow over complex terrain. Rohatgi & Nelson, (1994), Walmsley & Taylor, (1996), and Wood (2000) provided good reviews of the chronological development of wind modelling. There are two main categories of calculation theory used in current modelling practices, the mass-consistent model, and the Jackson – Hunt model (Rohatgi & Nelson, 1994). The operating principle of the mass-consistent model is quite simple. Wind data was used from within the modelled area to develop an initial estimate of the wind climate. This initial estimate, adjusted by way of coefficients, achieved a modelled wind

⁵ Small to medium sized in this context is from 0.5 kW to 50 kW.

field that departed from the original measured wind field only enough to satisfy the conservation of mass. A key feature of the adjustment coefficients was the minimisation of the amount required to conserve the mass flow, hence they are known as mass-consistent models. The most recent application of this theory has been the codes called numerical objective analysis of boundary layer (NOABL) and the NOABL* code, which accounts for thermal stratification (*ibid.*). Mass-consistent models will not be considered further due to the lack of suitable software appropriate for use in this study.

The second of the two models, based on the Jackson-Hunt theory (Figure 3.1), differed markedly from and has superseded the mass-consistent model (*ibid.*). It attempts to solve a set of equations based around the conservation of both momentum⁶ and mass. The momentum-conservation calculations include a representation of the incompressible, time dependent and neutrally stratified airflow (*ibid.*).

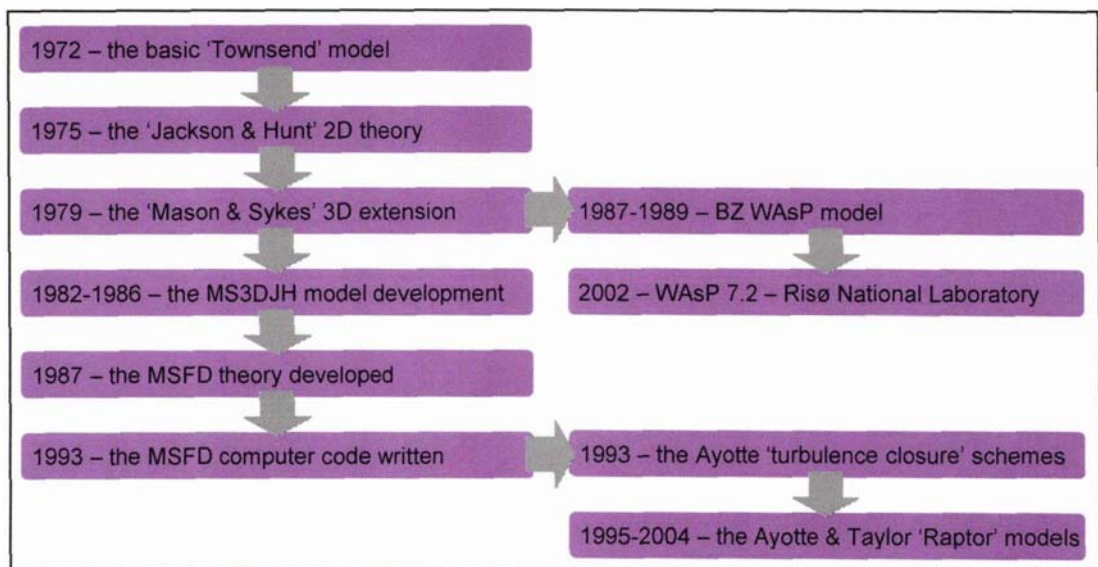


Figure 3.1 The chronological development of wind models based on the Jackson-Hunt theory.

Figure 3.1 was adapted from Rohatgi & Nelson (1994), Walmsley & Taylor (1996), and Wood (2000).

Various site research and benchmark field measurements exercises has seen these two distinct model theories evolve in two directions of development. Data from Askervein Hill (Scotland), Kettles Hill (Canada), Blasheval (Scotland), and several other locations were utilised either to validate the models or to develop them further (Walmsley & Taylor, 1996; Bowen & Mortensen, 1996; Beljaars *et al.*, 1987; Wood, 2000). As an example of such development Beljaars *et al.* (1987) introduced a new linear model for neutral surface-layer flow over complex terrain called 'mixed spectral finite-difference' (MSFD). This model was a successor to the 'Mason and Sykes 3D Jackson and Hunt' model (MS3DJH) developed by Walmsley in 1982 which was in turn based on the '2D Jackson and Hunt' theory of 1975 and its extension to 3D by Mason and Sykes in 1979. The contiguous development of the Jackson and Hunt based models (Figure 3.1) indicated the various branches that the research has taken over time and

⁶ This is based on the Navier-Stokes equation (Rohatgi & Nelson, 1994).

how the theory was now a component in many of the numerical models developed in the last 30 years.

3.1.1 WAsP

The Wind Atlas Analysis and Application Programme (WAsP), known initially as the BZ-WAsP model normalises wind-speed and direction data relative to the roughness and site obstacles at the reference wind-monitoring site. This normalised wind climate was then used to estimate the wind climate at other sites using their site-specific roughness and obstacle inputs and assumptions. WAsP has been shown to give accurate wind predictions over low, smooth hills of small to moderate slope and length that ensure attached flows (Bowen & Mortensen, 1996). It has a zooming grid coordinate system, which is one major difference from other Jackson – Hunt models (Rohatgi & Nelson, 1994). The Bessel expansion on a zooming grid (BZ) component was developed and added into the WAsP computer code in 1987. This radially zooming grid has the advantage of allowing an increasingly finer spatial resolution of calculated data and terrain details in the region of interest as the radial origin coincides with the site of the data collection e.g. anemometer location or modelled site.

The accuracy of WAsP was limited where the terrain was very steep and separating flows occur, as these flows were treated incorrectly by the linear calculations. This deficiency in the WAsP model was described in detail by Bowen & Mortensen (1996) (Appendix B – 14.1). In addition, WAsP does not consider any potential large-scale stratification due to thermally driven wind flow systems. In acknowledging this limitation, Farrugia & Scerri (1999) considered that the use of WAsP would still save money and avoid time-consuming monitoring programmes in a site prospecting exercise. This was confirmed by Hansen & Mortensen (1999) who used WAsP modelling for micro-siting and wind farm layout optimisation after a five month period of measurements using calibrated site parameters and reference data. The cost of WAsP software was NZ\$7000 in 2003.

Known Limitations of WAsP

As previously indicated, WAsP was designed to model the wind climate over relatively flat or gently hilly terrain but in many situations, the terrain was not as described and therefore WAsP was often used outside of its design performance envelope (Bowen & Mortensen, 1996; Bowen & Mortensen, 2004; Frank, 1999). Using the WAsP model this way could result in errors, and this was especially so when predicting the wind climate from one terrain type into another terrain type. Errors can also be introduced into WAsP by endeavouring to model a wind climate affected by atmospheric and terrain induced instability and stratification, diurnal sea breezes or land breezes, down slope and föhn winds in mountainous terrain and the channelling of wind in valleys.

Bowen & Mortensen (2004) and Frank (1999) indicated that a WAsP utility programme called the *Ruggedness Index* (RIX) produced a good measure of site terrain differences and, based on research by Bowen & Mortensen (1996), was reported as a good measure of the proportionality of any error present in a predicted wind climate.

Most modelling errors in wind resource modelling have their origins as either a data measurement and analysis or physical model error. Ayotte *et al.* (2001) indicated that this divides the error into that which is attributable to the wind model and associated parameters being used, and that which is due to the analysis method within which the measurements are examined and processed. As far as physical model error, Bowen & Mortensen (1996) have clearly outlined the origin of the accumulated error in WAsP to be dependent on the degree to which the operational performance limits of WAsP were exceeded by the atmospheric conditions at the time of data collection and the terrain over which the wind climate was modelled. A detailed analysis of the origin of such errors has been done (Appendix B – 14.1), and Bowen & Mortensen (1996) concluded that the “magnitudes of the individual procedure errors depend on the degree that each site contravenes the orographic limits of the WAsP prediction model.” Also, that the “relative sizes of the two procedure errors may be assumed to be roughly proportional to the individual site ruggedness, thus determining the accuracy and bias of the overall prediction by the WAsP model.” This led to the development of the RIX number as an indication of the magnitude and sign of the error in any WAsP modelling (*ibid.*). Thus, to some extent, the RIX number mitigates some of the inadequacies of the model in steep or rugged terrain.

3.1.2 *WindScape Raptor*

Ayotte & Taylor (1995) describe another model based closely on the mixed spectral finite difference (MSFD) model, where in this development; a more complex and technically complete turbulence closure scheme was introduced. Steggel *et al.* (2001) reported that several models were integrated as part of this model. The basis of the method was the regional-scale model, The Air Pollution Model (TAPM), developed by the Atmospheric Research department of the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). Ayotte & Taylor (1995) developed a fine scale model called *Raptor*, which in conjunction with the meteorological components of TAPM formed a suite of programmes called *WindScape*. *Raptor* is a MSFD three-dimensional model for the boundary layer flow over moderate terrain and assumes neutral stratification within the boundary layer. Being a model based on linear equations, it is restricted to flows over terrain of moderate slopes. Steggel *et al.* (2001) indicated that a non-linear version of the model (*Raptor_{NL}*) was under test and expected to be able to be used to model wind flow over steep slopes. The *WindScape* model continues to evolve as new modelling methodologies develop and validation sites become available, but “was not yet available in shrink wrapped form” (Ayotte, 2001). However, since April 2001, the *WindScape* system has been used by the model developers to map more than 30 areas on behalf of 10 clients (Steggel *et al.*, 2001).

The mechanisms of *WindScape* were described in some detail including the meteorological components of TAPM with the wind flow model, *Raptor*:

The meteorological component of TAPM employs a terrain-following vertical coordinate system for three-dimensional simulations. The model solves the momentum equations for horizontal wind components, the continuity equation for vertical velocity, and the

scalar equations for potential virtual temperature and specific humidity of water vapour, cloud water and rain water. A vegetative canopy and soil scheme is used at the surface while radiative fluxes, both at the surface and at the upper levels are also included (*ibid.*). (P 5).

The Raptor component is used in conjunction with the TAPM model which together form the WindScape model which is then able to provide;

...hourly estimates of wind-speed at a chosen height above the surface. These estimates include the effects of regional scale variations in wind climate that arise from large scale surface features, for example the roughness change from sea to land, as well as, the regional variation weather patterns caused by atmospheric phenomena such as sea breezes, katabatic and anabatic winds. Superimposed upon this is the fine scale perturbation to the flow (speed up or slow down) caused by smaller scale topographic features that have horizontal length scales from a few hundred metres to a few kilometres (*ibid.*). (P 8).

These advanced features have the ability to model such variables as thermally or terrain driven wind climates, which would lead to more detailed wind energy calculations in complex terrain being more accurate than was possible before. The output from WindScape has been shown to display a high level of skill "...in producing not just mean values but also statistics within each wind sector and historical time series" and it was indicated that further advantages this method has as being;

... applicable across the globe, does not require local wind measurements for input and is ideally suited to the task of identifying wind "hot spots" in an efficient and timely manner.... ...The *WindScape* model output is available in various formats compatible with commercial wind planning packages and GIS type applications. Since the regional climatology is well represented within *WindScape* this allows the developers the ability to plan preliminary turbine layouts and conduct feasibility studies at an early stage of the project before initiating a measurement campaign. (p 20). (*ibid.*).

The WindScape suite can therefore be used in two ways. In regional scale wind prospecting it would appear to have clear advantages in the early stages of regional-scale wind prospecting where no specific wind data are available to identify areas or specific locations suitable for possible wind farm development (*ibid.*). In addition, in site validation tests, WindScape has provided a high level of success in calculating the wind energy potential over wide areas. This information can be used primarily to rank sites or areas for further monitoring and analysis.

3.1.3 Wind Software Chosen

Raptor_{NL}, the non-linear version of the Raptor component of the WindScape suite of programmes appeared to be better suited than WASP in predicting wind flow over complex terrain. However, given that WindScape and in particular the non-linear version *Raptor_{NL}*, was not yet commercially available for use, WASP was the only readily available commercial

software programme suitable for use in this study and was therefore purchased in spite of the known limitations in steep terrain which were compensated for (section 8.3.3).

3.2 Distributed Generation Simulation and Optimisation Software

The key requirement for the renewable energy based distributed generation system design software was that it must be capable of modelling grid-connected systems and/or stand-alone systems over a one-year (8760-hour) duration. Key (software) model output capability that was required included:

- extensive output information on system performance such as peak load matching and load to resource matching capability of the system,
- capable of modelling renewable energy resources (solar, wind, hydro etc) and electricity load profiles, and inherent sensitivities based on the uncertainty introduced by use of short-term data, and
- a clear and easy to use interface.

A review of models yielded three of potential use in this study – RAPSIm32, Hybrid2, and HOMER. Of these, only HOMER (version 2.19) was also able to model renewable energy resources, electricity load profiles, and grid-connected distributed systems and therefore chosen for this study. HOMER (the Micropower Optimisation Model once known as the Hybrid Optimisation Model for Electric Renewables) has been in use since 1993, and continually developed over the last decade by staff at the International Programs group of the National Renewable Energy Laboratory in Colorado, US.

HOMER is a modelling tool for the simulation and optimisation of both stand-alone and grid-connected generation systems with the capacity to model many different configurations of distributed generation technologies. HOMER simulates the hourly operation of each singular and combined option as entered by the user by calculating the energy balance of both electrical and thermal demand in the hour, and the energy that the system can supply in that hour over 8760 hours of annual operation. Lilienthal *et al.* (2003) indicated these calculations were performed for each feasible system configuration possible from the list of component technology configurations and capacities. Once all feasible systems have been simulated, the costs of installing and operating the system over the specified lifetime are calculated to provide the system net present cost (*ibid.*). All possible technology combinations based on the user specified technologies are then ranked based on lowest to highest net present cost. Sensitivity analyses can be viewed if values relevant for such an analysis have been specifically entered.

3.3 Multiple Criteria Decision Analysis Software

Multiple criteria decision analysis processes take explicit account of multiple, sometimes conflicting criteria in aiding decision-making, help to structure the problem, as well as providing a focal point for further discussion (Belton & Stewart, 2002). These processes can help decision-makers learn about the problem situation and about their own and others values and judgments, and through such organisation, the synthesis and appropriate presentation of the relevant information can guide a course of action identified through the ensuing discussion (*ibid.*). Good supporting software can therefore be vital in the practice of MCDA.

Ideally, when used directly with decision-makers, a software-based model should be interactive to enable elicitation of constructive feedback that collectively should yield appropriate results. The most useful approaches should be conceptually simple and transparent (*ibid.*), as good user interactivity will allow for easy elicitation of values and preferences to be entered, amended, and the effects of any change to be better understood. Belton & Stewart (2002) indicated that software should therefore support the decision-making process and not be the driving force of it. The MCDA process should serve to both complement and challenge intuition by acting as a sounding board against which ideas can be tested. It should not seek to replace intuitive judgment or experience (*ibid.*). The process should thus lead to better-considered and explainable decisions by way of a transparent audit trail.

As to which MCDA method to use, Hobbs & Horn (1997) contend that no one MCDA method is better than others are and that different methods will yield different results. They conclude that a multi-method MCDA process should be utilised thus building a greater level of insight into decisions. This will result in a greater confidence in the decision choices even though there are many examples of the successful individual use of the various methods of MCDA (Forman & Gass, 2001; Butler *et al.*, 2001; Wallace, 2000; Belton & Stewart, 2002; Clemen, 1996).

The problem considered in this study, as stated (Section 1.1), is that of a discrete-choice problem where a decision needs to be made between alternatives. An internet-based search and a review of the literature identified 33 software titles, 23 of which are listed in further detail in Appendix C – 15.1. Of these 23, only 11 were available as evaluation copies and designed for use in discrete choice decisions. Initially, one product, TopDec was purchased but was found to be too simple for the complex level of analysis required. Of the 11 software titles that were left after the preliminary screening, only Criterium DecisionPlus 3.0 (CDP 3.0), EQUITY, HIVIEW, HiPriority, and Logical Decisions for Windows (LDW) were designed specifically for discrete choice situations and these were tested further (Table 3.1).

Of the many MCDA methods, the multi-attribute utility theory (MAUT) and the analytic hierarchy process (AHP) were the two methods that appeared in the majority of research papers. A key requisite therefore was that either of these methods, AHP or MAUT must be used in the model, but preference would be given to software that utilised both theories. Choosing between the five software programmes involved producing a list of capabilities required as related to this study.

The process of choosing the software to be used was undertaken considering the list of these requirements (Table 3.1), and the 'score' results of this screening is an indication whether the requirements were met or not. The two 'best' software titles were Logical Decisions for Windows (LDW) and Criterium DecisionPlus 3.0 (CDP 3.0). A further 'ease of use' assessment was undertaken on the evaluation copies of each of these to compare the two models (Table 3.2).

Table 3.1 A comparative analysis of the MCDA software capability relative to this study.

	Ease of use	Trade-off analysis between multiple objectives	Uncertainty representation	Probability representation	Scenario or multiple stakeholder capability	Import (database, spreadsheet)	Can model structure be displayed on screen?	Does the software support group weight elicitation?	Are graphical sensitivity analyses possible on weights?	Can analytical results be portrayed graphically?	Is the software capable of both AHP & MAUT?	Total score
CDP 3.0	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	10
EQUITY	✓	✓	✓	×	✓	✓	✓	×	×	✓	×	7
HiView	×	✓	✓	×	✓	✓	✓	×	✓	✓	×	7
Hi Priority	✓	✓	×	×	✓	✓	✓	×	✓	✓	×	7
LDW	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	10
¹ At the time of writing this software had a separate version capable of group work.												

Table 3.2 A comparison between the Criterion DecisionPlus and Logical Decision for Windows MCDA software for ease of use and value for this study.

	Criterion DecisionPlus (CDP)	Logical Decisions for Windows (LDW)
Hours in use	12	29
Malfunctions	No 'crashes' or malfunctions, apparently stable.	6 'crashes', all due to user error.
Sensitivity analyses & results analysis	Spider chart – clear & readable; Sensitivity by weights against decision scores; Contribution by criteria; Alternatives scatter plot – contours, accumulated values; Trade-off analysis; Uncertainty contribution	Dynamic weight sensitivity – adjustable; Individual criteria spider graph; Many more available
Clear/transparent	yes	yes
Scenario analysis	no	Yes, through preference settings
Uncertainty plotting	Based on probability – 5 distribution types available	Monte Carlo simulation capability with 6 distribution types available
Many alternatives	160 blocks	Unlimited as is based on PC memory
Methodology used	AHP or MAUT (SMART)	AHP or MAUT (SMART, SMARTER)
Problem structuring	Brainstorming chart to hierarchy	Matrix & simple hierarchy
Help files	Yes, clear, ordered and relevant – easy to use	Yes, but difficult to understand initially.
Graph & figure quality	Good graphs but poorly drawn, poorly reproduced	High quality & clear to read & understand
Cut-off sorting	No	Yes
Cost	US\$595 (no academic price)	US\$310 academic price.
General comments	Easy to use; graphics easy to interpret; logical process; good tutorial; Limits to the 'real' model are having only 200 alternatives and 300 goals or objectives.	Hierarchy procedures and terminology difficult to understand; jargon used but no glossary; no overview; Decision Lab in Auckland are distributors.

3.3.1 *Decision Analysis Software Chosen*

The advantages of LDW over CDP 3.0 were many (Table 3.2) even though there was no difference in the overall capability comparison (Table 3.1). These included the ability of scenario analysis using the preference settings facility; two methods of MAUT were available; six distribution types can be used to model probability values; file size is limited by computer memory only; cut-off sorting can be undertaken where limits are placed on criteria levels; and the cost of the software was favourable. Therefore, Logical Decisions for Windows was purchased.

3.4 Summary

The software selected for use within the framework described in Figure 1.1 was WAsP for wind resource modelling, HOMER for renewable energy based distributed generation systems modelling and Logical Decisions for Windows (LDW) for the decision modelling and analysis.

4 The Decision Analysis Framework – SPiRAL

The aim of this study was to develop a transparent decision modelling and analysis framework that could identify suitable feasible renewable energy resources and technologies for use in a distributed generation system within a period of *months to one year*, rather than years. In order to meet this stated duration, models that can utilise data sets of less than one-year duration will be required. The identified models to be utilised in this process (Chapter 3) are WAsP for wind energy resource modelling, HOMER for the simulation and optimisation of distributed generation systems, and Logical Decisions for Windows for the modelling of the decision process. These will be integrated into a process (Figure 1.1) for modelling sustainable power in rural areas and locations (SPiRAL).

A case study approach (Chapter 5) used the electricity load profiles of six households, two shearing sheds, two freezer sheds, and a workshop, monitored and recorded over a 23-month period. Over simultaneous period the renewable energy resources of wind, hydrological and solar were monitored and data collected. This *full-term* data set will be used in a *short-term* duration analysis to calculate the load and resource time-series modelling parameters pertinent for use in HOMER. These parameters are considered in detail in Section 4.2. Both these duration data sets will be used to model the *full-term* and *short-term* duration modelling of the distributed generation system (Chapter 9) and the decision modelling (Chapter 10). This indicates two project duration pathways, and they have been plotted as a one-year monitoring period for a full one-year time-series, and one of shorter duration (Figure 4.1).

4.1 Preliminary Project Short-Term Duration Analysis

An initial analysis of the durations required for the short-term programme (Figure 4.1) were estimated using a critical path and project evaluation and review technique (PERT) analysis (Equation 4.1) based on calculations with a pessimistic bias for the duration.

Equation 4.1 The project evaluation and review technique (PERT) equation.

$$T_{pessimistic} = \frac{t_{optimistic} + (t_{likely} \times 4) + t_{pessimistic}}{6}$$

Where :

$T_{pessimistic}$ = the resultant duration of the task with a pessimistic bias

$t_{optimistic}$ = the optimistic duration of the task

t_{likely} = the likely duration of the task

$t_{pessimistic}$ = the pessimistic duration of the task

Source: Lang, (1977).

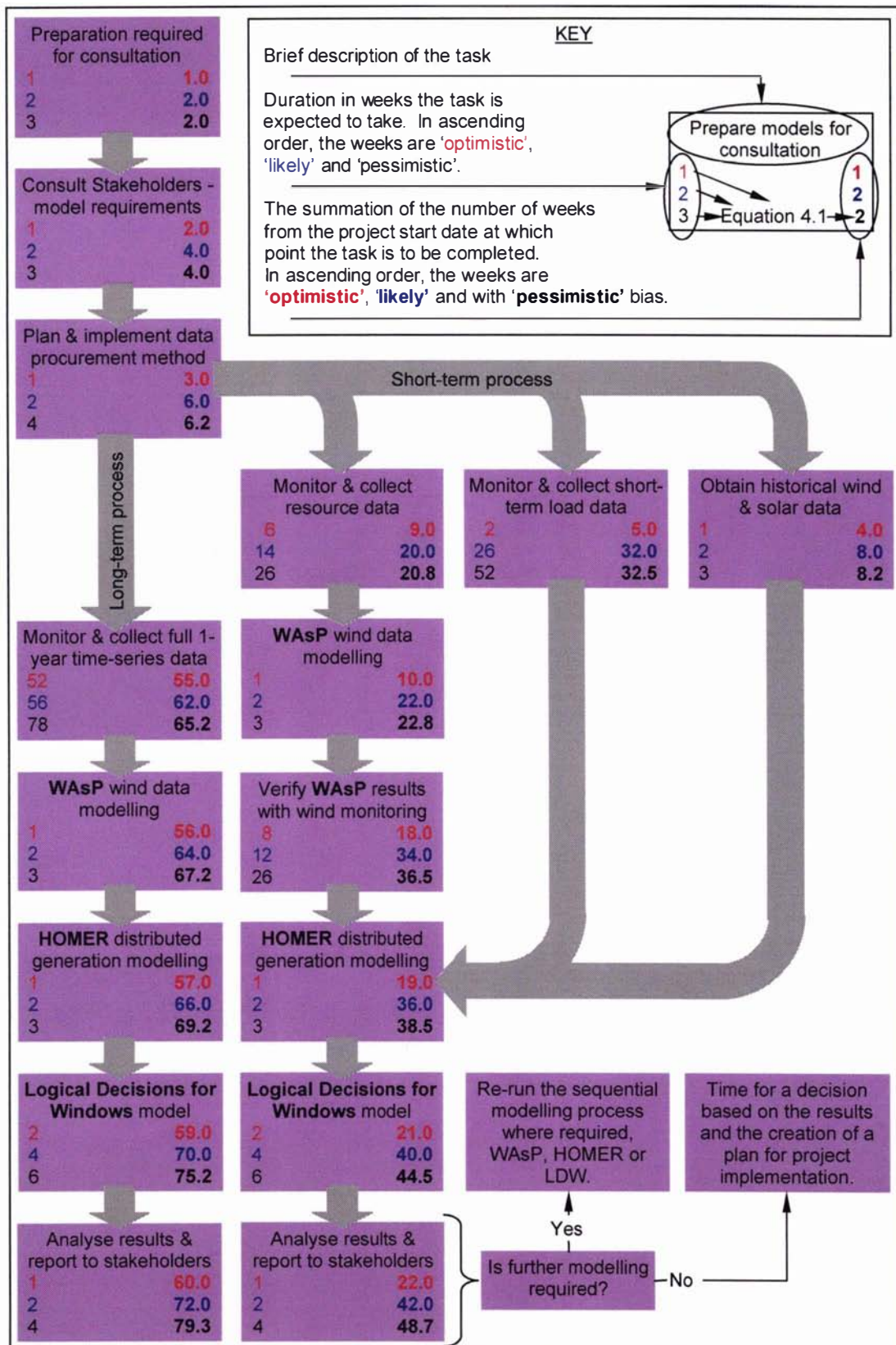


Figure 4.1 An initial critical path – project evaluation and review technique (PERT) analysis of the SPIRAL framework estimating the duration required for both short-term and full-term analyses.

For the short-term duration analysis, if optimistic task durations' were adhered to, it was estimated there would be a project outcome after a 22-week period (Figure 4.1). The most likely outcome would be a project of 42-weeks duration from start to finish. The PERT analysis, which included a pessimistic bias, indicated the project duration of approximately 49-weeks. Of the three diverging task-streams, the wind-monitoring programme was identified as being the critical path.

The process as presented indicated the first three to six weeks was essentially administration and preliminary consultation and design work. The first task was the preparation for the consultation process with the stakeholders. Information learned from consultation would be the desired duration of the project (short-term or long-term), types of preferences and weights and any other site-specific information related to load and resource monitoring.

Once the consultation process has been undertaken and the project scope decided, the data collection planning could proceed accordingly. The scope of the project was likely to dictate the data collection methods rather than duration. If the scope was wide, and all loads and all possible resources explored and monitored then obviously the planning duration would be longer than if the scope was narrower with fewer loads and only the obvious resources measured.

The difference between the long-term and short-term durations occurs at the monitoring stage. In the long-term, a full one-year time-series would be used once the load and resource data was collected and analysed. The subsequent decision modelling occurs as the data becomes available. In the short-term, the process splits into three 'streams', short-term electricity load and resource monitoring, and collecting historical or empirical data. The short-term resource monitoring provides early data for WAsP to model the regional wind atlas to confirm wind-monitoring sites. The subsequent wind monitoring both validates the WAsP wind atlas, and provides short-term modelling data for use in HOMER.

The modelling of distributed generation systems will be the next stage of the process whether or not the data was gathered over the long or short-term. HOMER utilises 8,760 hourly values in a load and resource time-series derived from monitoring, or 'synthetically', derived from modelling within the HOMER model. Data from the short-term duration electricity load profile monitoring would be used in HOMER to model a full 8,760-value time series based on the specific parameters listed in section 4.2.2. From the collected and analysed short-term duration wind data, a list of modelling parameters would be calculated and combined with the external profile data in the process of modelling the wind resource in HOMER.

Logical Decisions for Windows will be used to analyse the outputs from HOMER (Chapter 9) using the preferences of the stakeholders in a process that converted these preferences into weighted values (Chapter 10). The results of the decision process are analysed, and reported to the stakeholders. If any parts of the decision-analysis process were questioned, that part of the project would be adjusted to suit or undertaken again, though this has not been indicated in Figure 4.1.

4.2 Short-Term Duration – Data Requirements and Sources

4.2.1 WAsP – Wind Data

Recorded wind speed and direction data is the only useful input into WAsP and not limited by any data length or time resolution requirements. However, for the integrity of the results, the longer duration of the data length the less uncertainty there will be about the modelled results (Halliday, 1990; and Van Lieshout *et al.*, 1999).

4.2.2 HOMER – Electricity Load and Resource Data

Electricity Load Profile Data

The modelling procedure for producing a 'synthesised' electricity load in HOMER involves three key data types, hourly load levels (kW) for weekdays and weekends for each month thus forming a load profile, daily and hourly 'noise' fluctuations (%) based on the daily and hourly standard deviations, and annual mean daily load (kWh/d) (Figure 4.2).

Primary Load Inputs

File Edit Help

Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average value.

Each of the 24 values in the load table is the average electric demand for a single hour of the day. The values in the table also appear on the graph. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: **Primary Load 1** Load type: ☒ AC ☐ DC

Data source: ☒ Enter daily load profile(s) ☐ Import hourly data file Import File...

Baseline data Add noise

Hour	Load (kW)
00:00 - 01:00	0.000
01:00 - 02:00	0.000
02:00 - 03:00	0.000
03:00 - 04:00	0.000
04:00 - 05:00	0.000
05:00 - 06:00	0.000
06:00 - 07:00	0.000
07:00 - 08:00	0.000
08:00 - 09:00	0.000
09:00 - 10:00	0.000
10:00 - 11:00	0.000
11:00 - 12:00	0.000

Month: **January** Day type: **Weekday** Daily: **0 %** Hourly: **0 %**

Load Profile

Demand (kW) vs. Hour (0 to 24)

Scaled data for simulation Efficiency Inputs...

Scaled annual average (kWh/d): **0** Scaled peak: 0.000 kW

Annual average: 0.000 kWh/d Annual peak: 0.000 kW Load factor: 1.000

Plot... Export... Help Cancel OK

Figure 4.2 The inputs required in the electricity load-modelling page of HOMER 2.19.

First, numerical daily load profiles (i.e. a load for each hour of the day) are entered for each month. At this point, differentiation between weekends and weekdays can be entered if required. This allows the modelling of different working lifestyles, family sizes, occupant behaviours etc through the weeks and months (and hence, the seasons). The monthly load profiles and the differentiation between weekends and weekdays will need to be estimated if no

monitored data exists. Where the subject site is connected to the grid, historical monthly invoices can be used to calculate the mean daily load.

Secondly, statistical 'noise' can be introduced into the profile in the form of daily and hourly perturbation factors based on the standard deviations of both the daily and hourly loads (kW) (Equation 4.2). The process of adding noise into a profile uses a daily noise perturbation factor (randomly drawn once per day), and an hourly noise perturbation factor (randomly drawn every hour), both from a normal distribution with a mean of zero and a standard deviation equal to the daily and hourly 'noise' input values used (Lilienthal *et al.*, 2003). This factor will add randomness to a synthesised load thus reflecting reality in the final modelled profile as each hour of a modelled load is multiplied by the 'noise' factor (α) (Equation 4.2) (*ibid.*).

Equation 4.2 The electricity load noise perturbation calculation used in HOMER load modelling.

$$\alpha = 1 + \delta_d + \delta_h$$

Where :

α = the 'noise' factor

δ_d = the daily 'noise' factor

δ_h = the hourly 'noise' factor

Source: Lilienthal *et al.* (2003).

Thirdly, the annual mean daily load (kWh/d) is entered into the model. The profile, previously entered as the first stage, is then either re-scaled to match this entered value, or left at the default HOMER-calculated amount.

An alternative source for the mean daily load would be electricity invoices if the subject sites were currently receiving electricity via the grid. Although an analysis of a one-year set of invoices will produce the mean daily load data, monitoring of the load, or obtaining network load records will be necessary to produce the remaining data required.

Wind Resource Data

The monthly mean wind-speeds, the annual mean wind-speed, the Weibull 'k'⁷, the autocorrelation factor⁸, the diurnal pattern strength factor,⁹ and the hour of the peak wind-speed are the six parameters required by HOMER to model a wind resource at the subject site (Figure 4.3).

The Weibull 'k' value is the shape factor of the probability density distribution of the wind-speeds of a site and is typically between 1.5 and 2.5 (Lilienthal *et al.*, 2003; Hassan & Sykes, 1990). It is a measure of the 'width' of the distribution with high 'k' values equating to narrower wind-speed distributions, indicating that the wind-speeds are within a narrower range than lower 'k' values, where the wind-speeds are distributed over a larger range.

⁷ This is an indication of the spread of the distribution of wind-speeds.

⁸ The autocorrelation factor is a measure of the similarity of the wind-speed from one hour to the next, and indicates the correlation between the wind-speed in one-hour with the wind-speed in previous hours.

⁹ An indication of how strongly the wind-speed tends to depend on the time of day.

Lilienthal *et al.* (2003) indicated that the complexity of the terrain surrounding the subject site had significant effects on the level of the autocorrelation factor. Subject sites with surroundings of complex terrain had lower autocorrelation factors (0.70 – 0.80), whereas flat or rolling surroundings had the opposite effect, increasing the level of the autocorrelation factor (0.90 – 0.97).

The diurnal pattern strength (DPS) factor is used by HOMER to establish the shape of the diurnal pattern of wind-speeds relative to an assumed heating pattern from the sun. This factor is used in conjunction with the hour of peak wind-speed, which aligns the diurnal pattern with estimated hour of peak wind-speed.

Wind Resource Inputs

File Edit Help

HOMER uses wind resource inputs to calculate the wind turbine power each hour of the year. Enter the average wind speed for each month. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value. The advanced parameters allow you to control how HOMER generates the 8760 hourly values from the 12 monthly values in the table.

Hold the pointer over an element or click Help for more information.

Data source: ☒ Enter monthly averages ☐ Import hourly data file

Baseline data

Month	Wind Speed (m/s)
January	0.000
February	0.000
March	0.000
April	0.000
May	0.000
June	0.000
July	0.000
August	0.000
September	0.000
October	0.000
November	0.000
December	0.000
Annual average:	0.000

Wind Resource

Other parameters: Altitude (m above sea level) 0, Anemometer height (m) 0, Variation With Height...

Advanced parameters: Weibull k 0, Autocorrelation factor 0, Diurnal pattern strength 0, Hour of peak windspeed 0

Scaled data for simulation: Scaled annual average (m/s) 0

Figure 4.3 The inputs required in the wind resource-modelling page of HOMER 2.19.

Further modelling of the wind speed variation with height can be undertaken should the monitored or data source height vary from the anticipated height of the hub of the wind turbine to be modelled (Figure 4.4). An average surface roughness length is the driver of this dialog box setting. This has the effect of adjusting the wind speed in either a logarithmic or power law calculation and thus setting the wind speed relative to the established roughness length.

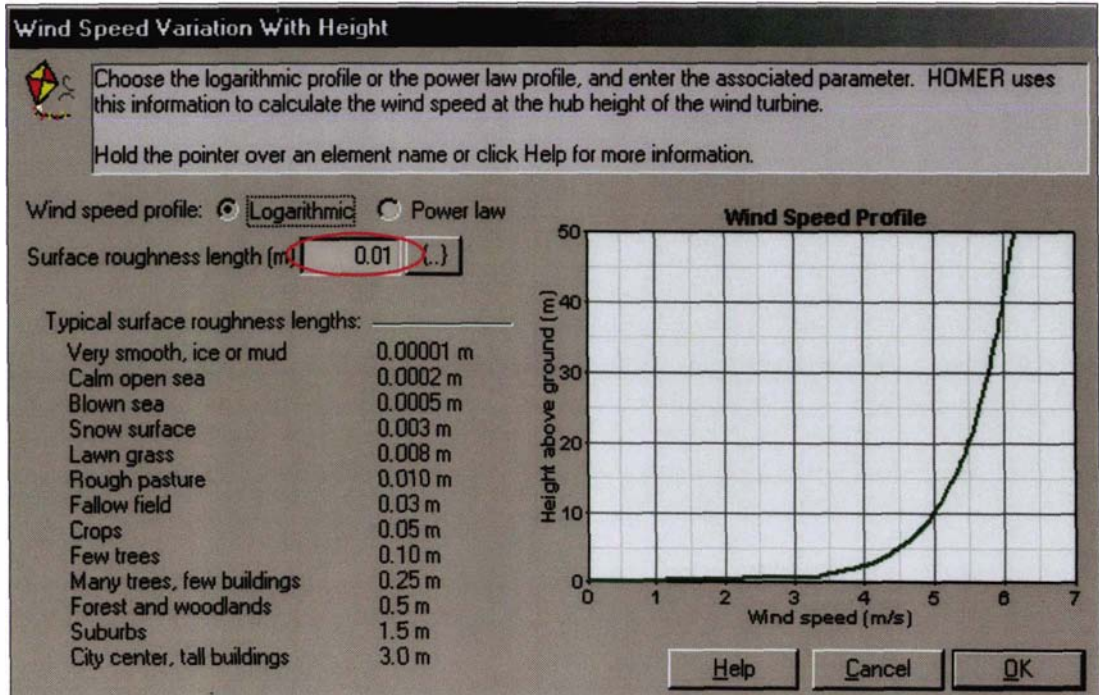


Figure 4.4 The wind speed variation with height modelling dialog box of HOMER 2.19.

Of the six parameters required, the mean wind-speeds (monthly and annual) and the Weibull 'k' were the most influential on the energy output of a modelled wind turbine (Figure 4.5). The autocorrelation factor and the diurnal pattern strength had little or no effect on the base levels of energy produced. The base parameters used in Figure 4.5, were 6 m/s annual mean wind-speed, Weibull 'k' of 2, an autocorrelation factor of 0.875, and diurnal pattern strength of 0.2. The hour of peak wind-speed was not considered for this analysis.

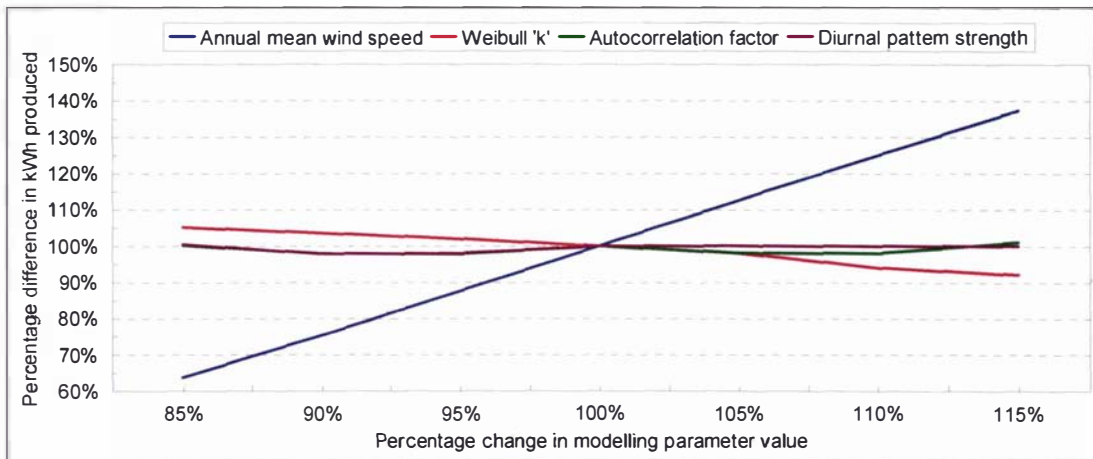


Figure 4.5 An example sensitivity analysis of the relative levels of energy produced to changes in the annual mean wind-speed, Weibull 'k', autocorrelation factor, and diurnal pattern strength.

Regional monthly wind-speed data useful in the HOMER wind modelling can be purchased from the National Institute of Water and Atmosphere (NIWA). This data has recently been released on a CD-ROM at a cost of \$5568 (2004 dollars and includes goods and services tax). However, only monthly mean wind-speeds would be of value to this study, and the remaining data (the Weibull 'k', autocorrelation factor, diurnal pattern strength, and the hour of

peak wind-speed) would only be available through analysis of data collected from the subject site.

Monthly mean wind-speed data is available from the New Zealand Meteorological Service climate database CliFlo for a fee. This would be of use when collating a monthly wind-speed profile for another site or application in HOMER.

Hydrological Data

The hydrological resource is modelled by simple monthly values and the amount of residual flow required in the stream to maintain aquatic life in times of low-flow (Figure 4.6). These values can be obtained from monitoring the stream flow, or from data collected by other means.

Regional Councils maintain hydrological databases for specific catchment locations. However, these are usually in the main rivers or significant parts of the catchments and may not be applicable to locations of the subject hydro developments. Periodic monitoring of the prospective hydro site remains the best option. Section 7.2 outlines the methods used and results of hydrological resource monitoring at Totara Valley.

Hydro Resource Inputs

File Edit Help

HOMER uses hydro resource inputs to calculate the power produced by the hydro turbine each hour of the year. Enter the average stream flow available to the hydro turbine each month. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Data source: ☒ Enter monthly averages ☐ Import hourly data file

Baseline data

Month	Stream Flow (L/s)
January	0.0
February	0.0
March	0.0
April	0.0
May	0.0
June	0.0
July	0.0
August	0.0
September	0.0
October	0.0
November	0.0
December	0.0

Annual average: 0.0

Hydro Resource

Stream flow (L/s)

Residual flow (L/s) {..}

Scaled data for simulation

Scaled annual average (L/s) {..}

Figure 4.6 The inputs required in the hydrological resource-modelling page in HOMER 2.19.

Solar Data

The solar resource is modelled (Figure 4.7) numerically by indicating mean daily levels of solar radiation ($\text{kWh/m}^2/\text{d}$) for each month, and a clearness index, a number between 0 and 1 indicating that fraction of solar radiation incident on the top of the atmosphere that reaches the surface of the Earth. Location latitude and longitude and time zone are also entered.

The National Aeronautic and Space Agency (NASA) had solar data¹⁰ available from its website¹¹ for any given latitude and longitude ("Get Data via Internet" - Figure 4.7). This data was in a format ready to use in HOMER. NIWA maintains a database of solar resource data and online access is through a website¹². Access to this data requires a subscription of approximately \$80 per year for low use (up to 500 lines of data) and up to \$500 per year for high use (5000 lines of data).

Solar Resource Inputs

File Edit Help

HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude: 0° 0' North South Time zone: (GMT+12:00) Kamchatka, New Zealand, Fiji

Longitude: 0° 0' East West

Data source: ☒ Enter monthly averages ☐ Import hourly data file

Baseline data

Month	Clearness Index	Daily Radiation ($\text{kWh/m}^2/\text{d}$)
January	0.000	0.000
February	0.000	0.000
March	0.000	0.000
April	0.000	0.000
May	0.000	0.000
June	0.000	0.000
July	0.000	0.000
August	0.000	0.000
September	0.000	0.000
October	0.000	0.000
November	0.000	0.000
December	0.000	0.000
Average:	0.000	0.000

Solar Resource

Daily Radiation ($\text{kWh/m}^2/\text{d}$)

Clearness Index

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Scaled data for simulation

Scaled annual average ($\text{kWh/m}^2/\text{d}$): 0

Plot... Export... Help Cancel OK

Figure 4.7 The inputs required in the solar resource-modelling page of HOMER 2.19.

¹⁰ This was the global solar radiation on the horizontal surface data, expressed in $\text{kWh/m}^2/\text{d}$.

¹¹ <http://eosweb.larc.nasa.gov/sse/>

¹² <http://cliflo.niwa.co.nz/>

4.3 Summary

A critical path and PERT analysis (Figure 4.1) revealed the estimated optimum, likely and pessimistic times for each task necessary to complete an electricity supply and renewable energy resource appraisal for a given community. A minimum project duration of between 21 to 40 weeks with 43 weeks as a pessimistically biased estimate would be required. Electricity load and resource modelling will need to be undertaken to provide modelling parameters in order to meet these short-term durations. In order to achieve a short time objective, alternative data sources have been given.

The full-term duration necessary to collect site-specific data over one-year was estimated to be 59 to 70 weeks with 73 weeks as a pessimistically biased approximation.

The HOMER modelling parameters required in order to undertake the short-term duration analysis have been assessed and documented. In order to undertake a short-term duration analysis these parameters will either be calculated directly from the data sets or will be estimated with WAsP modelling with respect to the wind resource.

5 The Totara Valley Case Study Site

The rural sites monitored in this study comprised the small community of Totara Valley east of Palmerston North (Figure 2.3). The Totara Valley community is 50 kilometres east of Palmerston North in the southern Hawke Bay hill country (40° 28' S 176° 04' E) but is within the Wanganui – Manawatu region and classified as being “rural with low urban influence” (Figure 2.3) (Statistics New Zealand, 2005). The community consists of three separate farm properties (Figure 5.1), and at the time of this study comprised six occupied dwellings, three shearing sheds, two freezer sheds and a workshop.

Totara Valley was chosen for this case study on several premises. The community had already been part of an earlier renewable energy study (Irving, 2000) and therefore members were familiar with research practices and requirements, and all were interested in furthering the existing knowledge base of renewable energy based distributed generation. Following from the previous research work already taken place, all the electricity monitoring equipment was in place within the community. The rationale for choosing Totara Valley for this case study was that it is located at the end of a spur line of 11 kV electricity supply and so was considered ‘fringe’ of grid, and given that the current situation with the Electricity Act 1992 (Appendix A), the supply to the community may at some stage be considered marginal. Security of supply to such marginal areas is an important issue facing such communities and this location was ideal for researching the issues.

A second case study site, Limestone Downs, was assessed but was not analysed further in this study of decision modelling. The electricity used in the large Limestone Downs shearing shed complex is included in detail in Appendix D. It adds to the electricity use data now available for sheep shearing and will be of considerable value in any further rural electricity use modelling work. The data from Limestone Downs is seen as complimentary to this study and was included in this research in so far as it relates to the electricity consumption profiles of a key aspect of sheep farming, that of shearing.

5.1 Monitored Electricity Load Sites

The electricity usage of six domestic dwellings, a shearing shed/freezer shed complex, a workshop/freezer shed complex and an individual shearing shed at Totara Valley were recorded over a 15-month period. The monitoring equipment at Site 9, a shearing shed, malfunctioned and the data from this site was not suitable for subsequent use. The locations of these monitored sites are indicated in Figure 5.1 and are numbered Sites 1 to 6 for the domestic sites, and sites 7 to 9 for the other farm related electricity loads. A view from the western ridgeline of the southern end of the valley indicates the rugged character of the surrounding land (Figure 5.2). This photo looks northeast from the point indicated in Figure 5.1, and is the Wind Site 3 (Figure 5.3). The white and red roofs are Sites 1 & 7. Sites 3, 4, & 9 are behind the trees in the centre foreground.

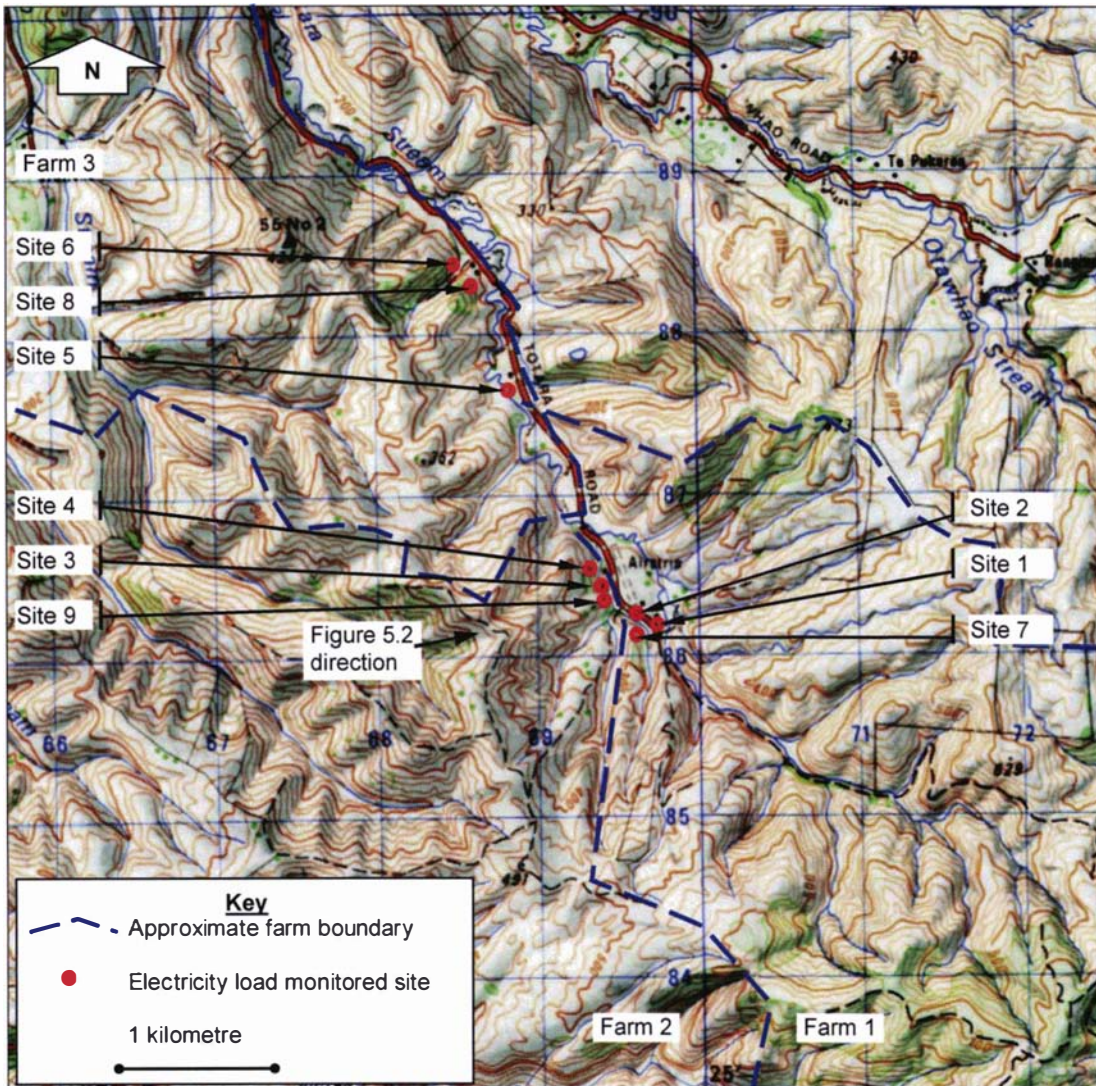


Figure 5.1 The Totara Valley region and monitored electricity load site locations. Approximate farm boundaries and the monitored sites are marked.

The map is from the 1:50,000 NZMS 260 series.



Figure 5.2 A view of the southern end of Totara Valley as seen from the ridgeline on Farm 2.

5.2 Monitored Renewable Energy Resource Sites

The wind, hydro, and solar renewable energy resources of Totara Valley were monitored (Figure 5.3) and the results are detailed in Chapter 7. Five sites were assessed for a potential wind resource including one site on Farm 1 and two sites on both Farm 2 and 3. Solar monitoring equipment was installed on Farm 1. Several sites were inspected for a potential hydro resource but only three sites were further assessed, one on Farm 1, and two on Farm 3. The hydro site selection criteria considered the location of the site relative to the load site, the available head with a minimum of in-stream intervention, and the approximate all-year available flow of the stream.

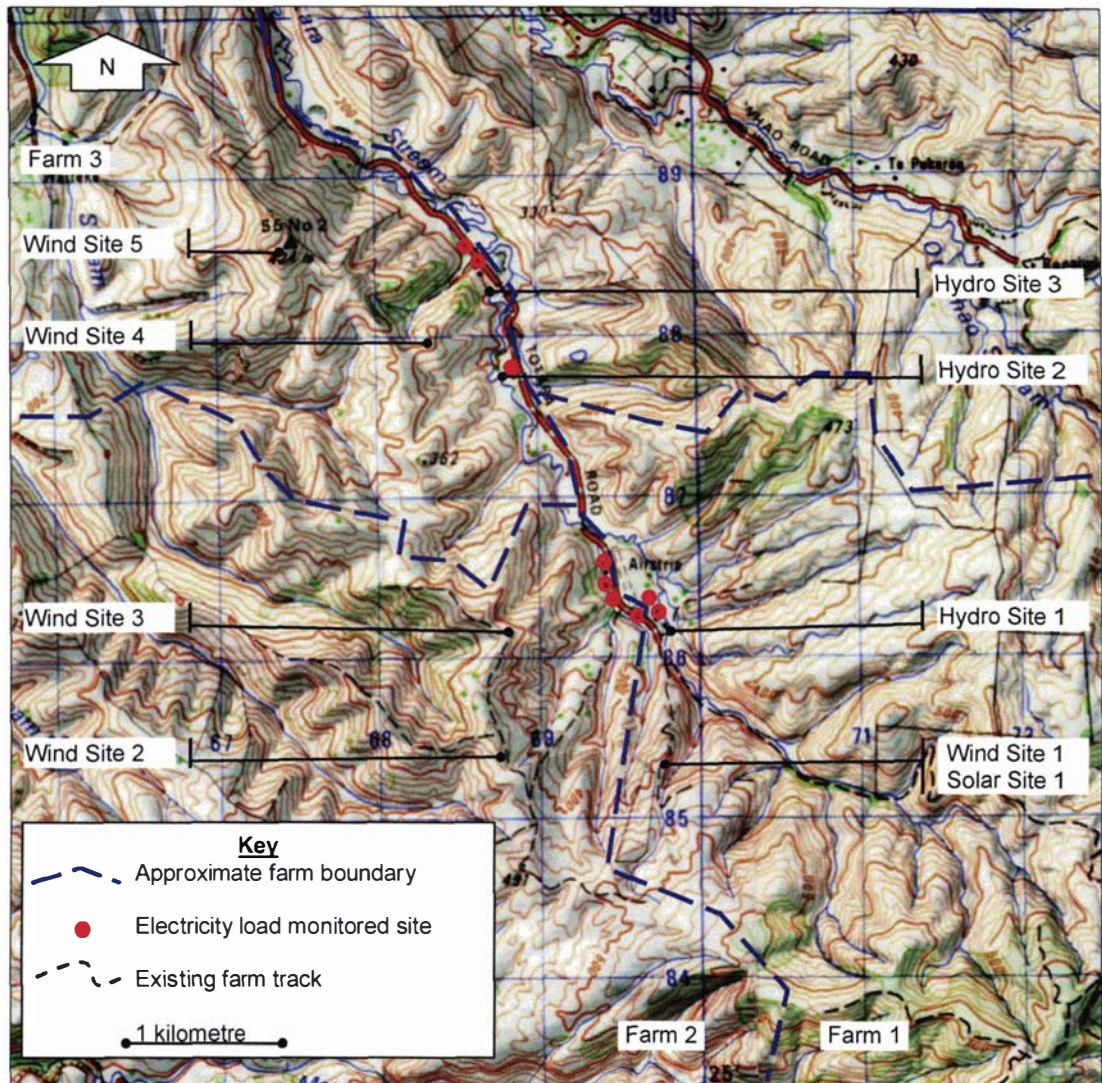


Figure 5.3 The Totara Valley region and locations of the renewable energy resource monitoring sites. Approximate farm boundaries and monitored sites are marked. Site labels 'Hydro Site 1' etc are standard throughout the text.

Map is from the 1:50,000 NZMS 260 series.

The solar monitoring pyranometer was installed on the anemometer mast at Wind Site 1. This places it approximately 405 metres above sea level, which places it at an estimated 145 metres above the southern valley floor and 200 metres higher than the northern valley floor.

Wind Site 1 was in place prior to the author setting the monitoring locations of this study (Irving, 2000) and became the first of two reference wind sites. The second reference site was Wind Site 5, sited on a clear isolated hill surrounded by steep slopes on two sides. At 420 metres above sea level, this site was the highest site to be monitored. The intermediary wind sites were monitored along the ridgeline between Wind Sites 1 and 5 starting with Wind Site 2.

The three hydro sites were identified after a preliminary visual inspection of Totara Stream and some of the tributaries located near to the load sites.

5.3 Summary

Wind was monitored at five sites in a sequential method with two sites used as reference sites. An extensive data set of the global horizontal solar resource was gathered from Solar Site 1. The stream flow of Totara Stream was assessed for potential sites catchment wide and was measured at three locations.

The data from all assessments as outlined (apart from the Limestone Downs data) will be used in a case study approach to test both the full-term duration method of decision-analysis using the selected software in an expert integrated approach, and the efficacy of the short-term duration as proposed in the critical path and PERT analysis (Figure 4.1). These data sets provided material for both load modelling for the full-term duration analysis, and for the short-term duration analysis of modelling parameters required for HOMER.

Part two: the data collection

Totara Valley community electricity load profile

Totara Valley renewable energy resources

6 Totara Valley Community Electricity Load Profiles

Accurate electricity use information is vital to the successful design and implementation of grid-connected or stand-alone renewable energy systems so if there is an increased demand of these methods for electricity supply, there will also need to be more information on the electricity peak loads, durations, and seasonal patterns of use than there is currently.

There was little documented information or knowledge available on electricity use and electricity load profiles of the hill-country sheep and beef farming sector. Knowledge of temporal electricity load variability is a vital component of renewable energy system design. If no data exists, electricity auditing methods can be used to estimate what appliances were used and when. Profile shape, mean load magnitude and an understanding of load profiles and variation of the subject site is required in order to match the available renewable energy resources to the varying demand loads. To date there is no documented electricity load profile data to indicate rural domestic and commercial (diurnal to monthly to seasonal) profile shapes and variations. Therefore, the objective of this part of the study was to produce accurate load profiles for use in the renewable energy system design and modelling process (Chapter 9).

The renewable energy simulation and optimisation software, HOMER, can use a contiguous time-series data set of up to 8760 hourly values of the modelled electricity load. The community data presented in this section is the collated result of monitoring electricity loads at Totara Valley from 30th September 1999 to 10th January 2001 and the required 8760-value data set for HOMER came from this data.

A contour method of electricity load profile plotting has been used throughout this study and was used to show large data sets in a compact method and a clear illustration of the profiles. This method depicts mean hourly load profiles on a monthly basis using a surface graph resembling a contour map and provides a clear '3D picture' of mean diurnal and monthly/annual energy profile shapes.

This section details brief community demographics (Section 6.1), methods and materials used to monitor and record the electricity use (Section 6.2). The detailed results (Section 6.3) of the community electricity load monitoring are presented using the unique contour presentation method (section 6.3.1). An analysis is undertaken on this data to collate the load data required for the HOMER modelling for both the full-term duration (section 6.3.2), and the short-term duration (section 6.3.3). The results are discussed in Section 6.4, and a summary given in Section 6.5.

6.1 Community Demographic Details

To understand the electricity load profiles of Figure 6.3 (and those in Appendix F), it is necessary to have pertinent information on the users of the electricity. In Table 6.1, a brief description of the house occupier status, the type of household and the number of adults and

children is given. Table 6.2 details the residential appliance ownership data for the Sites 1 – 6. A brief description of the non-residential loads monitored is given in Table 6.3.

Table 6.1 A brief demographic description of the monitored residential electricity load sites.

Farm	Site	Occupier status	Family status	Adults (resident)	Children (resident)
1	1	Manager	Single	1	0
	2	Owner-Retired	Couple	2	Varies
2	3	Owner-Manager	Family	2	2
	4	Tenant	Family	2	1
3	5	Owner	Couple	2	Varies
	6	Manager	Family	2	2

"Varies" indicates that various family members often stay for visits but do not reside full time at the site.

Table 6.2 A listing of appliance use/ownership of each electricity load site.

Farm	Site	TV	Microwave	Stereo	Refrigerator	Electric oven	Electric space heating	Electric blankets	Wet back water heating	Cook on solid fuel stove	Dishwasher	Chest freezer	Clothes dryer
1	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓
	2	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	x
2	3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	4	✓	✓	✓	✓	✓	nd	nd	nd	nd	nd	nd	nd
3	5	✓	✓	✓	✓	✓	✓	✓	x	x	✓	✓	✓
	6	✓	✓	✓	✓	✓	✓	x	x	✓	x	x	x

"nd" indicates no data available.

Table 6.3 A brief description of the non-domestic electricity load sites.

Farm	Site	Building use	Description
1	7	Shearing shed.	Four stand shearing shed.
		Freezer shed.	A walk-in chiller and two chest freezers.
3	8	Shearing shed.	Four stand shearing shed.
		Workshop freezer shed.	Walk-in freezer and general use workshop facilities.

No information on the community housing, including housing age, insulation status, or construction material, was taken through the duration of this study, as the purpose was to obtain electricity profiles only. No demand-side analysis was undertaken either, even though this would be a prerequisite for the design of stand-alone renewable energy systems. This study was for distributed generation system design modelling and decision analysis, and therefore, only the electricity load profiles were of importance to this study.

6.2 Research Method

6.2.1 Load metering Details

Multiple Siemens S2A-100 single-phase meters and Seaward MD-300 three-phase meters were used to record load data at Totara Valley (Figure 6.1). As the meters were already in place in Totara Valley when this study was initiated (Irving, 2000) there was minimal input possible into what meters were used, where they were put and what loads they monitored (Table 6.4). Due to cost limitations and the number of available meters, additional metering was not considered.

Table 6.4 A description of the electricity loads types monitored and meter type for all monitored sites.

Farm	Site	Separately monitored loads	Meter type
1	1	Domestic, Cooking, & Water heating.	3 Siemens S2A-100.
	2	Domestic, Cooking, & Water heating.	1 Seaward MD-300.
2	3	Domestic, Cooking, & Water heating.	2 Siemens S2A-100, 1 Seaward MD-300.
	4	General, Water heating, & Workshop.	1 Seaward MD-300.
3	5	General & Water heating.	2 Siemens S2A-100.
	6	Domestic, Cooking, & Water heating.	3 Siemens S2A-100.
1	7	Shearing shed & freezer shed.	4 Siemens S2A-100.
3	8	Shearing shed & freezer shed.	3 Siemens S2A-100.
2	9 ¹⁴	Shearing shed.	1 Seaward MD-300 (Malfunctioned).
"Domestic" is all domestic loads "Cooking" is all cooking loads "Water heating" is all water heating loads "General" is a domestic and cooking load combined "Workshop" is a workshop load "Shearing shed" is a shearing shed load "Freezer shed" is a freezer shed load			

The Siemens S2A-100 single-phase meters were either hard-wired into electricity distribution point within the site being monitored (the meter boards) (Figure 6.1) or placed between the monitored load and the power supply point (Figure 16.3 A). These meters had the capacity to store either a seven-day rolling average profile averaged over eight weeks or a seven-day half-hourly mean, both in kWh units. In this study, the latter was used. A serious flaw of these meters was that of the meter power requirement (of less than 2 W with the meter voltage rating 230 volts $\pm$ 10%) being met by the mains connection so in any event of power failure or grid power outage the profile data held in memory was lost. On power-up after an outage, the memory automatically reset to record from that moment. Although the seven-day profile memory was volatile, the total accumulated electricity used was saved to a non-volatile section of memory and this data was recoverable after a power outage.

¹⁴ The Seawards MD-300 meter at the shearing shed on Farm 2, Site 9 malfunctioned and this was not discovered until late into the monitoring period, thus no useful data was able to be presented for this site.

The memory of the Siemens meters, once full after a seven-day period, followed a looping process with the oldest data overwritten by the newest. The memory format recorded consumption over a half-hour period and data retrieved and saved was in a comma-separated-variable format for subsequent spreadsheet analysis. The data was recorded at a resolution of 1/100 kWh at power levels less than 1.28 kW and at 1/10 kWh above this level. Data from these meters was downloaded directly onto a laptop computer via a two-way communication cable.

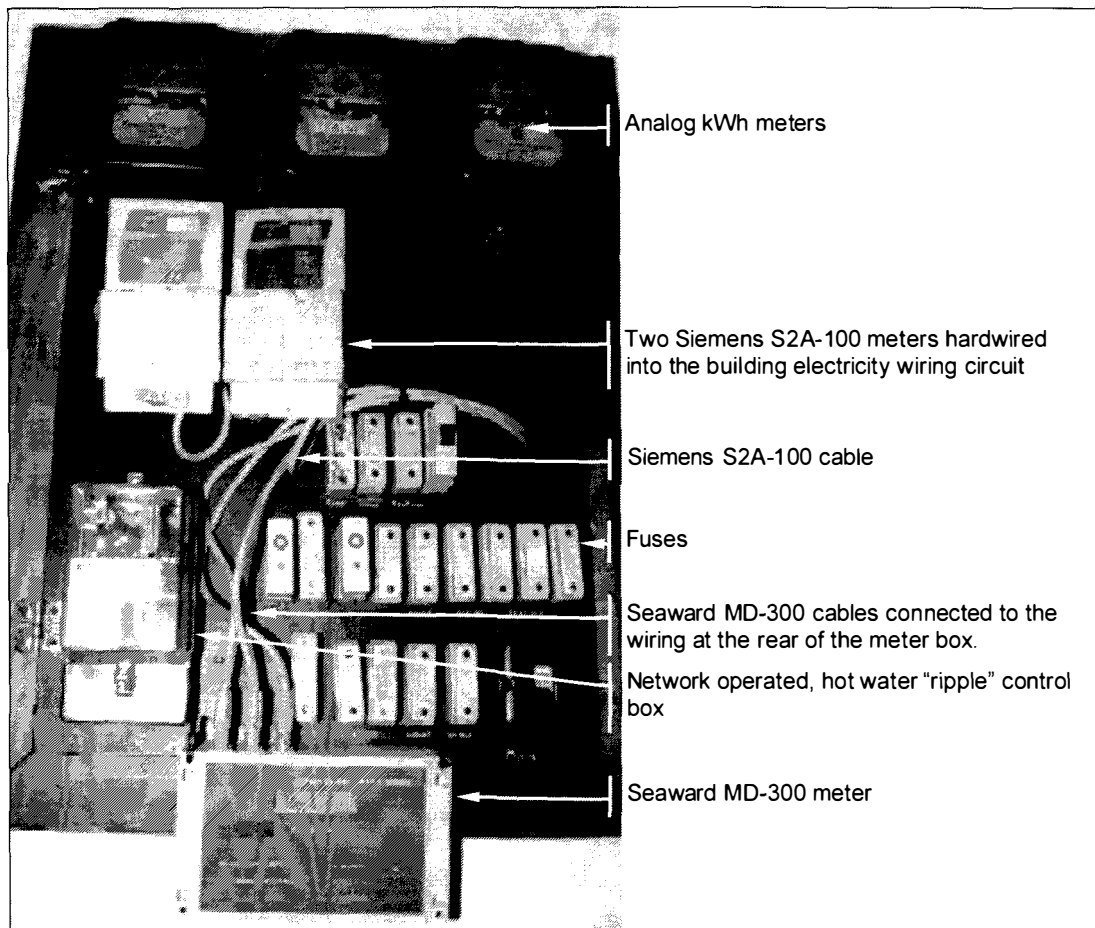


Figure 6.1 An electricity meter box with two Siemens S2A-100 meters and a Seaward MD-300 meter installed.

The other meter type, the Seaward MD300 (Figure 6.1), was used in conjunction with three Rogowski current transducer clamps and leads supplied by the manufacturer. These clamps were able to monitor a single line of supply each and the meters had a non-volatile memory capacity for three months of half-hourly recording. They assessed the current from each clamp every 32 seconds, averaged the collected data every 30 minutes on a root mean squared basis, and recorded the figure into a non-volatile memory for downloading via a laptop computer and communication leads. The Seaward MD300 meter was not affected by power outages as the meter had an independent primary battery power supply. However, a limitation of this meter was the 1-Ampere minimum data resolution, which led to the data set lacking in fine detail. The recorded amperage values were calculated through to kilowatt-hour units assuming a steady voltage level of 230 volts by the author.

The data was collected from all meters at approximately the same time each week over the monitoring duration. Despite this, there was still some data missed through either over-writing or power outages; hence, all of the monitored load data had gaps where data was either lost through a power outage or corrupted by other means. Any gaps in the data undoubtedly affected the time series data required for Chapter 9 but will not have affected the representative nature of the profiles in this section or of those in Appendix F. To produce these profiles, any gaps present in the data set were treated as 'blank' and therefore did not adversely affect the average values.

Where gaps were present in the time series data required for Chapter 9, the missing data was extrapolated (Equation 6.1), and inserted into the time-series. A table was calculated for each of the separate load data sets that contained the mean and standard deviation values categorised by month and time (e.g. the mean data point for 1400 hours in February or for 0400 hours in June). If a data point or section of data was missing from the required time series, the missing load was calculated for that month and time using the mean, standard deviation, a random number to change the sign and a random number to alter the magnitude of the value (Equation 6.1). Although this is a simple method of interpolation it could lead to a 'stepping' of the interpolated data above or below that of the preceding and subsequent data set.

Equation 6.1 The equation used to fill gaps in the electricity load-profile data by interpolation.

$$D_{m,t} = \bar{x}_{m,t} + (\sigma_{m,t} R_1 R_2)$$

Where :

$D_{m,t}$ = the missing data for month m for time t

$\bar{x}_{m,t}$ = the electricity load level for month m for time t

$\sigma_{m,t}$ = the standard deviation for month m for time t

R_1 = a random number of either -1, 0, or 1

R_2 = a random fractional number between 0 and 1

Although the standard deviation is the usual measure of the statistical dispersion, the coefficient of variation (Equation 6.2) can highlight variation not easily seen with this measure, and will be used in this study to clearly indicate variability of the electricity load means. It is effectively a dimensionless number.

Equation 6.2 The formula for the coefficient of variation used in this study.

$$\text{Coefficient of variation} = \frac{\sigma}{\bar{x}}$$

Where :

σ = the standard deviation

$\bar{x}$ = the mean

6.3 Results of the Electricity Load Monitoring

The use of the electricity load profile data obtained through the extensive monitoring programme has been analysed and used for various aspects of this study (Figure 6.2). The mean load profile (and the standard deviation, coefficient of variation, and data solidity) of all monitored loads combined is presented in this section, while the individual components of the

community loads (domestic, water heating and farm loads) are presented in Appendix F – 18.1, while the individual load profiles are presented in Appendix F – 18.2.

Ongoing analysis of the community load profile was undertaken in order to compile the required profiles for the HOMER modelling, and to obtain the data required for the short-term duration analysis.

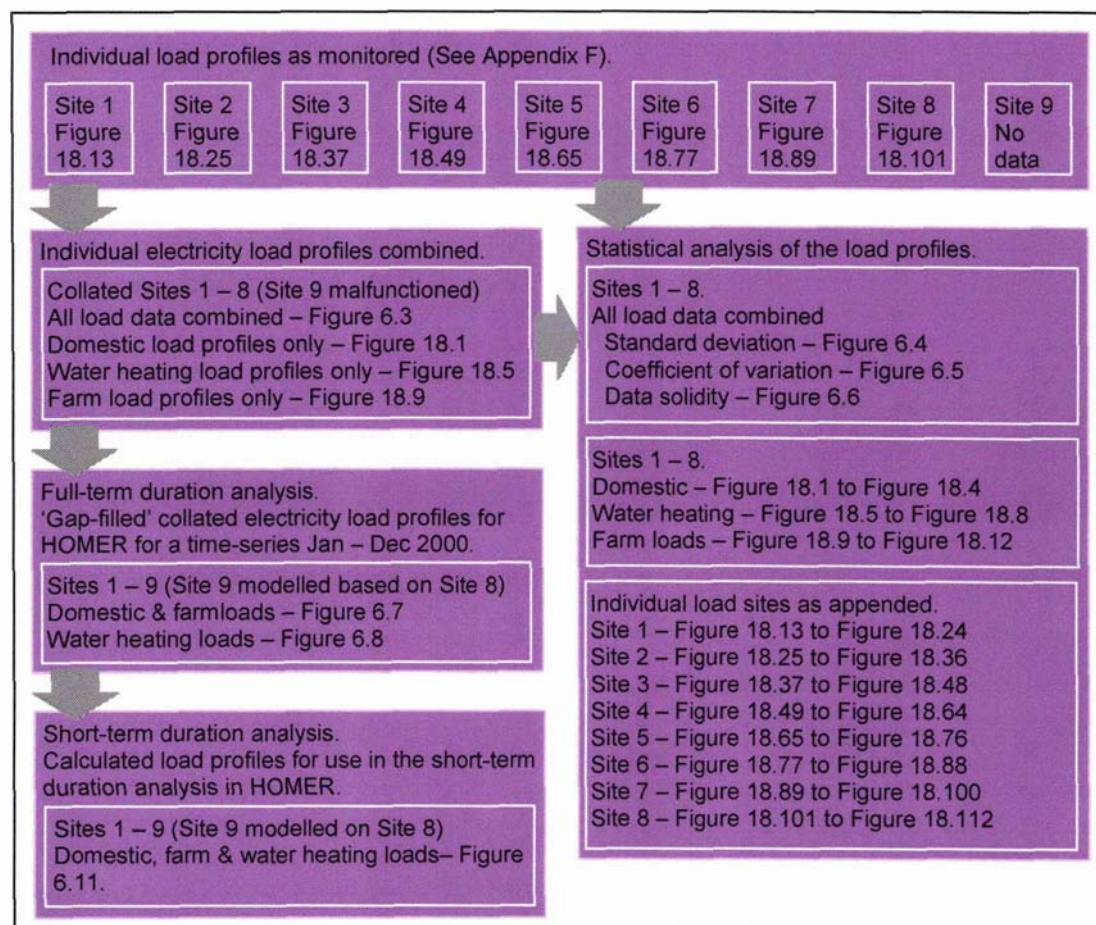


Figure 6.2 A schematic diagram illustrating the flow of use of the electricity load data from this study from the individual load profiles through to the full-term and short-term duration profiles.

6.3.1 Monitored Electricity Load Profiles

The community electricity load profile presented in this section was collated from the monitoring of eight individual sites at Totara Valley (Table 6.4) and although the monitored duration was from September 1999 to July 2001 the profiles in this section are from January to December 2000. A further analysis of the separate domestic, water heating, and farm loads is given in Appendix F.

The mean hourly load presented (Figure 6.3) indicates the seasonal variation over the monitored duration. The variation of this mean load is presented as the standard deviation (Figure 6.4), and the co-efficient of variation (Figure 6.5). The level of data solidity, the fraction of data recorded from the monitored duration is plotted in Figure 6.6.

The community electricity profile (Figure 6.3) comprised two residential load types, general domestic and water heating, and three non-residential load types – two shearing sheds,

two freezer sheds and a small workshop. The data from the shearing shed on Farm 2 was not accurate because of a meter malfunction so was not included in this analysis.

The trough that occurred throughout the day in July and August 2000 is attributable to the author being unable to download the data between 12th July 2000 and 16th August 2000. Sites 1, 3, 5, 6, 7, and 8 were affected as these sites utilised the Siemens meter and therefore required downloading weekly to obtain the load profile data. All other sites had the Seawards meter and due to the ability of these meters to record longer durations the data was not lost from these sites.

The mean electricity load profile of the Totara Valley community (Figure 6.3) indicates a very clear seasonal pattern of electricity use. An evening peak occurs at 1900 hours over the months of April, May, June, and September. Throughout the duration of monitoring, the base load ranged from 1.0 to 5.0 kWh and occurred between the hours of 0100 and 0700.

The occurrence of a slight 'trough' in the load profile between the hours of 1930 and 2130 about the months of January – February 2000 relates to the 'ripple' control of the water heating loads by the electricity supply company. This can be seen clearly in the community water-heating load (Figure 18.5). This had the effect of delaying the water-heating load until later in the evening between 2200 hours and midnight. Not all sites monitored displayed 'ripple' control of their water heating electricity supply. Individual sites 1, 3, 5, and 6 all indicated 'ripple' control from early September 1999 through to February 2000. Sites 2 and 4 did not display any indication of 'ripple' control and this may be indicative of control mechanism malfunction (Appendix F).

The plot of the standard deviation (Figure 6.4) indicated that the evening (1900 hours) from April to November 2000 had the highest level of standard deviation, being between 2.75 to 3.75 kWh. The high standard deviation in the morning was evident throughout the year and was between 1.75 to 3.25 kWh. The standard deviation of the base load was between 0.75 to 2.25 kWh. An analysis of the coefficient of variation (Figure 6.5) indicated a relative even spread of variation with no outstanding highs or lows, with the spread of variation magnitude from 0.20 to 0.70. The coefficient of variation was reasonably flat throughout the duration of monitoring varying from 20% to 60%.

Over the duration of the monitoring, some data was lost from some of the sites due to meter installation problems, ongoing meter malfunction or maintenance problems, power outages, corrupt files on transfer from the meter to the computer, and missed down-load times leading to data overwriting. Full details of the missing data and the reasons for this loss are in Appendix F.

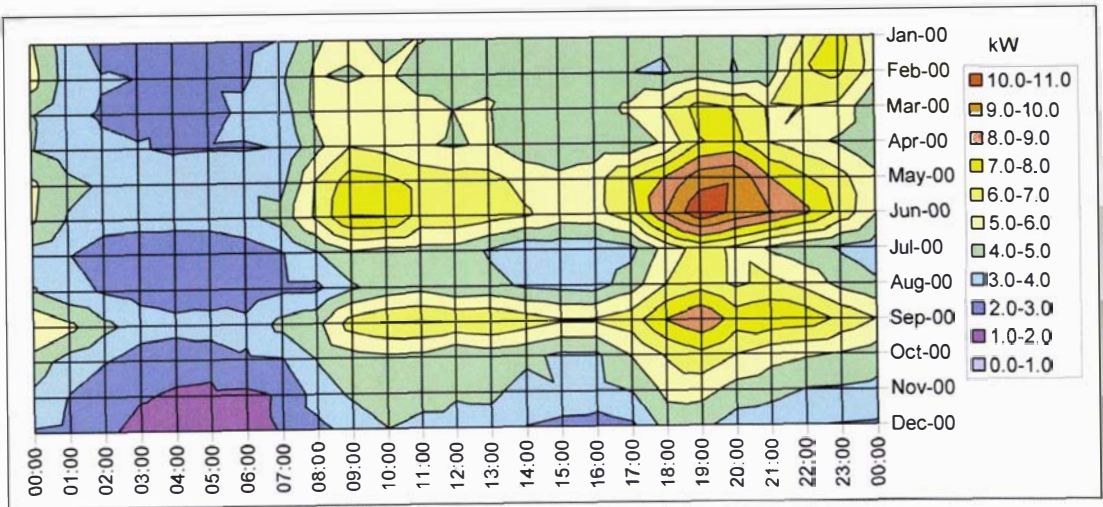


Figure 6.3 The mean hourly electrical load profile as it varies through the day and from month to month for the Totara Valley Community.

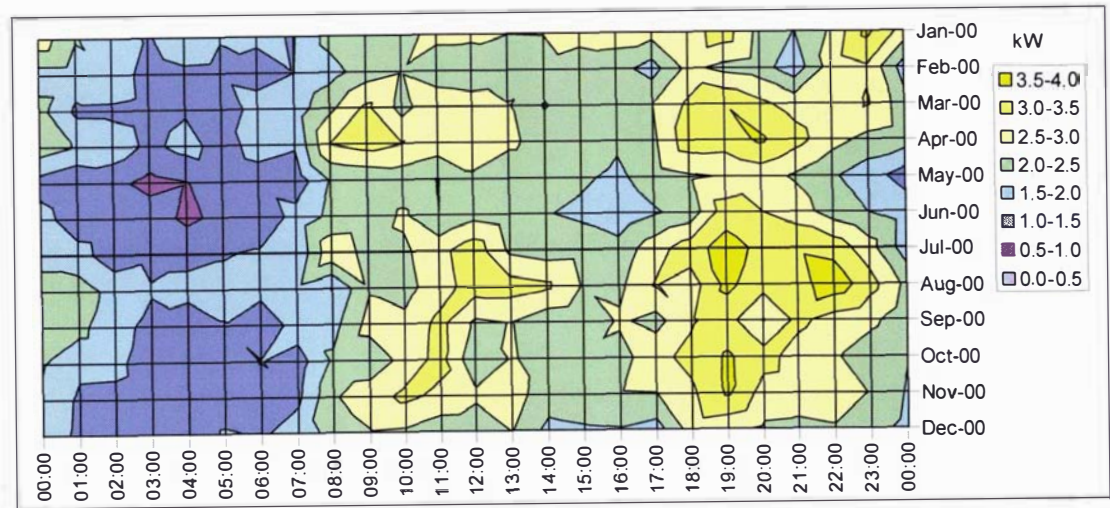


Figure 6.4 The standard deviation of the mean hourly electrical load profile as it varies through the day and from month to month for the Totara Valley Community.

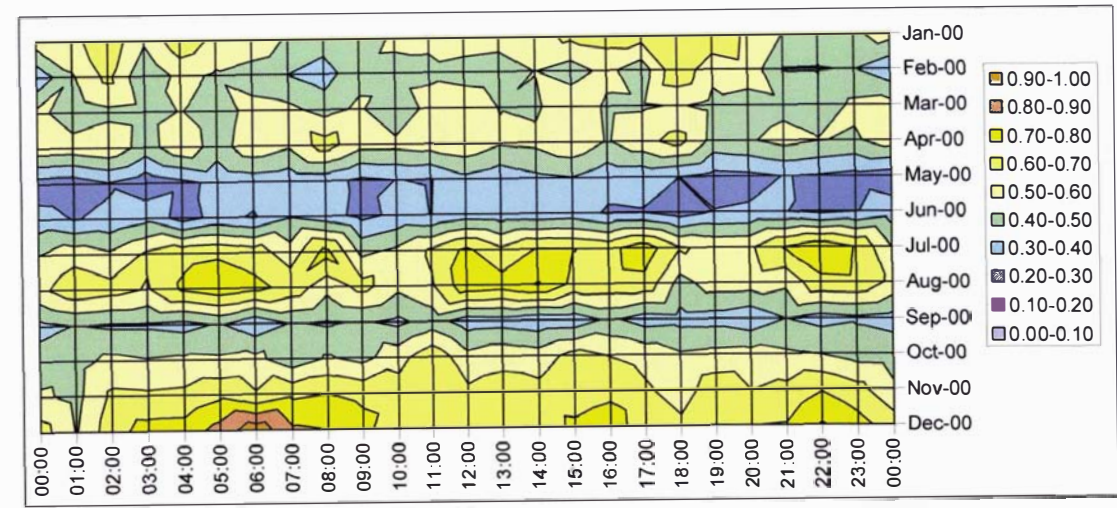


Figure 6.5 The coefficient of variation for the mean hourly electrical load profile as it varies through the day and from month to month for the Totara Valley Community.

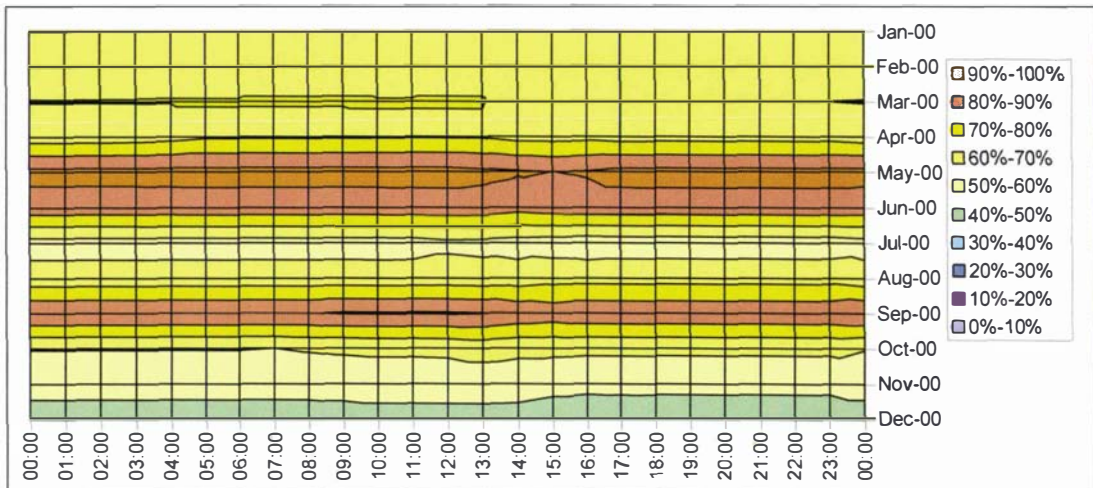


Figure 6.6 The percentage of data solidity for mean hourly electrical load profile as it varies through the day and from month to month for the Totara Valley Community.

An indication of data solidity is the percentage of possible data actually recorded (Figure 6.6). As the monitoring programme was developed (September to December 1999), the amount of data coming from Totara Valley increased from approximately 30% to 70% of possible data (Figure 18.4, Figure 18.8 and Figure 18.12). Over the duration from January 2000 to January 2001, this percentage varied from 30% to 95%. The data was downloaded each Wednesday at approximately 1500 hours onwards where possible. This can be seen in the slight fluctuation over the duration of the monitoring at this time.

6.3.2 Collated Electricity Load Profiles for HOMER

From Figure 6.6 (and Figure 18.4, Figure 18.8 and Figure 18.12), it was noted the varying levels of data solidity of the monitored load, indicating that there were some data-gaps needing to be filled before it could be used in HOMER modelling. The data gaps were from individual site loads not being monitored thereby decreasing the mean hourly load. The load was therefore modelled to fill the data gaps (Figure 6.7 to Figure 6.9) using Equation 6.1. These profiles were produced for the 'full-term' duration HOMER modelling (section 9.1.2).

The magnitudes of these load profiles (Figure 6.7 to Figure 6.9) were higher than for the monitored loads. This occurred due to the data gaps in the original individual site load data. In the process of filling the individual site data gaps, the magnitude of the mean loads increased due to the sum of the loads increasing. The largest data gap occurred in the July – August duration and this therefore is the period that has the greatest level of change from the monitored load.

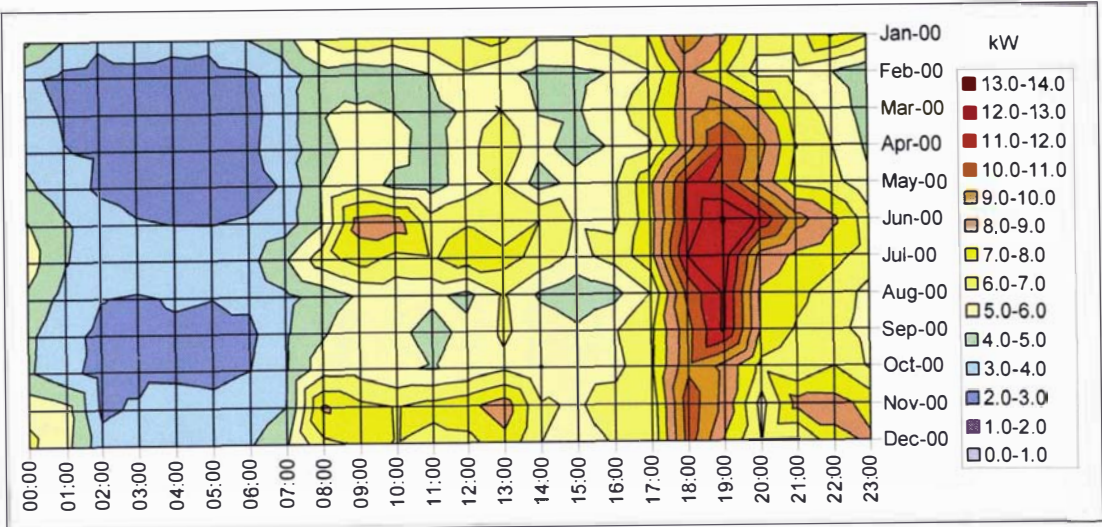


Figure 6.7 The 1-year modelled 'gap-filled' domestic, shearing shed and freezer shed electricity load profile for the community.

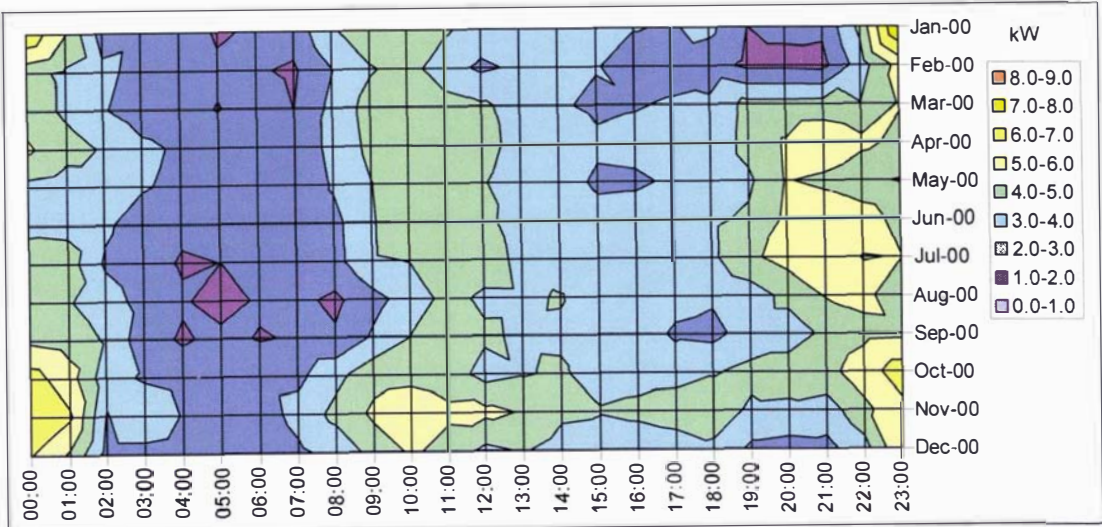


Figure 6.8 The 1-year modelled 'gap-filled' water heating electricity load profile for the community.

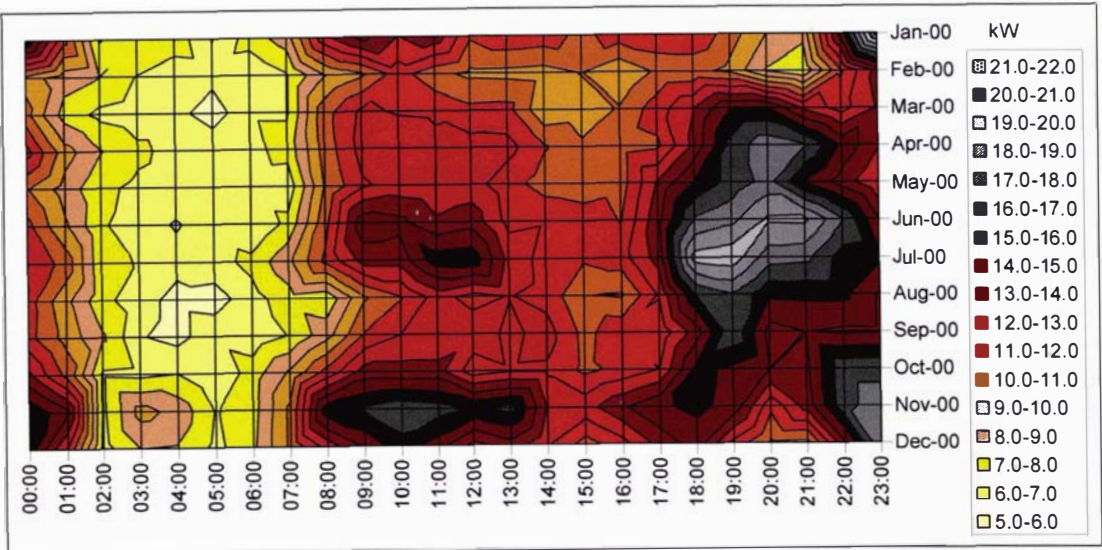


Figure 6.9 The 1-year modelled 'gap-filled' total electricity load profile for the community.

6.3.3 Short-Term Duration Analysis – Electricity Load Profile Modelling

If the short-term period were adopted, the monthly electricity load profiles would require modelling in HOMER by necessity. The key parameters for such modelling (daily load profiles for each month, mean daily load (kWh/d), and 'noise' – section 4.2.2) are calculated and presented in this section. The mean daily load profiles were developed from the January load profile monitored in this study, in conjunction with knowledge of the previous 12 months electricity use levels. The mean daily load (kWh/d) was developed from the previous 12 months of data. The 'noise' used in the modelling were estimated based on the analysis of the monitored loads.

Mean Daily Load Profiles

The daily load profiles for each month were required inputs into load modelling with HOMER (Figure 4.2). Without monitored data, or data from any other source on profile shape and load magnitudes, these monthly profiles needed to be modelled. For the purposes of this study, it was assumed that the profile shape and magnitude (199 kWh/d) for January 2000 (Figure 6.10) and the monthly total electricity usage for the previous 12 months of were the only sources of information on which to base the modelling. Therefore, the January 2000 monthly profile (Figure 6.10), and the mean daily loads of 1999 (Table 6.5) (kWh/d – calculated from the monthly totals), were used to model the remaining 11 months of 2000.

Firstly, the January 2000 profile (as monitored) was 'distorted' by the affects of 'ripple' control of the water heating (Figure 6.3 and Figure 18.5). If this profile was to be used as the basis of the remaining 11 months, this 'distortion' needed 'correcting', as it was a feature of the summer load profiles only (Figure 6.3 and Figure 18.5). This was done by manually shifting the load such that the daily mean load (199 kWh/d) was unaffected and remained the same (Figure 6.10).

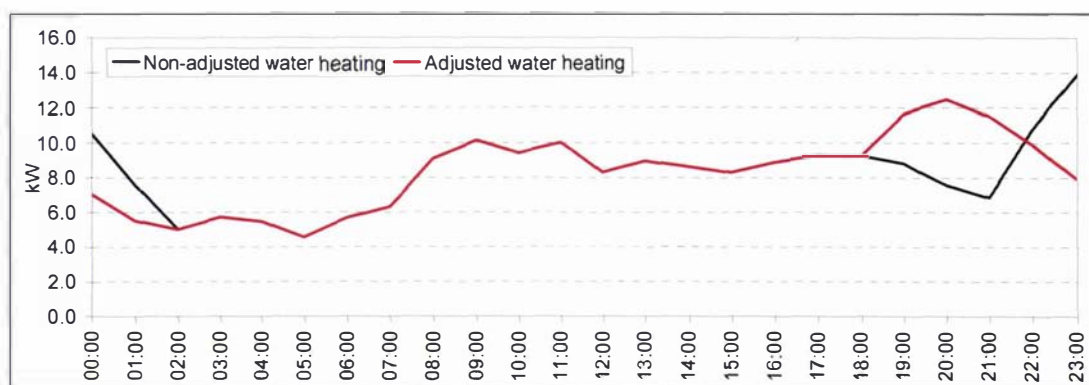


Figure 6.10 The adjusted (Red line) and unadjusted (black line) load profile for January 2000 for the Totara Valley community.

The previous 12-months (1999) electricity usage (Irving, 2000) was analysed and the percentage differences between January and the subsequent months were calculated (Table 6.5). This percentage differential will form the basis for scaling the magnitude of the January 2000 profile to form the modelled monthly load profiles for 2000.

Table 6.5 The mean daily loads (kWh/d) by month for 1999 for the Totara Valley community and the monthly percentage difference compared with January 1999.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999 kWh/d	181	179	201	195	198	182	202	198	189	181	175	186
% diff by Jan 1999		-1%	11%	8%	9%	1%	12%	9%	4%	0%	-3%	3%

These percentage differences from 1999 were then used as the basis on which to derive the difference between the months of 2000 and the January 2000 profile. Which produced the modelled monthly loads (kWh/d) as presented in Table 6.6.

Table 6.6 The modelled mean daily loads (kWh/d) for the Totara Valley community and the monthly difference compared with January 1999.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
% diff by Jan 1999		-1%	11%	8%	9%	1%	12%	9%	4%	0%	-3%	3%
2000 based on 1999	199	197	221	214	218	200	222	218	208	199	192	205

The product of each hour of the monitored January load profile and the percentage difference associated with a particular month were used to produce the re-scaled load profile (Figure 6.11). This will be used in HOMER for the short-term duration analysis.

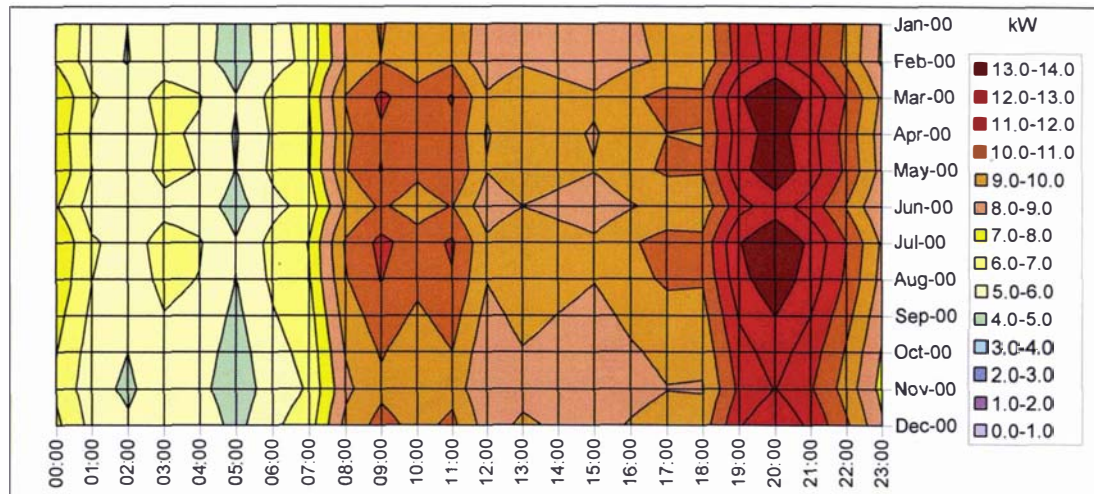


Figure 6.11 The modelled load profile for the Totara Valley community for 2000 based on the monitored profile for January 2000 and the previous 12 months electricity usage.

Mean Daily Load

The mean daily load profiles (Figure 6.11) are entered into the HOMER electricity load-modelling module (Figure 4.2) and these profiles are either left at the default mean daily load calculated by HOMER (kWh/d) or re-scaled to match a required level, while essentially retaining the profile shape.

'Noise' Calculations

Once the modelled load profile and the mean daily load (if different from the default) are entered into the HOMER electricity load modelling module, daily and hourly 'noise' values

can be used to introduce a load fluctuation component to the modelled data. The results of the standard deviation analysis (Table 6.7) will be of value if modelling the 'noise' inherent in electricity loads in HOMER.

Table 6.7 The standard deviation percentage values for individual and community electricity load profiles at the end of the monitoring duration.

Site	Load type	Mean load (kWh/d)	Whole days of data	Daily SD. (% of daily load)	Number of hours	Hourly SD. (% of hourly load)
1	Domestic	11.34	291	18.96	7,678	45.71
	Water heating	7.27	468	42.51	11,257	142.05
2	Domestic	10.67	406	38.82	9,787	123.08
	Water heating	12.46	406	26.46	9,787	76.60
3	Domestic	19.62	238	33.50	6,519	83.50
	Water heating	19.97	272	45.09	6,541	121.24
4	Domestic	7.32	589	42.23	14,156	135.25
	Water heating	14.27	589	32.28	14,156	95.47
5	Domestic	15.61	288	48.57	6,948	105.14
	Water heating	7.65	254	62.69	6,949	212.56
6	Domestic	7.85	238	97.78	6,503	123.44
	Water heating	10.87	199	80.75	5,585	175.37
7	Shearing shed	12.02	252	45.51	6,935	73.94
	Freezer shed	7.52	273	27.71	7,344	29.82
8	Shearing shed	1.16	233	311.19	6,331	454.81
	Freezer shed	5.26	269	20.71	7,132	26.26
	Whole community	166.07	19	8.09	456	8.56

The number of 'whole days' of data (Table 6.7) were restricted by meter malfunctions, meter inaccessibility (in the house), small data gaps due to mismatched meter reading times, and rarely, post-download data corruption. The number of meters read for whole day data, the mean daily load (kWh/d) of these meters, the standard deviation of this mean, and the percentage value of this is given in Table 6.8. This indicates the difficulty involved in obtaining representative 'whole day' data over the course of the monitoring programme.

The mean daily electricity loads, and the daily and hourly standard deviations for the individual electricity loads are given in Table 6.7 as a percentage of the mean loads. Only complete *whole days* of data were used to obtain the standard deviation of the mean daily electricity load, and the complete hourly data set was used to obtain the hourly standard deviation figure.

Table 6.8 The number of simultaneous readings for the community profile statistics leading to 'whole day' data.

Number of meters read	Number of days readings made	Daily mean (kWh/d)	Standard deviation of the mean (kWh)	Percentage of the mean (%)
2	13	21.89	3.71	17
3	8	35.28	16.36	46
5	202	49.21	8.49	17
6	78	57.22	10.31	18
7	51	69.92	13.91	20
8	26	81.54	30.08	37
9	28	99.77	44.14	44
10	26	97.38	14.62	15
11	13	102.88	15.50	15
12	14	110.32	14.01	13
13	33	125.72	14.85	12
14	46	129.11	16.23	13
15	74	146.00	17.81	12
16	27	156.75	17.72	11
17	19	157.73	11.93	8

6.4 Discussion

The unique load presentation method used to depict the community loads (Figure 6.3 to Figure 6.5), the community domestic and water heating load profiles, and the individual site load profiles (Appendix F) were useful in highlighting patterns of electricity use, the standard deviation and co-efficient of variation of each hour, and the data solidity. These patterns would not have been as obvious in linear graphs or tabulated data. The overall diurnal patterns suggested a morning peak occurring about 0900 – 1000 hours tapering off to a low midday level of load. An evening peak, higher than the morning peak, occurred about 1900 – 2000 hours and slowly tapered off into the early morning hours.

Monthly patterns of energy use were evident and related directly to the seasons, with summer loads levels generally lower than the winter levels. A 'trough' in the winter profile (July – August) could be attributed to: the duration over which many of the residents took a holiday; a winter peak in the use of both solid-fuel space-heating and water heating; and a lower level of successful meter reading and hence lower level of data solidity (50% - 70%).

Winter on a sheep and beef farm is generally a period of repair and maintenance of farm equipment and infrastructure and involves a lower level of stock-work. Many decide to take a short holiday during this period. This winter 'trough' was visible in analysis of the domestic electricity profile (Figure 18.1), and in the individual load profiles of Site 1 (Figure 18.13), Site 3 (Figure 18.37), Site 5 (Figure 18.65), and Site 6 (Figure 18.77).

This period also coincides with increased use of solid-fuel space heaters equipped with secondary water heating capacity. The individual and combined effects of these factors

can be seen in the separated loads of domestic, and water heating (Figure 18.1 and Figure 18.5).

The lower level of data solidity relates to the combined effects of closed homes being unavailable to the author while the residents were away on holiday, and to inclement weather precluding the downloading of data from outdoor electricity meter enclosures.

The usage of the coefficient of variation to depict variation in the load profiles produced clear illustrations of variation not otherwise noticeable using the standard deviation. The variation of the winter 'trough' was visible in analysis of the domestic electricity profile (Figure 18.3), and in the individual load profiles of Site 1 (Figure 18.15), Site 3 (Figure 18.39), Site 5 (Figure 18.67), and Site 6 (Figure 18.79).

As an alternative to actual monitoring in this situation, the results of the HEEP research may be used to produce a model to use for profile modelling based on socio-demographic data (Isaacs *et al.*, 2002). Because of this, it is anticipated that future load monitoring of a community in New Zealand could be of shorter duration to provide useful information with the data recorded used to aid or validate the application of the HEEP model in assessing the community's electricity requirement.

When compared with the HEEP profiles (Figure 2.12), only four of the six Totara Valley profiles appeared directly similar to two of the HEEP classifications (Figure 6.12) (Camilleri *et al.*, 2000; Stoecklein *et al.*, 2001b). Sites 1 and 6 of the Totara Valley case study did not appear to match any of the classifications, whereas, Sites 2, 3, and 4 appeared to match Class 5, and Site 5 appeared similar to Class 3. Please note that the scales are the same in order to assess the magnitude of the sites and the various classifications.

The composition of the Class 5 profiles was 79% superannuatants and 21% other socio-demographic. The composition of Class 3 was virtually the reverse of this. Of the Sites 2, 3, and 4, only Site 2 had superannuatants resident, with the other two sites being young families. Site 5 had a couple whose independent children lived away from home and therefore represented a working couple.

Given the results of this comparison, there may be little or no significant difference between rural and urban domestic profiles. However, both the Totara Valley case study, and the HEEP classifications were small samples and no conclusion can be drawn as to any difference between urban and rural electricity consumption or otherwise. Data from the extended HEEP monitoring of rural loads will produce further data that will highlight any differences between the two differing lifestyles.

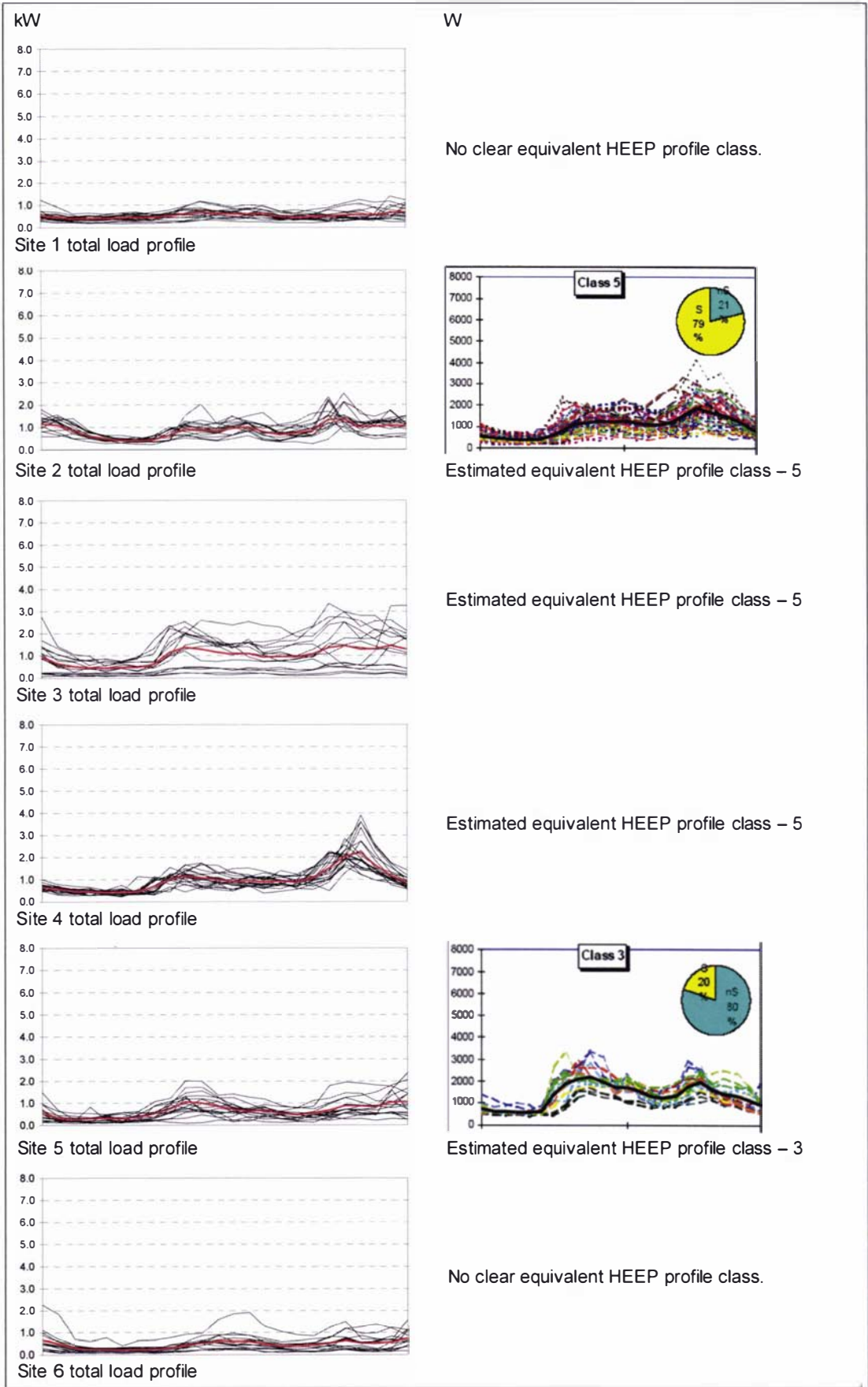


Figure 6.12 The monthly total electricity load profiles of the six households in the Totara Valley case study sites compared with their equivalent (if applicable) HEEP profile class.

A comparison between the 1999 loads (Table 6.5 and Table 6.6), the 'gap-filled' 2000 monthly loads (Figure 6.9), and the modelled loads (Figure 6.11) indicated a range of differences (Figure 6.13). All the modelled loads were higher than the gap-filled loads with the exception of June July, and November, whereas, the modelled loads were all higher than the 1999 loads because the January 2000 load was higher.

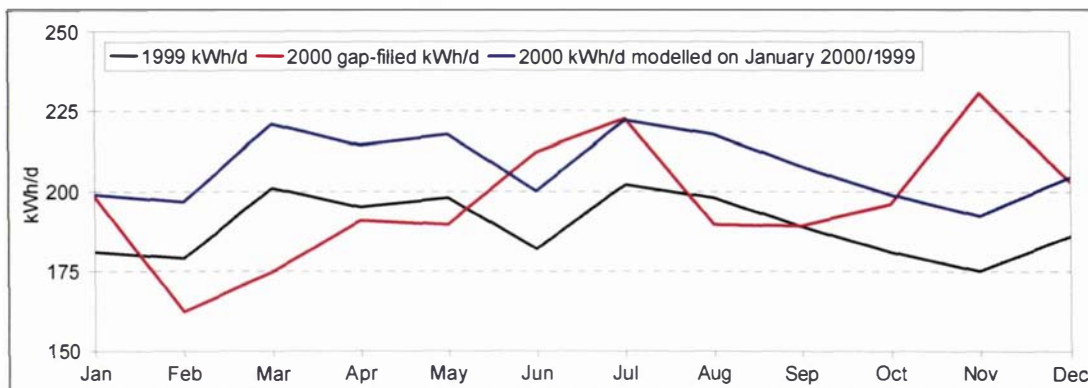


Figure 6.13 A comparison between the monthly mean kWh/d profiles from 1999, the gap-filled 2000 data, and the 2000 loads modelled based on the 1999 data.

6.5 Summary

The objectives of this section of the study were to monitor and record rural load profiles and renewable energy resources of a selected case study to:

- provide data on rural electricity load profiles,
- to assess the effect of the interpolation of the 2000 data based on the 1999 data,
- to provide data to test the efficacy of the software used for modelling renewable energy generation system design.

This has been achieved with respect to the documentation of rural electricity load profiles. The presentation of these profiles revealed distinct seasonal patterns of electricity use and indicated some of the effects of the farming lifestyle on the electricity loads. The short-term duration modelling of mean electricity loads, mean monthly profiles, and hourly and daily 'noise' levels were assessed. The full-term duration data was used to form the collated profile used in HOMER modelling.

7 Totara Valley Renewable Energy Resources

The renewable energy simulation and optimisation software, HOMER, can use a contiguous time-series data of up to 8760 hourly values of renewable energy resource data. These data can be obtained by either measuring at a subject site, or modelling a viable set of wind, solar and hydro time series data. The renewable energy resources of wind, solar and hydrological were monitored in Totara Valley and data recorded from 26th February 1999 to 9th June 2001.

The method used to measure and record the data is given in Section 7.1. The results of the monitoring or measuring (Section 7.2) and include the wind assessment results (section 7.2.1) which includes unique plots of the spatial and temporal resource, the hydrological resource results (section 7.2.3), and the solar resource results (section 7.2.6). Further details of all the resource data obtained through monitoring are available in Appendix G. Data pertinent to the short-duration analysis was calculated and presented in section 7.2.7. A discussion (Section 7.3) considers the results on an individual site-by-site basis and a concluding statement is given in Section 7.4.

7.1 Research Methods

7.1.1 Wind Energy Resource Monitoring Method

Of the five locations monitored (Figure 5.3), Wind Site 1 was already in place from a previous research project (Irving, 2000). Four further sites (Wind Sites 2 – 5) were identified from anecdotal evidence by the landowners, and subsequent site inspection by the author, and preliminary WAsP modelling (Figure 14.1). Wind Site 5 was chosen and implemented as a possible alternative reference site to Wind Site 1 for modelling purposes as it was too far from any load site to be considered feasible for a wind turbine site in this study. The clear and unobstructed hill had steep sides and not influenced by any obvious terrain channelling effects (Figure 5.3 and Figure 7.20).

The wind resource data was recorded at Wind Site 1 using a programmable *Campbell CR500* data logger and the data was downloaded directly to a laptop (Figure 7.1). *NRG Wind Explorer™* data loggers (A & B – Figure 7.2) mounted on anemometer masts made especially for this study by the author and the data was obtained via a data plug exchange (Figure 7.3). The data-logger resolution was set to 10-minute mean durations in all data-loggers. The anemometer used at each site was the *Type 40 Maximum* used in conjunction with a *200 Series* Wind Vane (B – Figure 7.3). Wind Site 1 utilised an existing mast, while two 10-metre high anemometer masts specially designed for this study to enable ease of assembly, erection, and activation by one person, allowed rapid and easy mobility of the intermediary masts at Wind Sites 2 to 4. This led to a considerable saving of time and money over the previous system employed at Wind Site 1 where up to 3 people were required to raise the mast ready for data recording.

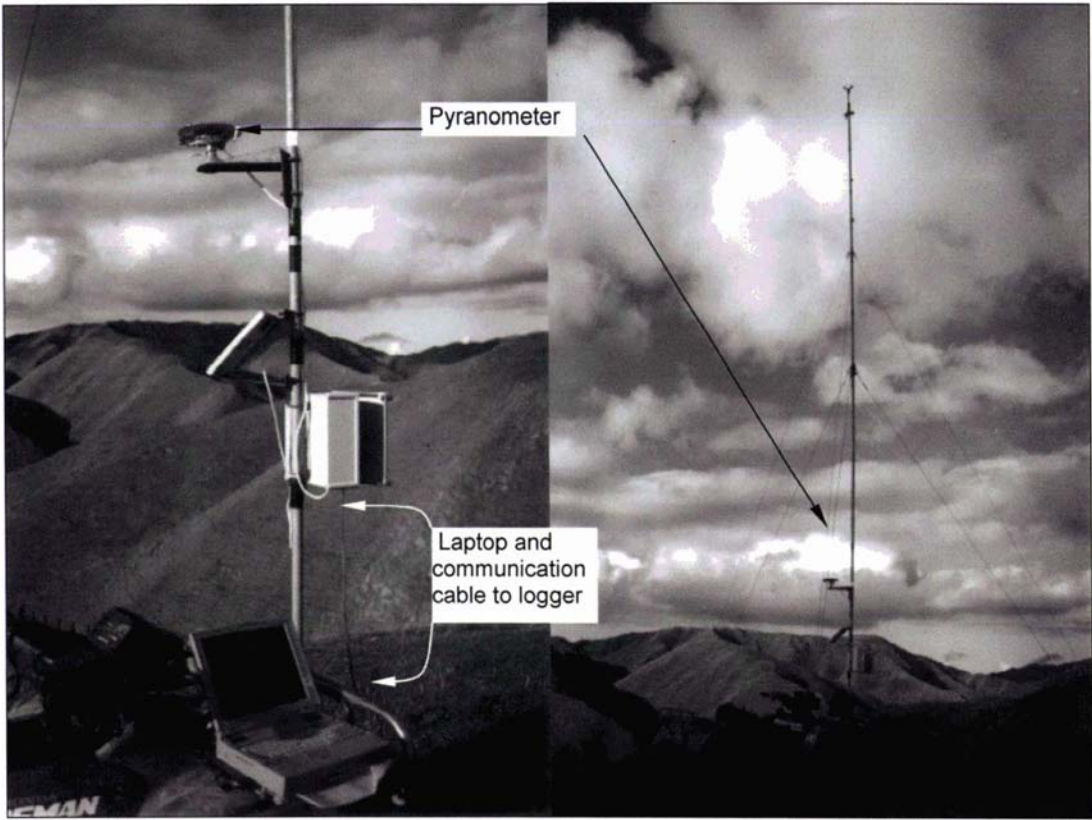


Figure 7.1 The anemometer mast and pyranometer at Wind Site 1.

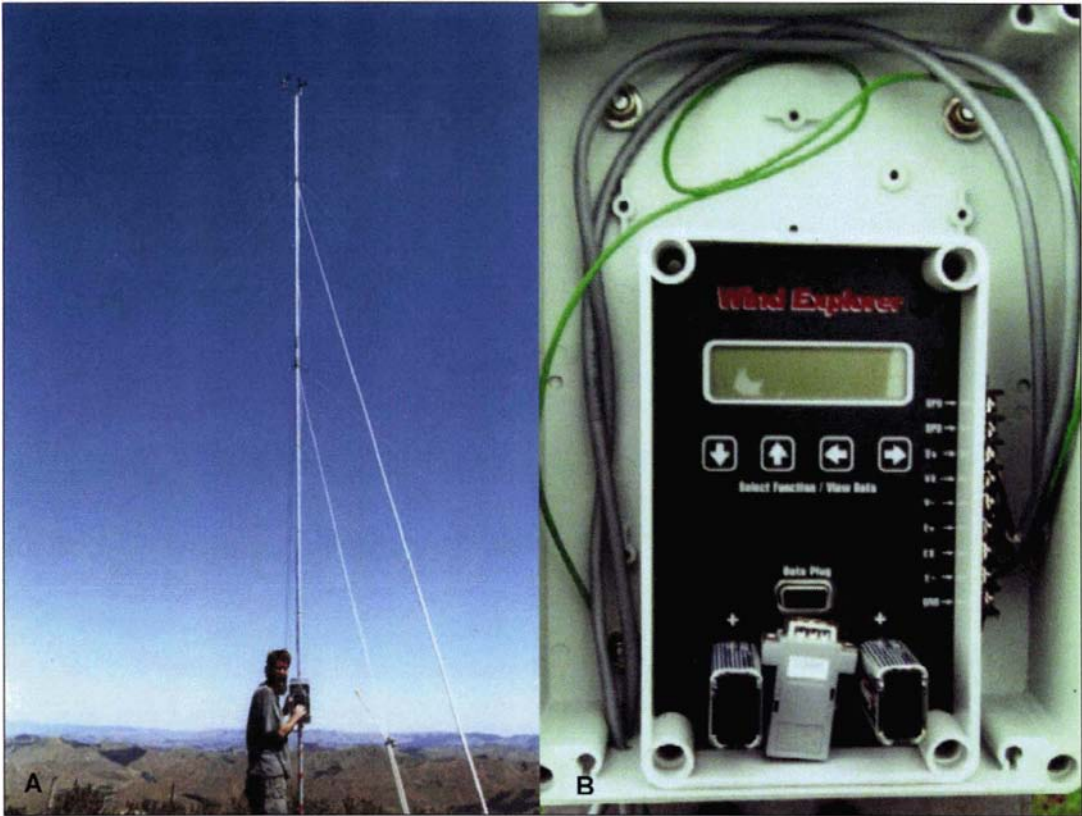


Figure 7.2 The NRG Wind Explorer data-logger as used at Wind Sites 2 – 5 (Site 5 shown).



Figure 7.3 The systematic anemometer mast raising technique including details of the mast assembly.

A: The initial site setup required calculations of where the cables were secured at ground level. B: The anemometer and wind vane were secured to the framework. The wind vane was fixed such that 0° on the wind vane was magnetic north. C: Cables from the mast to the lifting 'Gin-pole' were set-up at the required length. D, E & F: The lift commenced at a steady rate. G: The final tie-off of the lifting cables preceded adjustment of the other three cable sets. H: The mast lifting is finished, mast vertical to the horizontal, all tied off, and all ready to log data (Figure 7.2 A).

Details of the installation process used in the new mast are shown sequentially in Figure 7.3, A to H. The key attribute of this system was the ease and simplicity of moving the mast and associated equipment from one location to another. The mobile mast system was assembled on-site in approximately four hours ready to log data, and took three hours to dismantle and pack ready for transportation by whatever means practicable to the next location. This method of mast assembly was developed to minimise the time spent moving to different sites and raising the mast to an operational status and would thus prove valuable in the short-term duration project timetable (Figure 4.1). This method also enabled mast-raising to be conducted safely in high winds, with one such event being during 15 m/s winds.

One such mast was used at Wind Site 5, while a second mobile mast was used to sequentially log wind data at the intermediary Wind Sites 2 to 4. The duration of monitoring at each of these sites was sufficient to record wind from most directions simultaneously with the two reference masts (Wind Sites 1 & 5). The long-term reference site data from Wind Sites 1 and 5 was then used to model Wind Sites 2 to 4 with model validation undertaken with the recorded data. The data modelling and validation processes were undertaken using the WAsP model (Murray & Sims, 2001c & 2002) (Chapter 8).

7.1.2 Hydrological Energy Monitoring Method

Three locations of hydro energy potential within Totara Stream were clearly identified¹⁵ and the stream flow measured (Figure 5.3). The 'velocity – area' method was used for the assessment of stream flow calculations. This method requires a relatively straight and uniform section of stream, approximately five to 10 metres in length, free of in-stream obstacles and any ensuing areas of eddy flow, and ideally should have a relatively even cross sectional flow rate.

Floats, placed *within* the stream flow were timed from the upstream start point to the downstream finish point (Figure 7.4). These timed runs were repeated a number of times and from the results, the average velocity of the stream was calculated in metres per second. From the cross-sectional measurements and the velocity of water flow, an estimate was made as to flow rate in cubic metres per second.

Oranges proved to be an ideal float in this study as they were visible, their specific gravity was close to unity (Christensen, 1994), and therefore they floated predominantly submerged in the average velocity stream of the flowing water and not subjected to the slightly slower surface flow. They were easy to see, inexpensive, potentially expendable, and up to eight at a time were 'floated' thus obtaining a large number of timed runs for averaging. A stopwatch able to record 'lap- times' was used to record each orange 'float' as it crossed the finish point. The drift path of two the oranges, seen in this 10-second time-lapsed photo (Figure 7.4), is approximately mid-point between the start and finish position of the stream section being assessed.

¹⁵ Although high-head low-flow opportunities may exist within the Totara Valley catchment, this was based on anecdotal evidence only as at the time of monitoring, all flows appeared to be low or ephemeral by nature. One opportunity may have been included but the uncertainty over flow rates precluded this stream from use in this analysis.

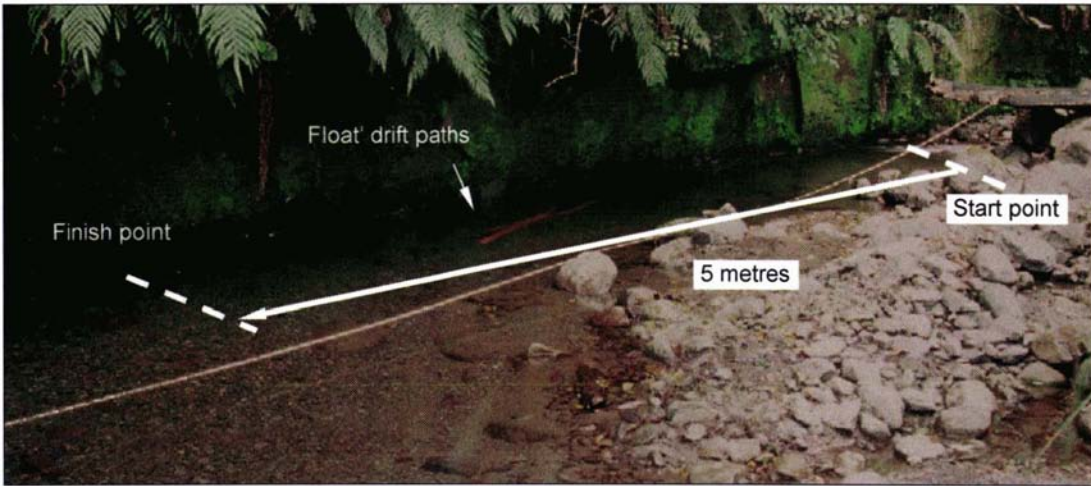


Figure 7.4 An example of the timed-float method of stream flow assessment utilising oranges as floats.

At each assessment, the depths of at least five sections across the stream were measured to ascertain an average cross-sectional area in square metres. The *Simpson's* formula (Equation 7.1) was used to calculate this and can only be used when the section being calculated is divided into an odd number of co-ordinate points across the cross-sectional area (Figure 7.5).

Equation 7.1 The Simpson's formula for calculating the cross-sectional area of a stream.

$$A = \frac{d((y_1 + y_n) + 4(y_2 + y_4 + y_6) + 2(y_3 + y_5))}{3}$$

Where :

A = the cross - sectional area of the stream

d = the distance between depth measures

y_n = the depth of the water at point y_n

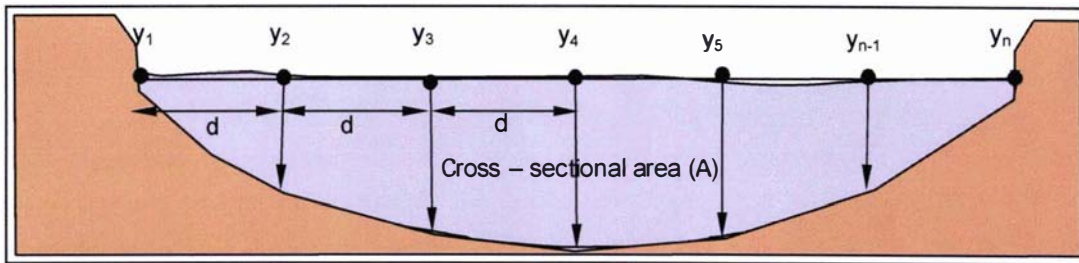


Figure 7.5 An illustration of the method of cross-sectional area measurement of a stream using Simpson's formula.

The estimated stream velocity was then calculated using Equation 7.2. ' A ' is the cross-sectional area (Equation 7.1), and V_{mean} was obtained from the averaged velocity of the 'floats'. The correction factor ' f ' (Table 7.1) was assessed based on the observed streambed characteristics (Harvey *et al.*, 1993).

Equation 7.2 The formula used to calculate the flow rate of a stream.

$$Q = A \times V_{mean} \times f$$

Where :

Q = the calculated stream flow

A = the cross - sectional area

V_{mean} = the mean stream flow velocity

f = the correction factor to account for the stream bed friction

Table 7.1 The velocity correction factors for stream flows in various channels that were used in this study.

Stream channel condition	Velocity correction factor
Large slow clear stream	0.75
Small regular stream, smooth bed	0.65
Shallow (>0.5 m) turbulent stream	0.45
Very shallow rocky stream	0.25
Source: Harvey <i>et al.</i> (1993).	

7.1.3 Solar Energy Monitoring Method

The pyranometer at Wind Site 1 (Figure 5.3 and Figure 7.1) had a clear unimpeded solar access facing due solar north (approximately 21.5° west of magnetic north). The Campbell CR500 data logger recorded data from this pyranometer. The data collected, measured on the horizontal plane in Watts per square metre (W/m^2), was a measure of the horizontal global insolation (*incoming solar radiation*). These data were downloaded in conjunction with the wind data. The last calibration date for this pyranometer was not known and therefore the veracity of the data is also unclear.

7.2 Results of the Renewable Energy Resource Monitoring

The results of the renewable energy resource assessments of Totara Valley are given in both this section, and in Appendix G. Plots of the wind resource are given in varying formats with temporal plots for diurnal monthly and monthly spatial magnitude for Wind Site 1, diurnal monthly magnitude for Wind Site 5, and windrose for all sites indicating maximum wind-speed, the duration, and direction. The hydrological resources of the Totara Stream are summarised in section 7.2.3 and include details of the available heads, type of likely in-stream construction required, and the nominal flow rate at each of the three sites assessed. The solar resource (section 7.2.6) is plotted in a diurnal-monthly-magnitude format with the mean, standard deviation, and coefficient of variation shown in this manner.

7.2.1 The Wind Energy Resource

Wind Site 1

The first site to be monitored in Totara Valley was Wind Site 1 (Figure 5.3 and Figure 7.6) which was monitored from 26th February 1999 to 9th June 2001 (Irving, 2000; Murray & Sims, 2001c & 2002). This site had the longest duration of data and became the first reference site in the study. Data was recorded at one-hour averaged values from 26th February 1999 to

2nd August 2000 and then ten-minute mean values from 2nd August 2000 to 9th June 2001¹⁶. The mean wind-speed at Wind Site 1 over one hour averaging periods (from 16,317 hours of data) was 5.61 m/s and over ten minute averaging periods (from 6,175 hours of data) was 5.65 m/s.

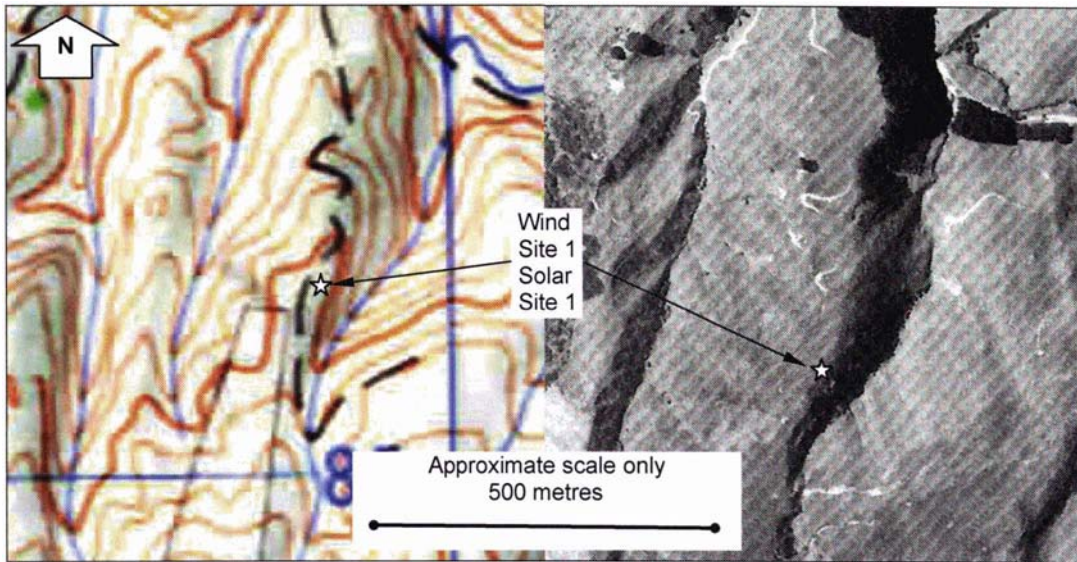


Figure 7.6 Wind site 1, Solar Site 1 location map, and aerial photo illustrating terrain and roughness features.

In the temporal presentation of data (Figure 7.7 to Figure 7.9), the entire duration of monitoring (March 1999 to July 2001) is presented as one hour values of the mean wind-speed, standard deviation, and the coefficient of variation. In Figure 7.7, the hourly mean diurnal – monthly wind velocity patterns show an increasing wind-speed through the day with the peak mean wind-speed usually occurring sometime between 1400 hours and 1900 hours through most of the year.

The months of October, November and December 2000, and April, May 2001 experienced relatively higher hourly mean wind-speeds, especially in the evening. There was also a clear evening peak in the mean wind-speeds evident throughout the duration. The months of August 1999, January, August and September 2000, and February 2001 all had a lower than usual daily mean peak wind-speed.

¹⁶ This one hour averaging period was changed to ten minutes when the NRG Wind Explorer loggers were added to the monitoring programme to monitor Wind Sites 2, 3, 4, and 5.

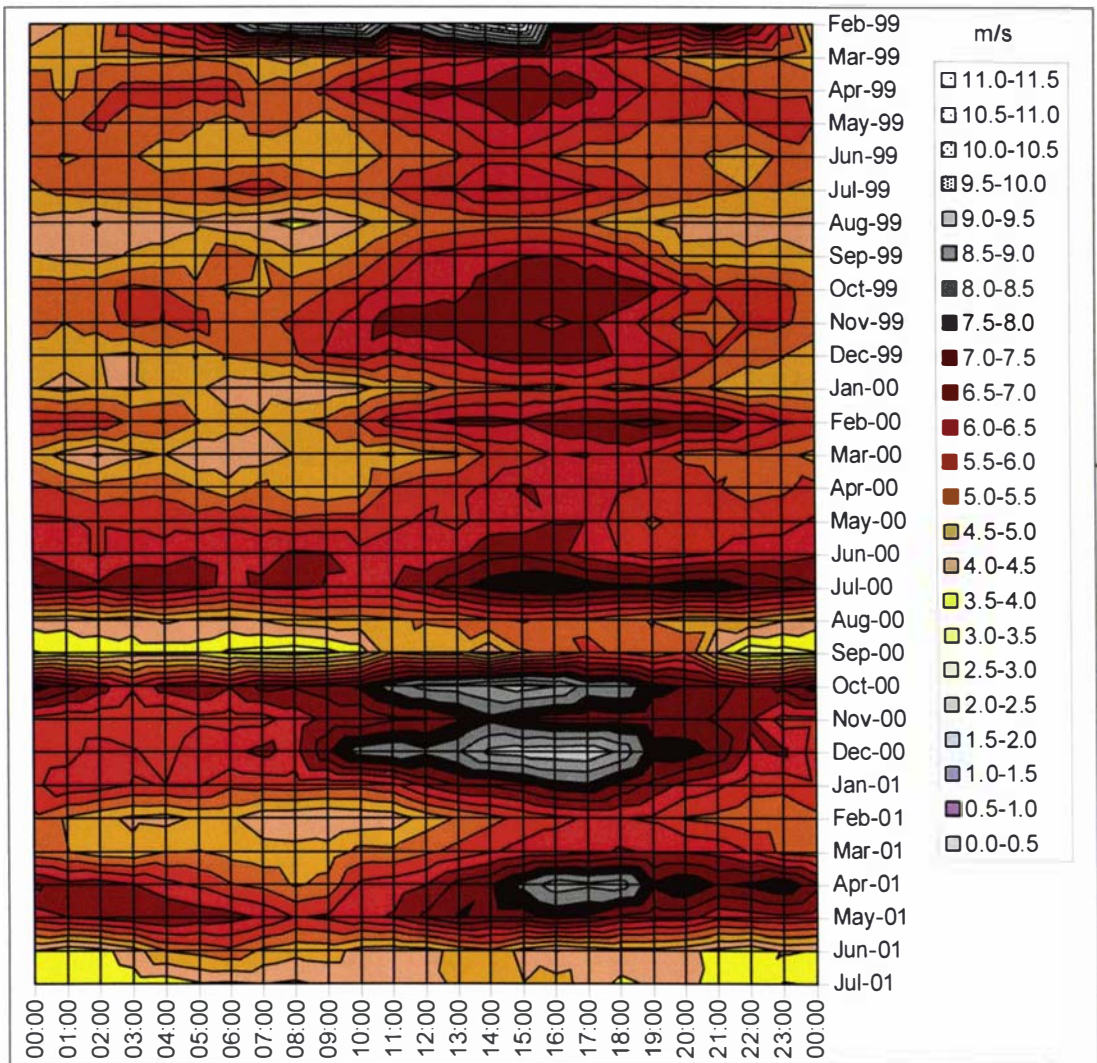


Figure 7.7 Wind Site 1 mean monthly – diurnal hourly wind-speed data for the monitoring duration.

The periods of relatively higher variation about the mean were October 2000 and April – May 2001, and the magnitude of this variation was up to 5.25 m/s (Figure 7.8). October 2000 had a very high standard deviation in the early morning hours. This relatively higher level of variation can also be seen, though at a lesser level throughout most of the monitoring duration.

The coefficient of variation plotted relative levels of variation not seen in the standard deviation plot (Figure 7.9). The late evening (2000 to midnight) and the morning hours (midnight to midday), particularly June, August – October 1999; March, May, August – September 2000; February and April – May 2001, had the highest level of variation of wind-speed (Figure 7.9) of between 50% to 85% of the mean. Overall, the midday period to 2000 hours had a lower relative level of variation of 30% to 50% of the mean.

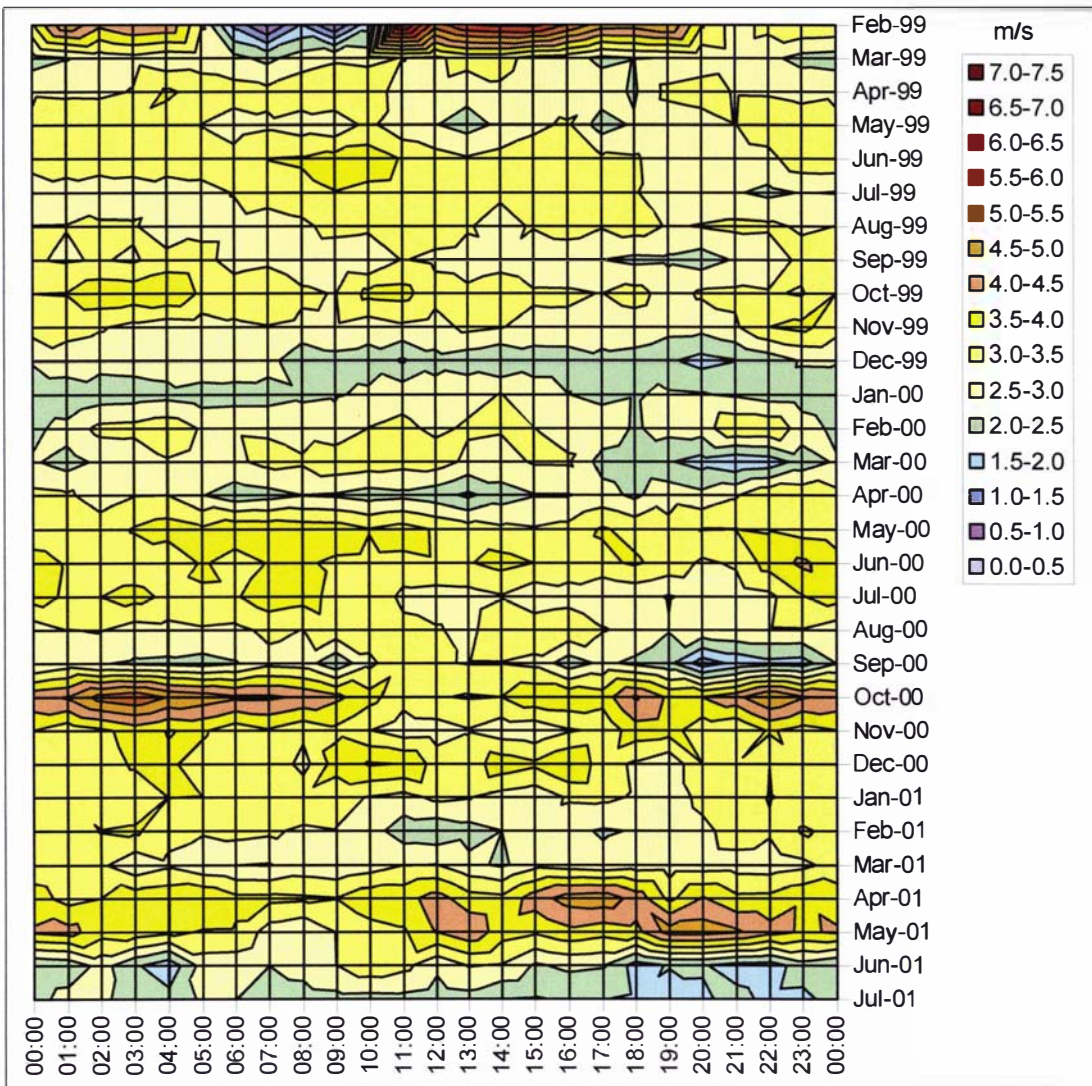


Figure 7.8 Wind Site 1 standard deviation of the hourly mean wind-speed data for the monitoring duration.

Two windrose diagrams were plotted (Figure 7.11 and Figure 7.12) for Wind Site 1 using one-hour mean and ten minute mean periods to indicate the duration of wind-speeds at certain magnitudes and directions. At Site 1 the predominant wind direction was from the west (270°) veering to west-south-west (248°), and the predominant wind-speeds were between 4 m/s and 9 m/s (the space between the intervening wind-speed bands is wider which indicates longer durations at those wind-speeds).

As an alternative to the wind rose plot, a spatial – temporal plot of the mean wind-speeds of each month from 16 points of the compass (Figure 7.10) gave the predominant direction as westerly (270°). This mirrors the overall direction of westerly winds seen in the windrose diagrams throughout the duration of the analysis. June, July and August of 2000 had very strong easterly winds, a direction and magnitude not often experienced in Totara Valley according to the anecdotal evidence of Mr M. Poulton snr, a long-time resident of the area.

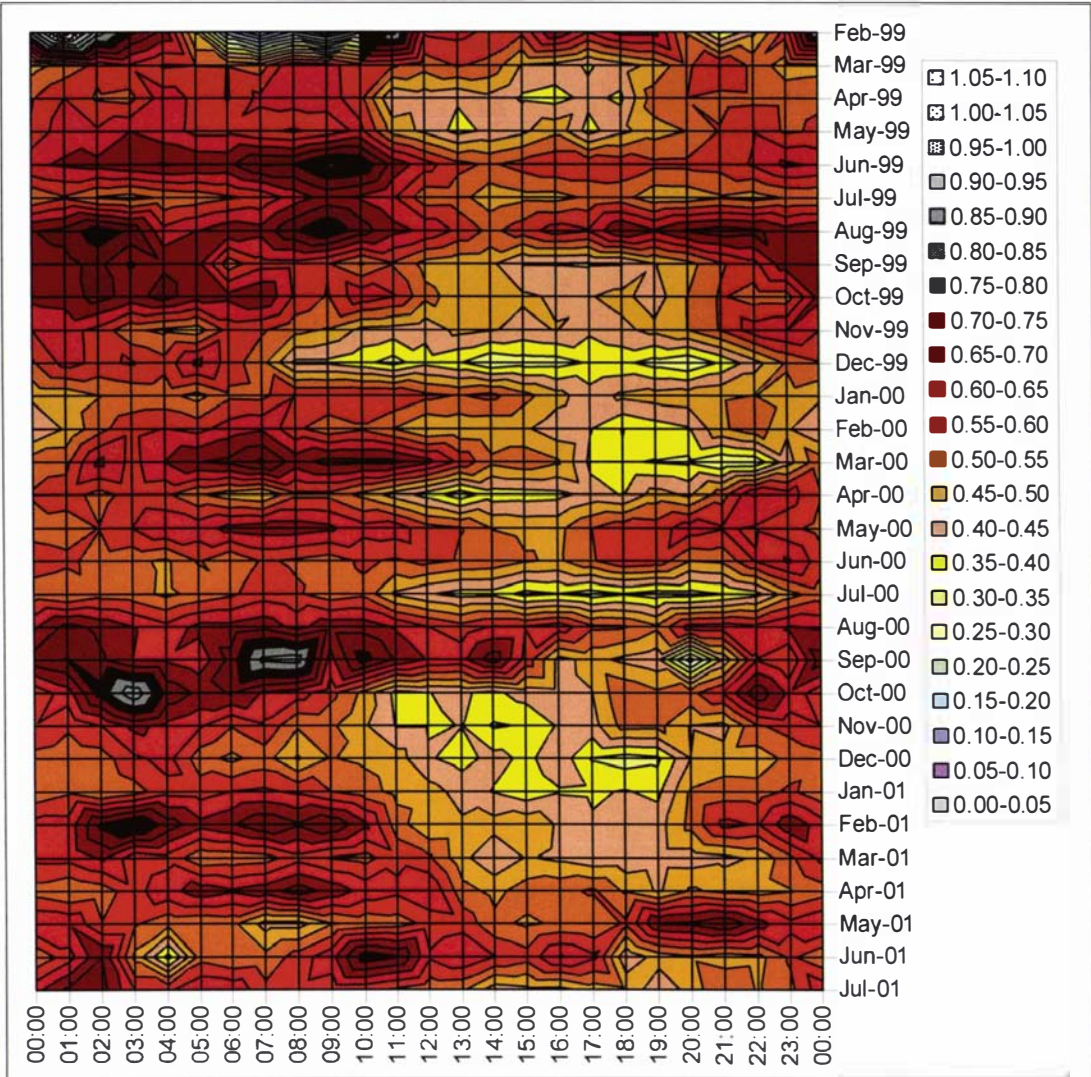


Figure 7.9 Wind Site 1 coefficient of variation of the hourly wind-speed data for the monitoring duration.

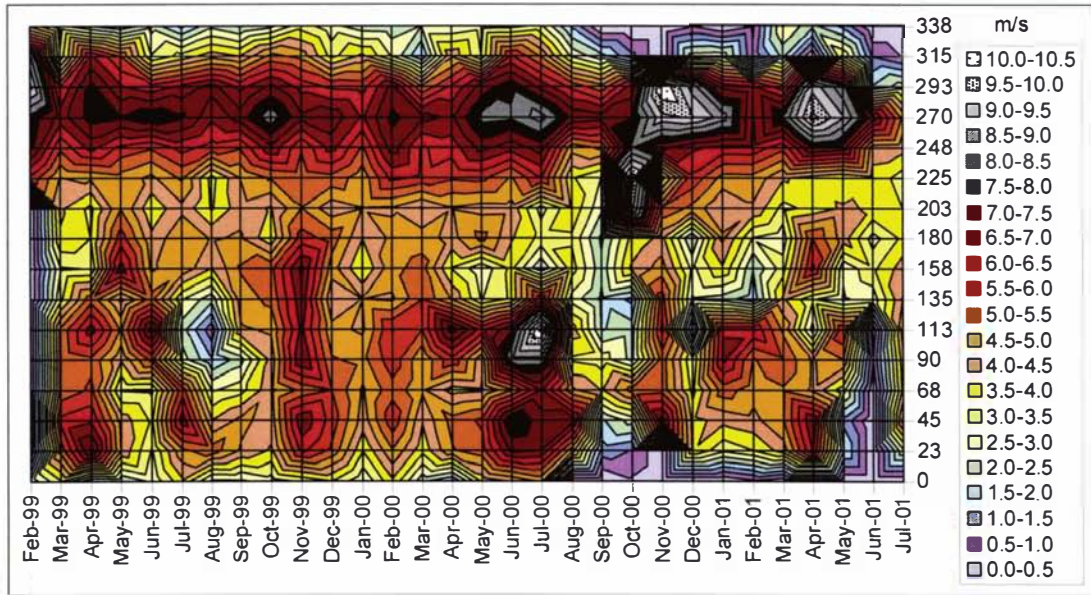


Figure 7.10 Wind Site 1 monthly – spatial mean hourly wind-speed data.

The axial difference between colour-coded inner lines within the windrose (Figure 7.11 and Figure 7.12) represents the duration of time (in multiples of either one hour or ten minutes) at which the wind-speed was at the represented wind-speed from the direction indicated.

The wind speeds indicated (Figure 7.11 and Figure 7.12) will differ from those shown in Figure 7.7 due to the difference between averaging by hour and by direction.

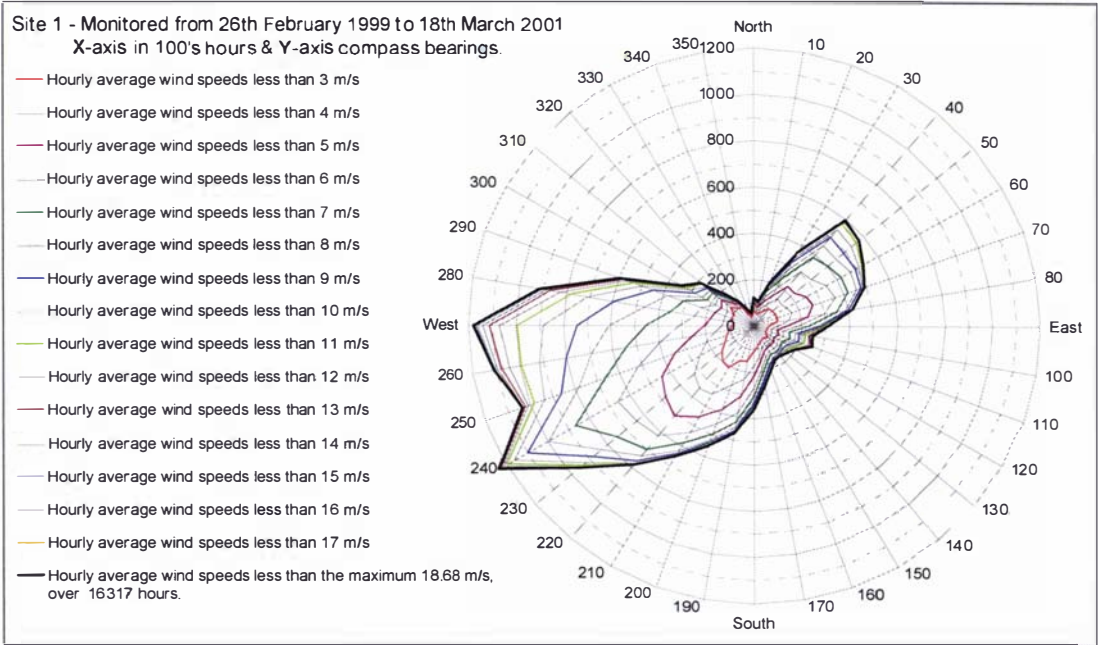


Figure 7.11 Wind Site 1 one-hour mean windrose.

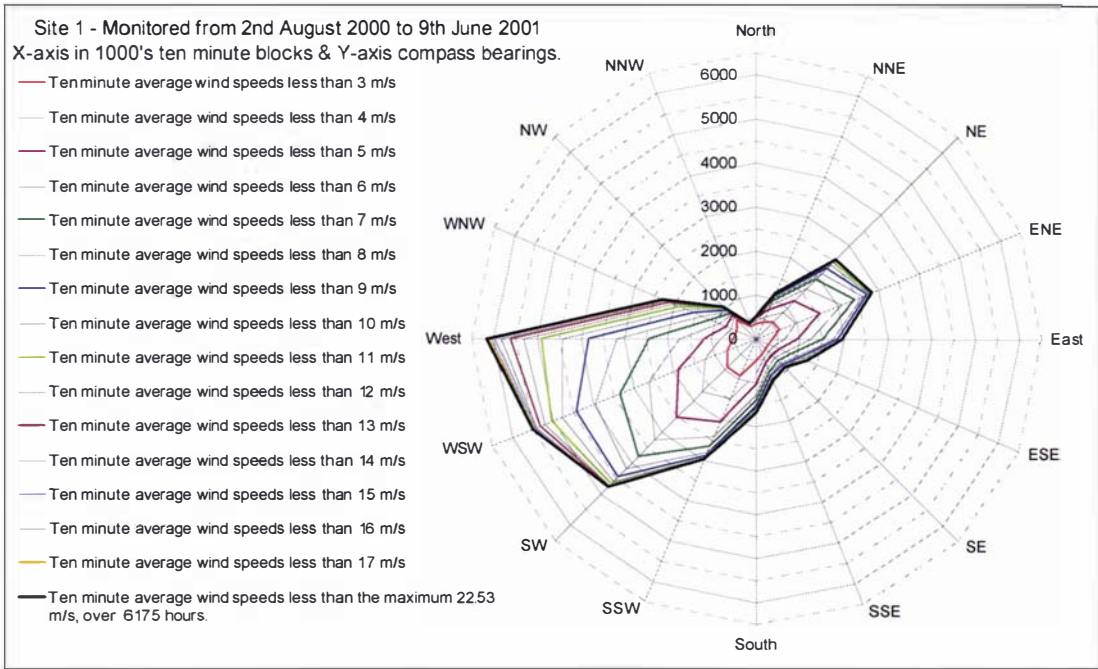


Figure 7.12 Wind Site 1 ten-minute mean windrose.

Wind Site 2

Wind Site 2 (Figure 7.13) was the first of the 'intermediary' mast placements and was in place from 29th July 2000 to 2nd February 2001 recording 1,997 hours of data in ten-minute mean periods. The failure of the anemometer in mid-duration was undiscovered until four months had passed (Figure 7.29). The windrose indicated the predominant direction was west south west (248°) and the mean speed over ten minute averaging periods was 6.04 m/s (Figure 7.14). The 'narrowness' of the wind rose was caused by the channelling of the wind up the adjacent valley to the west of the site (Figure 5.3). There was good four-wheel drive vehicular access to this site in all weathers.

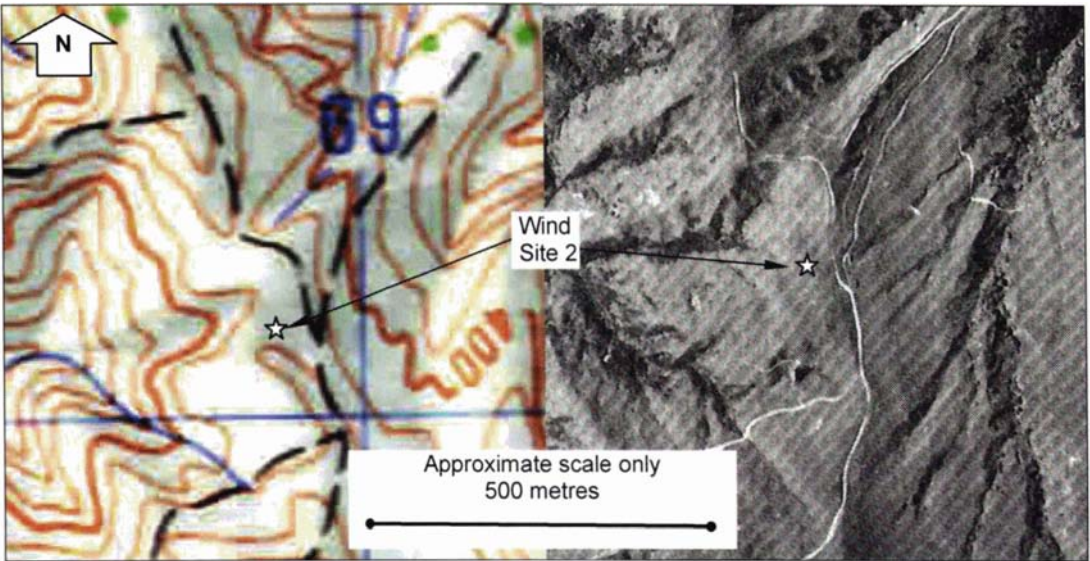


Figure 7.13 Wind Site 2 location map and aerial photo illustrating terrain roughness features.

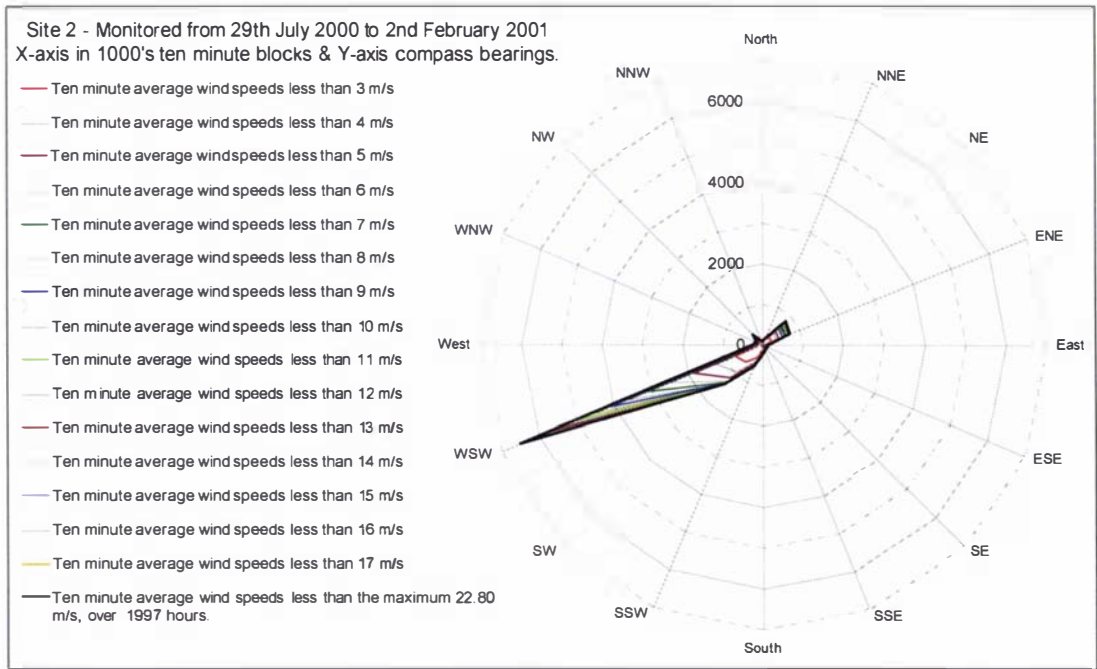


Figure 7.14 Wind Site 2 ten-minute mean windrose.

Wind Site 3

Wind Site 3 (Figure 7.15) was the second of the 'mobile' mast placements in place and recording data from 2nd February 2001 to 30th March 2001 and recorded 1,341 hours of data in ten-minute mean periods. The windrose indicated the predominant direction was north-west (338°) with a mean speed over ten minute averaging periods of 6.27 m/s (Figure 7.16). The 'narrowness' of the wind rose was caused by the channelling of the wind by the valley to the west of the Wind Site 3 (Figure 5.3). There were two good wet weather four-wheel drive vehicular routes available to this site.

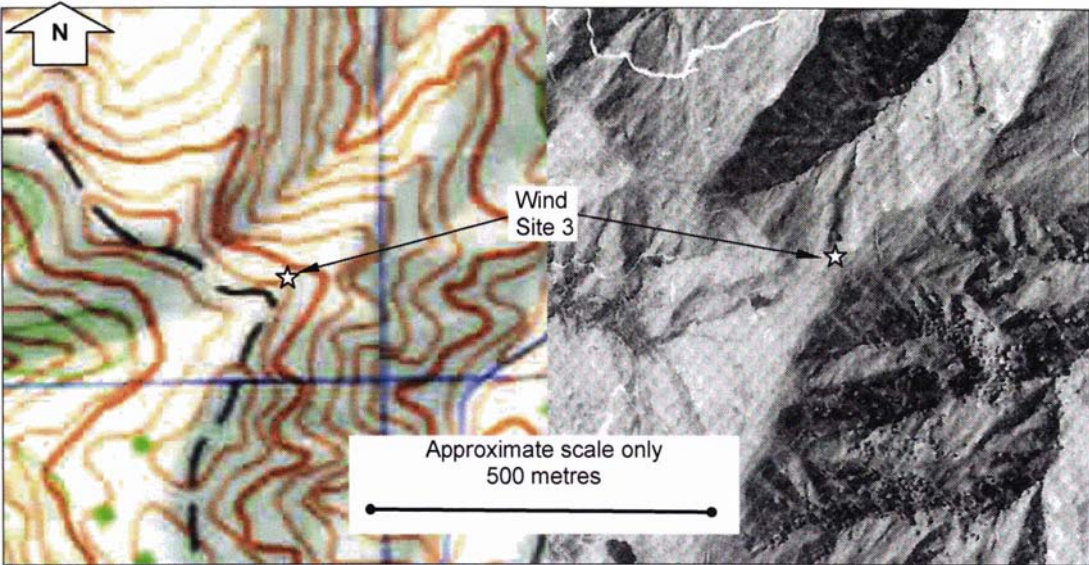


Figure 7.15 Wind Site 3 location map and aerial photo illustrating terrain roughness features.

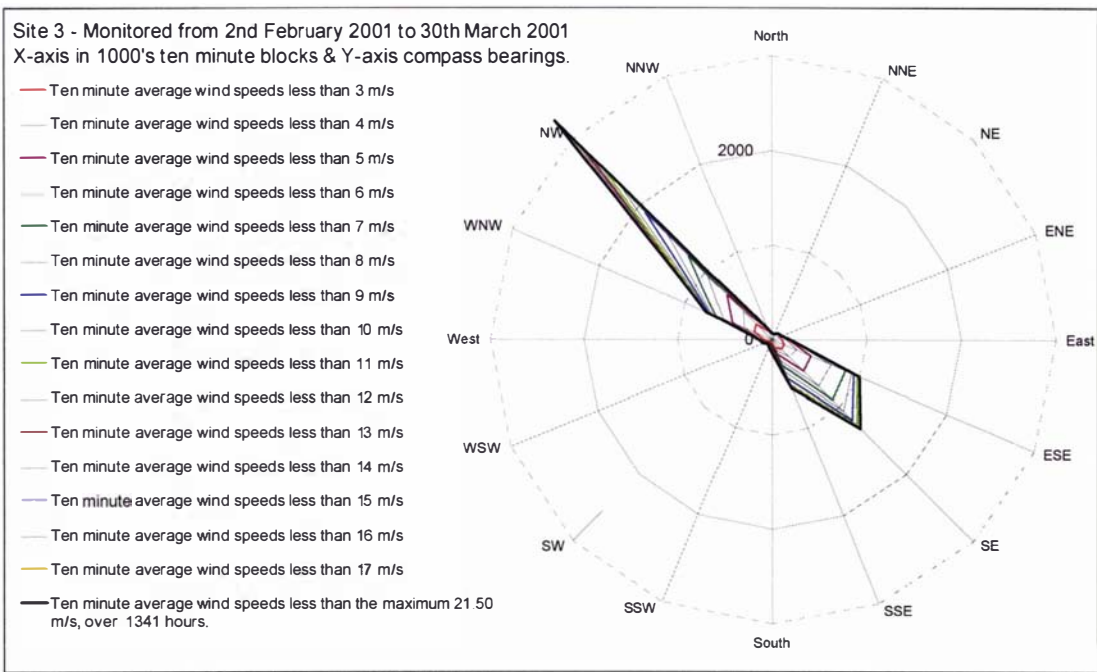


Figure 7.16 Wind Site 3 ten-minute mean windrose.

Wind Site 4

Wind Site 4 (Figure 7.17) was the third and final 'mobile' mast placements in place from 1st April 2001 to 15th December 2001 and recorded 5,147 hours of data in ten-minute mean periods. The windrose indicated the predominant direction was from west-north-west (292°) with a mean speed over ten minute averaging periods of 4.29 m/s (Figure 7.18 and Figure 7.19). The rolling nature of the terrain in the general location of this site would indicate no immediate channelling effect (Figure 5.3). The access to this site required four-wheel drive capability in all weathers.

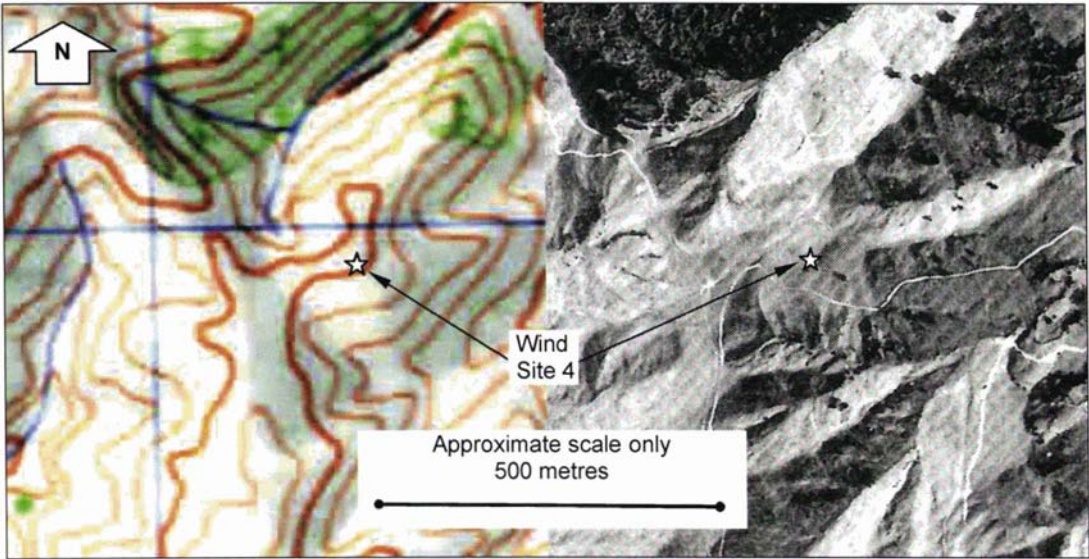


Figure 7.17 Wind Site 4 location map and aerial photo illustrating terrain roughness features.

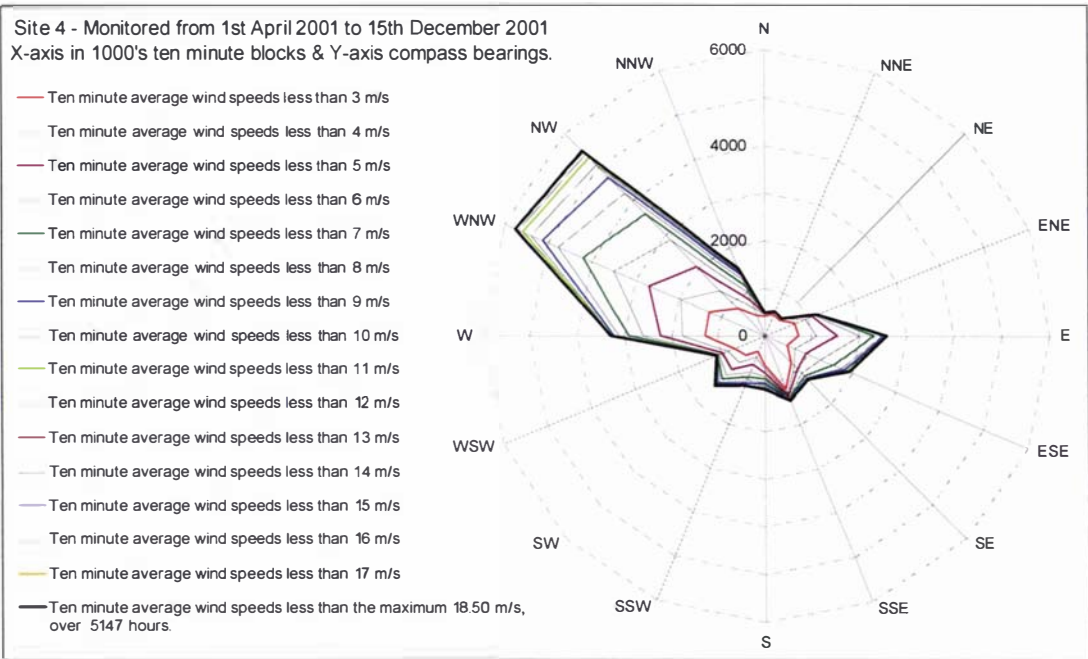


Figure 7.18 Wind Site 4 ten-minute mean windrose.

As an alternative to the wind rose plot, a spatial – temporal plot of the mean wind-speeds of each month from 16 points of the compass (Figure 7.19) gave the predominant direction as north-west (293-315°).

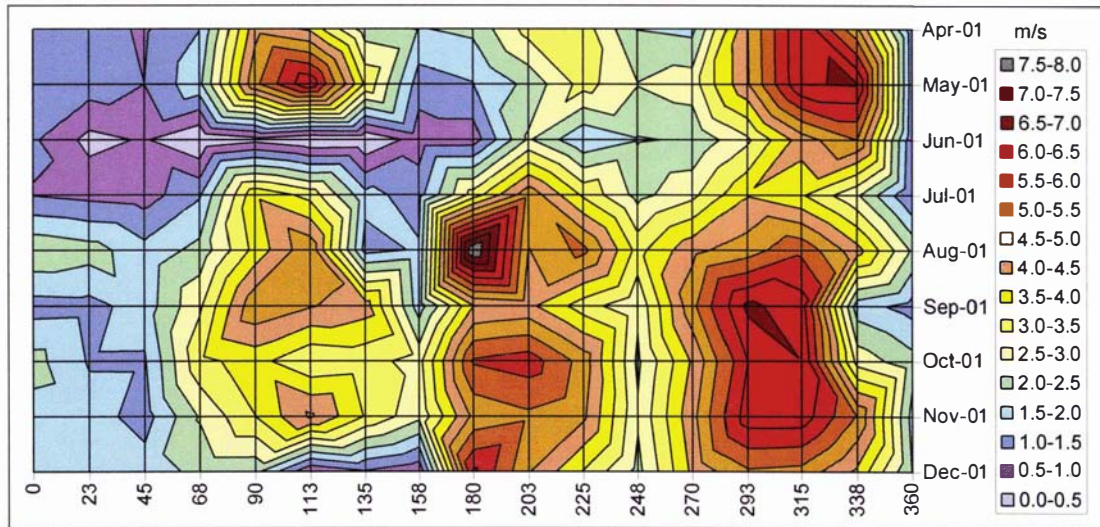


Figure 7.19 Wind Site 4 mean ten-minute monthly – directional – magnitude plot of wind-speed.

Wind Site 5

Wind Site 5 (Figure 7.20), the second of two reference sites, was monitored from 15th April 2001 to 7th March 2002 and recorded 7,004 hours of data in ten-minute mean periods. The mean wind-speed at this site was 5.95 m/s and the windrose indicated the predominant direction was from west-north-west (292°) (Figure 7.24 and Figure 7.25).

The monitoring at this site was actually started four months prior to the stated date but the data from this duration was abandoned after a lightening strike (actual date unknown) caused irreparable instrument damage and thus led to doubts about the data integrity (Figure 7.29). This data was not used in any subsequent analysis. The access to this site requires four-wheel drive in all weathers.

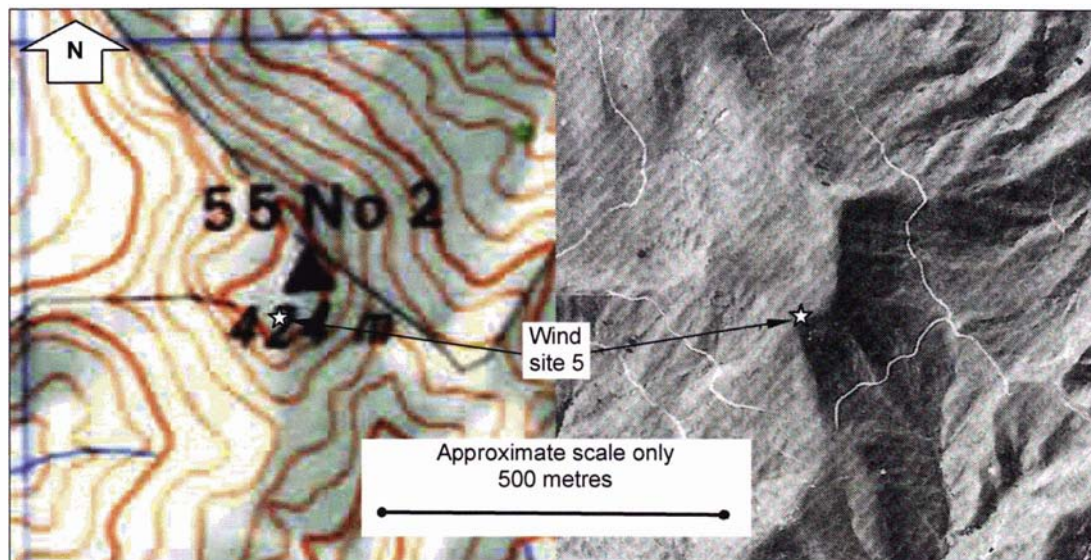


Figure 7.20 Wind Site 5 location map and aerial photo illustrating terrain roughness features.

The recorded Wind Site 5 hourly mean diurnal – monthly wind velocities indicated an increasing wind-speed through the day with a peak mean wind-speed often occurring between 1200 to 1900 hours through the duration monitored (Figure 7.21).

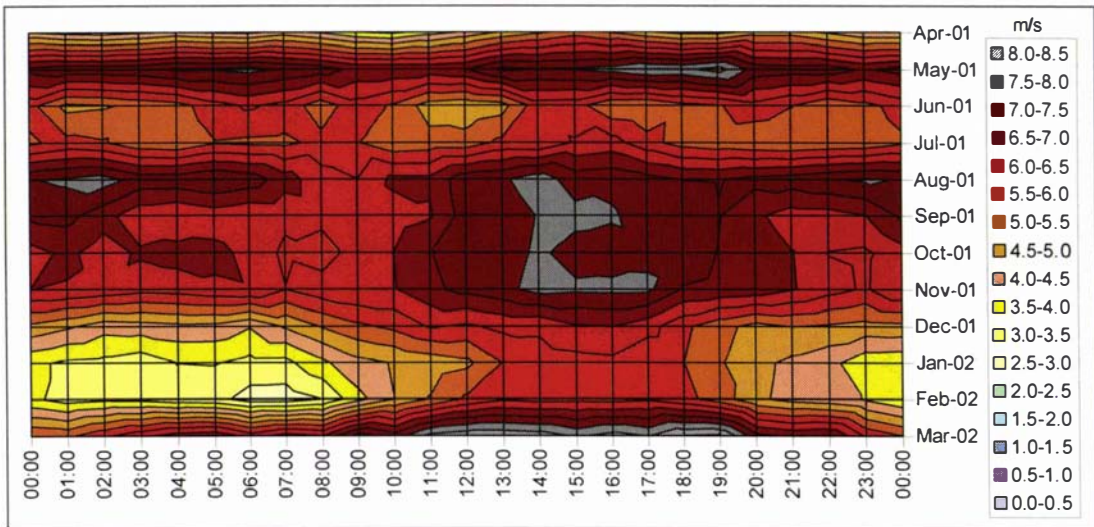


Figure 7.21 Wind Site 5 diurnal – monthly mean hourly wind-speed.

Both the standard deviation and the coefficient of variation plot of the hourly diurnal – monthly variation showed some relatively high variation throughout the year (Figure 7.22 and Figure 7.23). There was a period of higher standard deviation variation (up to 4.5 m/s) around midday from August to October. June had the lower variation (down to 2 m/s) throughout the day whereas May had the highest level of variation (up to 5 m/s). Generally, early morning had the lowest level of wind-speed variation (Figure 7.22). The coefficient of variation indicates relatively high variation in the early summer morning periods, and lower summer afternoon variation. Winter mornings had relatively lower variation with the midday period experiencing relatively higher variation (Figure 7.23).

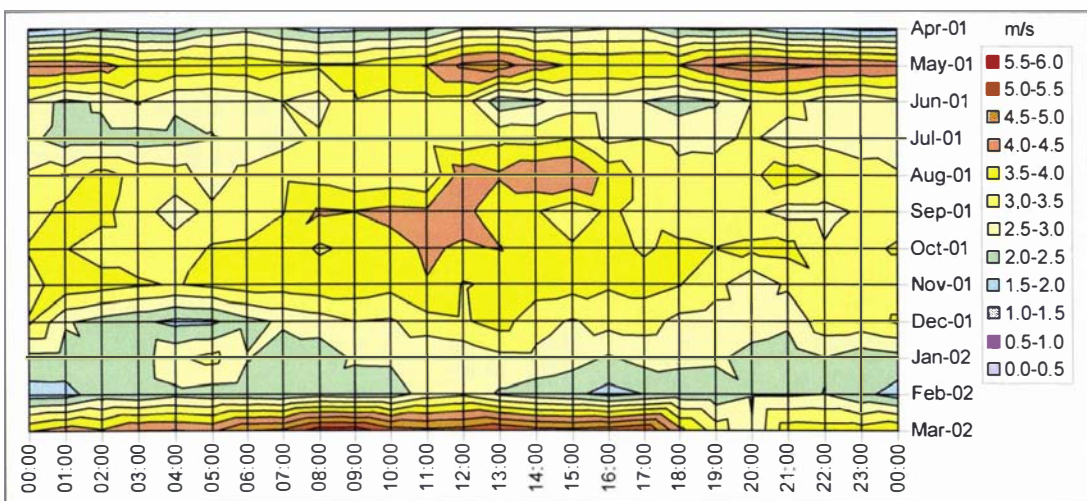


Figure 7.22 Wind Site 5 diurnal – monthly standard deviation of the mean hourly wind-speed.

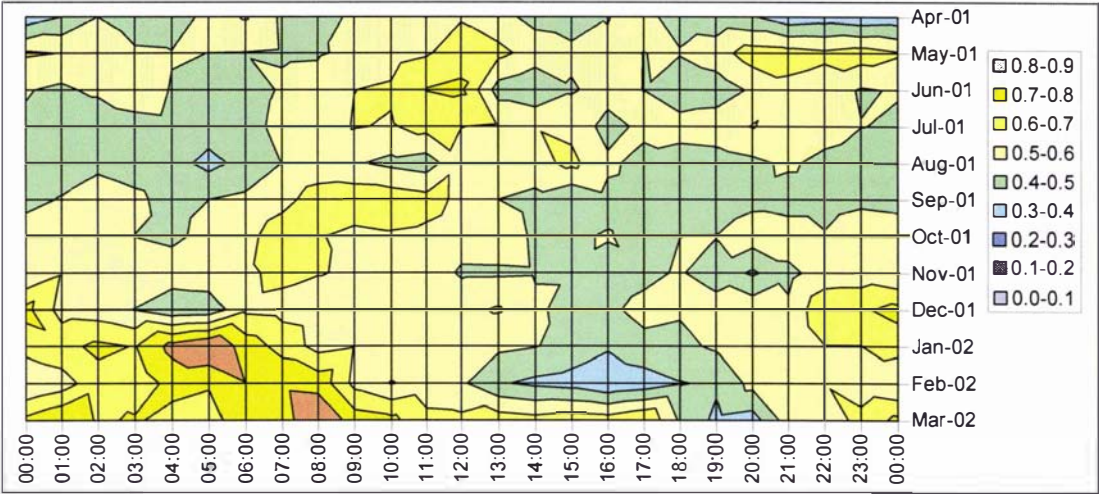


Figure 7.23 Wind Site 5 diurnal – monthly hourly coefficient of variation of the wind-speed.

The windrose for Wind Site 5 (Figure 7.24) and the plot of direction indicated a predominant west-north west-direction (292°), and the most frequent wind-speeds between 4 m/s and 10 m/s (the spaces between the intervening wind-speed bands were wider and therefore indicated a longer duration at those wind-speeds).

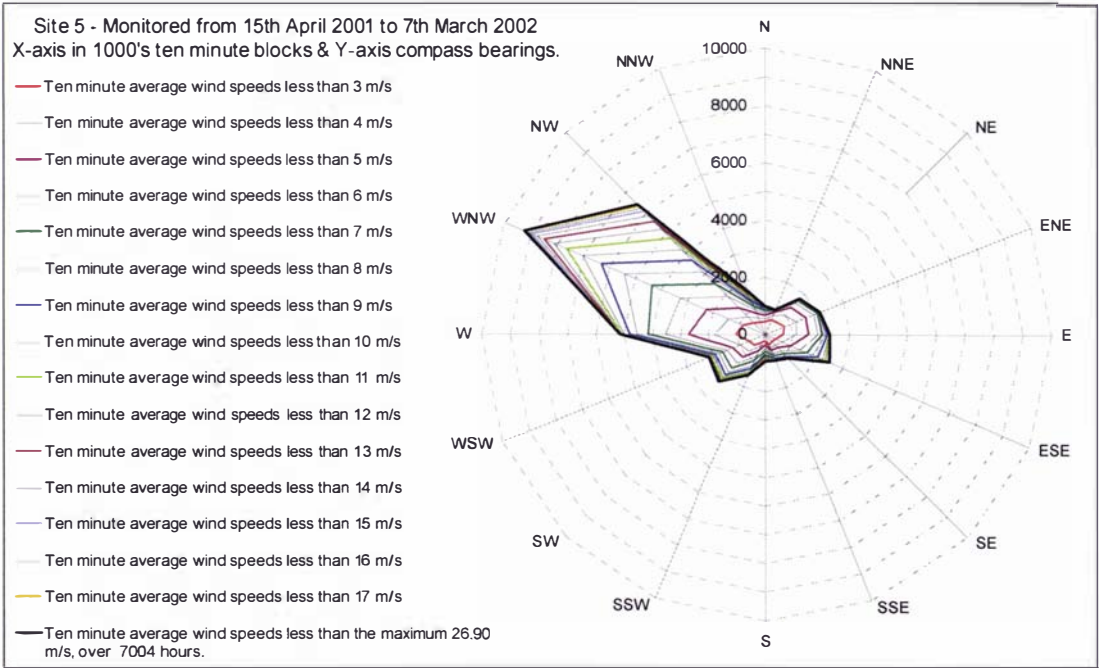


Figure 7.24 Wind Site 5 ten-minute mean windrose.

As an alternative to the wind rose plot, a spatial – temporal plot of the mean wind-speeds of each month from 16 points of the compass (Figure 7.25) gave the predominant direction as westerly (270°).

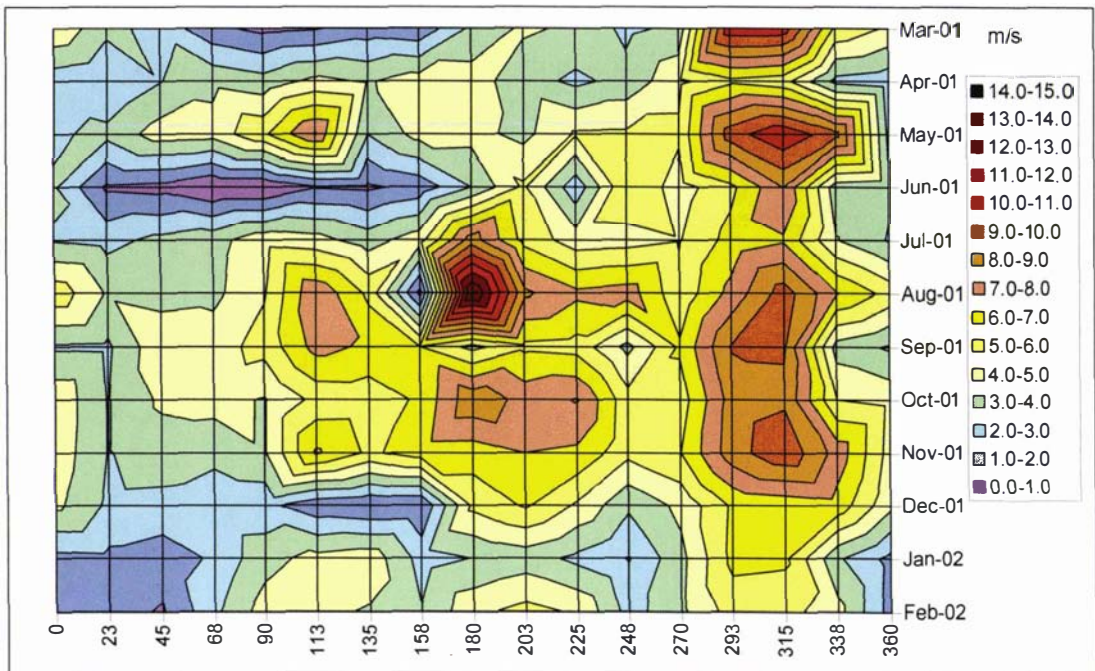


Figure 7.25 Wind Site 5 mean ten-minute monthly – directional – magnitude plot of wind-speed.

7.2.2 Wind Site Comparison Wind Rose

An important aspect of wind modelling (Chapter 8) needing consideration was the effect the complex terrain had over the wind-speed and directions. A simple initial windrose analysis compared Site 1 with each of Site 2, Site 3, and Sites 4 and 5 separately over simultaneous durations. From the simultaneous period of monitoring of Sites 1 and 2 (Figure 7.26) it was clear that a terrain effect was channelling the wind at Wind Site 2 parallel to Wind Site 1. A result from this channelling was a slight increase in both mean and maximum wind-speeds at this site as the wind was forced through a narrow 'saddle' at the end of the valley.

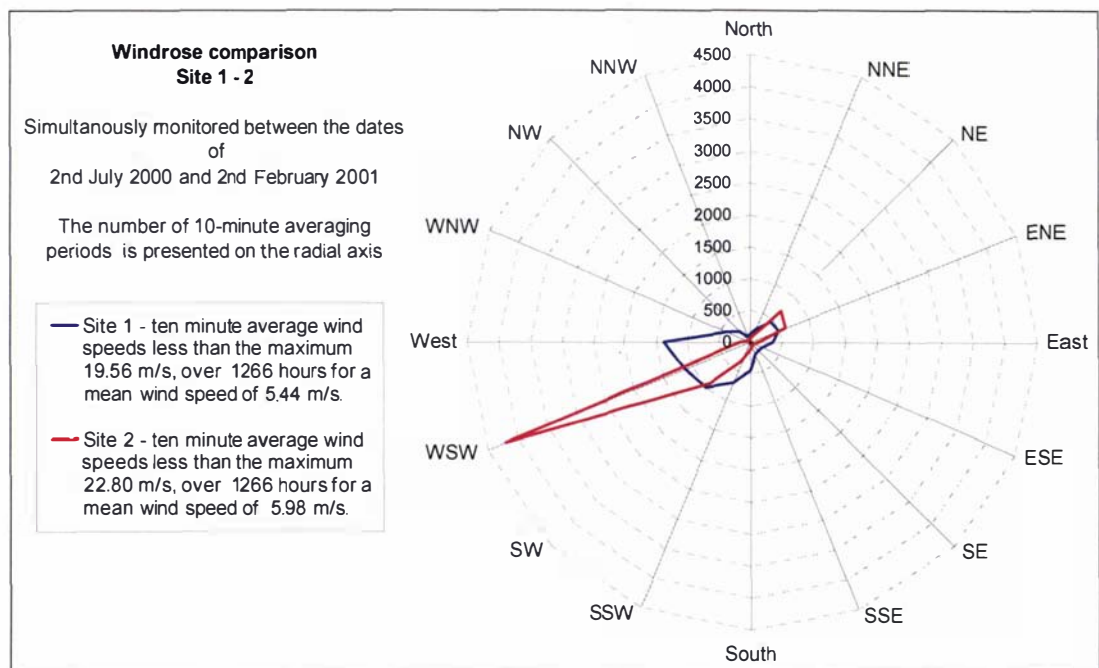


Figure 7.26 The comparison windrose between Wind Sites 1 and 2.

From the simultaneous period of monitoring of Sites 1 and 3 (Figure 7.27) it was clear that a terrain effect was channelling the wind at Wind Site 3 in a very different direction from Wind Site 1. A result of this was a slight increase in both mean and maximum wind-speeds at this site, also due to the channelling through a narrow area.

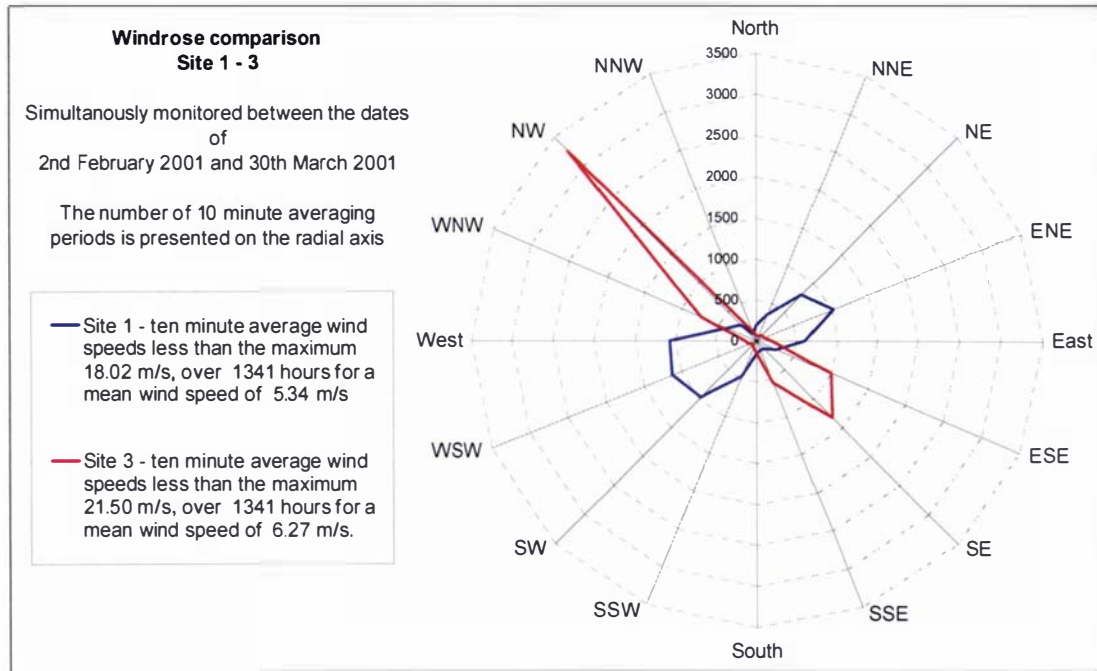


Figure 7.27 The comparison windrose between Wind Sites 1 and 3.

From the results of the simultaneous period of monitoring of Sites 1, 4 and 5 (Figure 7.28) there was only a small amount of terrain effect channelling visible as compared to other sites. Awareness of this channelling will be required when modelling the wind-speed atlas with WAsP (Chapter 8).

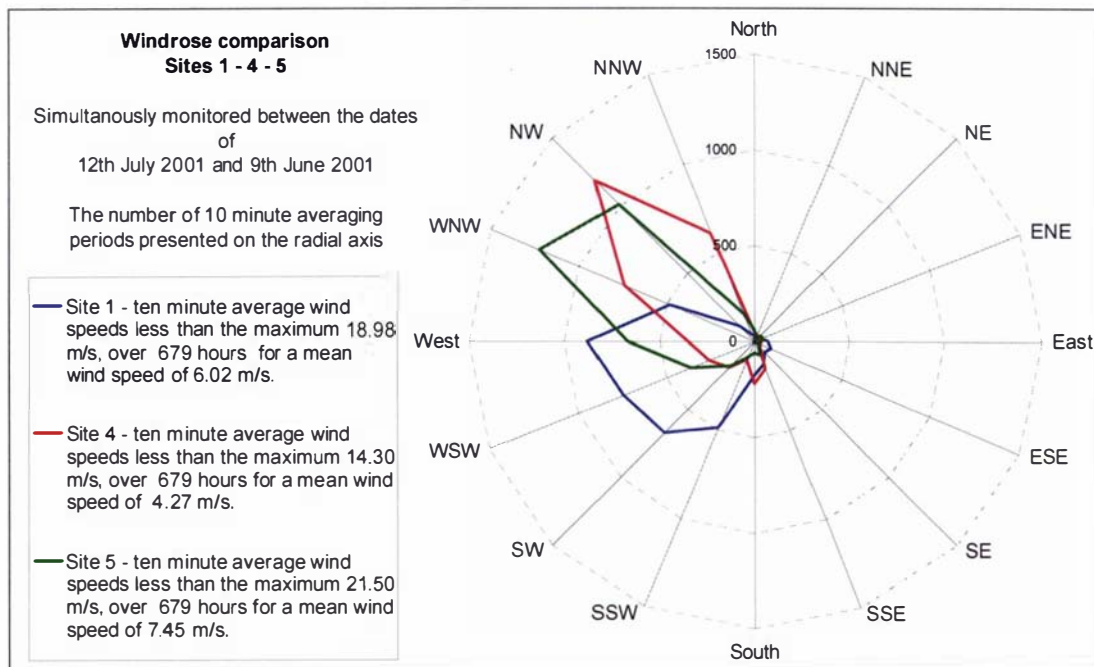


Figure 7.28 The comparison windrose between Wind Sites 1, 4 and 5.

The direction and shape of Wind Site 1 (Figure 7.26 to Figure 7.28) varied because each period of simultaneous readings was for a different site and therefore represented different wind data.

7.2.3 Wind Site Monitoring Time-Line

The wind resources were monitored in the chronological order as indicated (Figure 7.29). The monthly mean wind-speeds as displayed indicate an approximation of the site-to-site correlation of the wind-speeds. Site 2 and Site 5 each experienced monitoring instrument failure – Site 2 mid-duration, and Site 5 from December 2000 to April 2001.

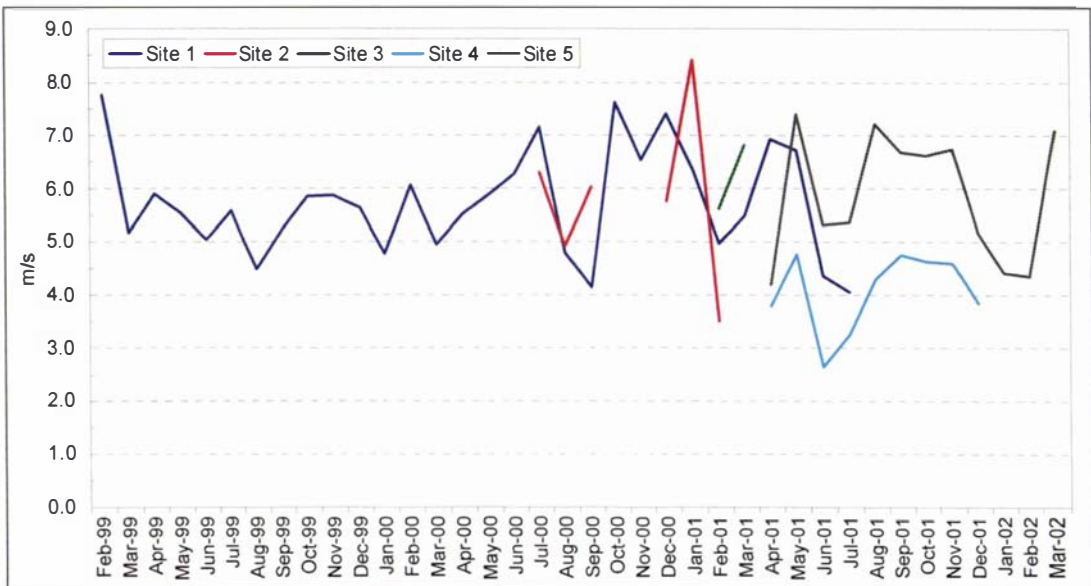


Figure 7.29 The wind monitoring time-line with the monthly mean wind-speeds in chronological order of measurement.

7.2.4 NIWA Data

The National Institute of Water and Atmospheric Research (NIWA) maintains a user-pays database of national wind related data. For comparative purposes, the wind speed profiles for 1997 to 2000 of Ohakea, Palmerston North, and Waione (Figure 7.30) were drawn from this database and the differences can be noted between the Totara Valley dataset and these data (Figure 7.31). The mean profiles were calculated and will be of use in the short-term duration model (Figure 7.32). There was a good level of cross-correlation between Ohakea and Palmerston North and only moderate levels of correlation between Totara Valley and the other locations (Table 7.2).

Table 7.2 Cross-correlation statistics for the Ohakea, Palmerston North, Waione, and Totara Valley data.

	Ohakea	Palmerston North	Waione	Totara Valley
Ohakea	1.00			
Palmerston North	0.96	1.00		
Waione	0.66	0.80	1.00	
Totara Valley	0.57	0.60	0.51	1.00

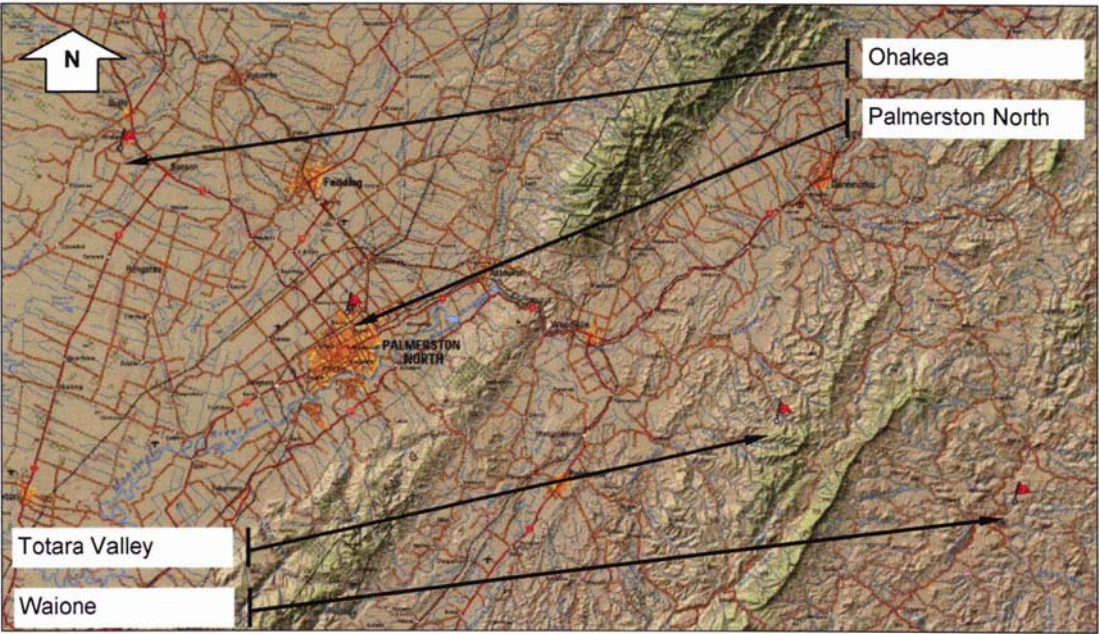


Figure 7.30 Locations of the comparison wind sites Ohakea, Palmerston North, and Waione relative to Site 1 Totara Valley.

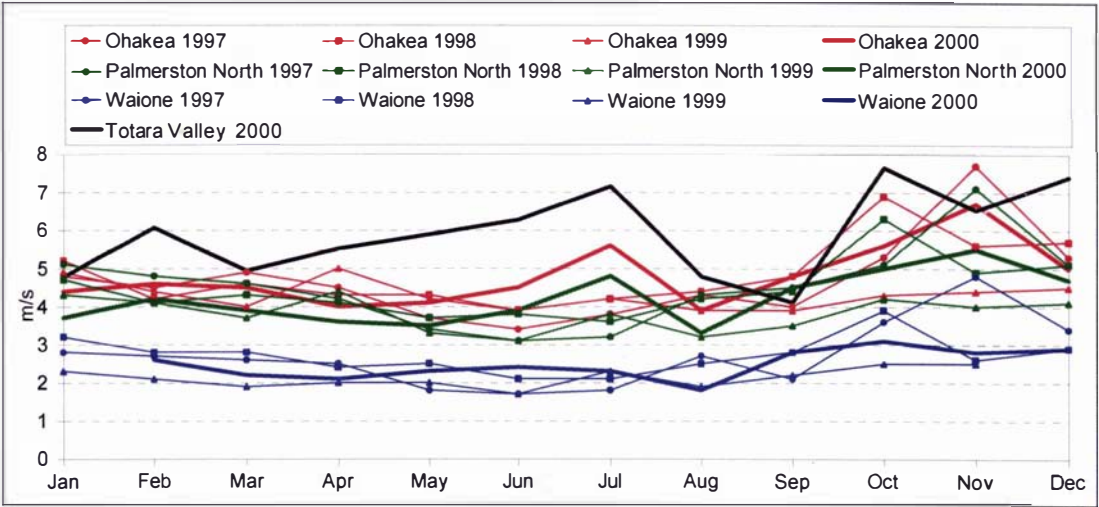


Figure 7.31 Comparative analysis of the mean monthly wind speeds between Ohakea, Palmerston North, Waione, and Totara Valley for 1997 to 2000.

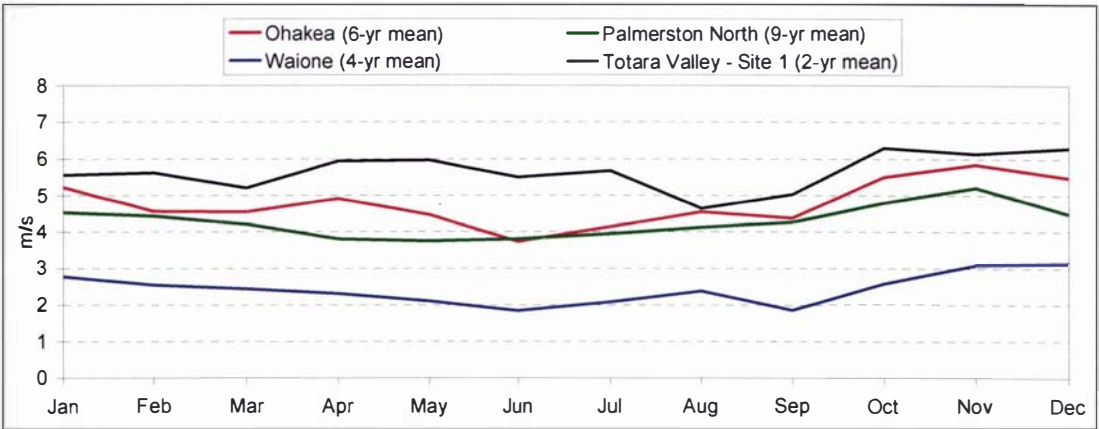


Figure 7.32 The mean monthly wind speeds of Ohakea, Palmerston North, and Waione, and for comparative purposes, Totara Valley (Site 1).

Also available is the NIWA CD-ROM from which a sample output is given in Figure 7.33 as the median wind-speed map for the lower North Island of New Zealand.

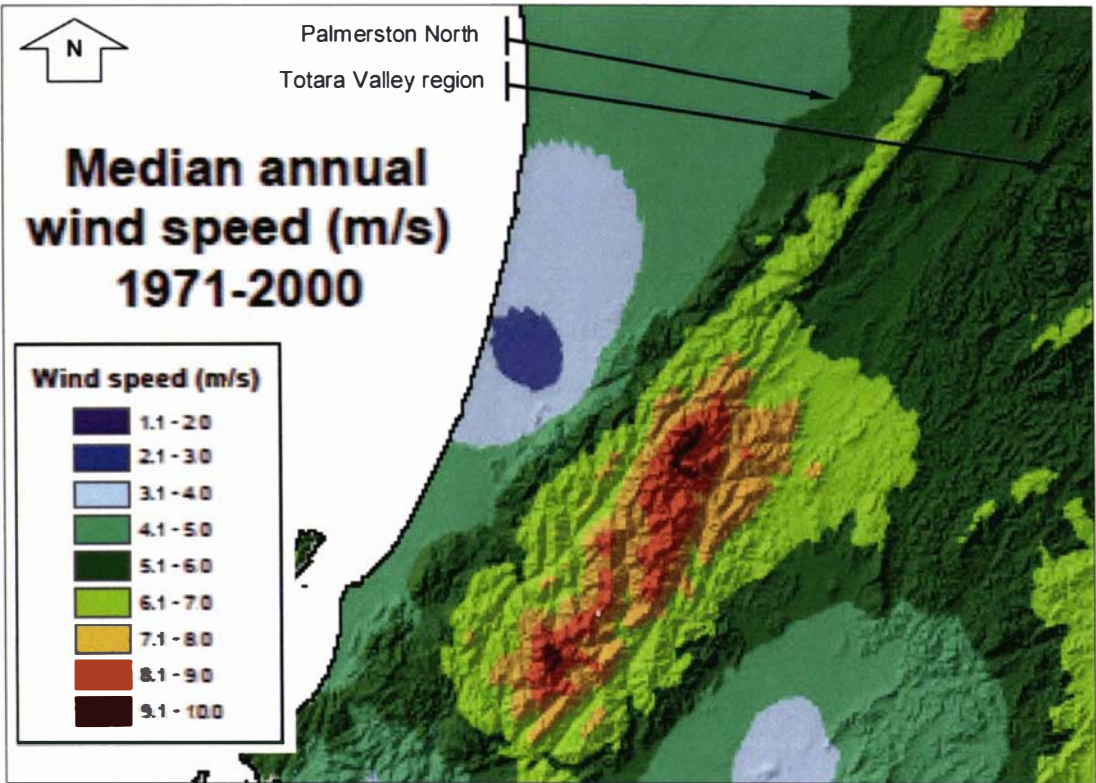


Figure 7.33 Median wind-speed data for the lower North Island from the NIWA data set.

Source: Dr. Andrew Tait (Personal communication, January 2005).

7.2.5 The Hydrological Energy Resources

Hydro Site 1

The results of a series of stream flow assessments at Hydro Site 1 – Farm 1 (Figure 5.3 & Figure 7.34) in January and March 2000 indicated a summer low-level flow rate of the Totara Stream of approximately 46 ℓ/s and 50 ℓ/s respectively. An assessment of a stable winter stream flow rate in August 2000 indicated a flow rate of 195 ℓ/s . Measurement details are given in Appendix G – 19.1.

A potential earth dam site already exists for a dam approximately three metres high to feed a penstock of 300 mm diameter PVC pipe (A – Figure 7.35). The unstable flood plains indicate the exact streambed location could vary so a relatively safe powerhouse site could be located just downstream of the culvert (B – Figure 7.35). The approximate cable distance from the generation source to the load would be 100 metres.

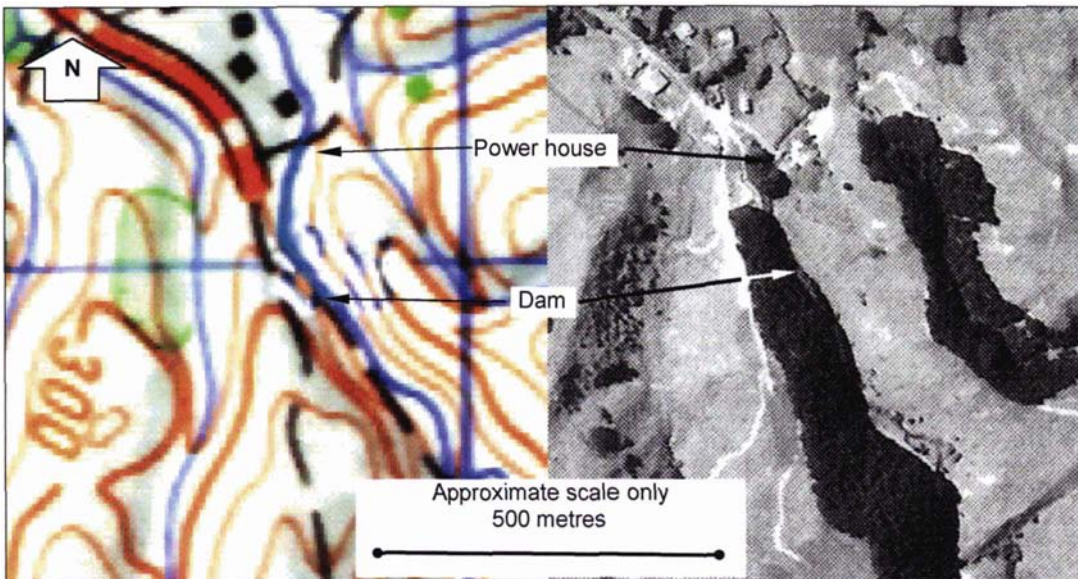


Figure 7.34 The Hydro Site 1 on Farm 1 location map and aerial photo illustrating infrastructure locations.

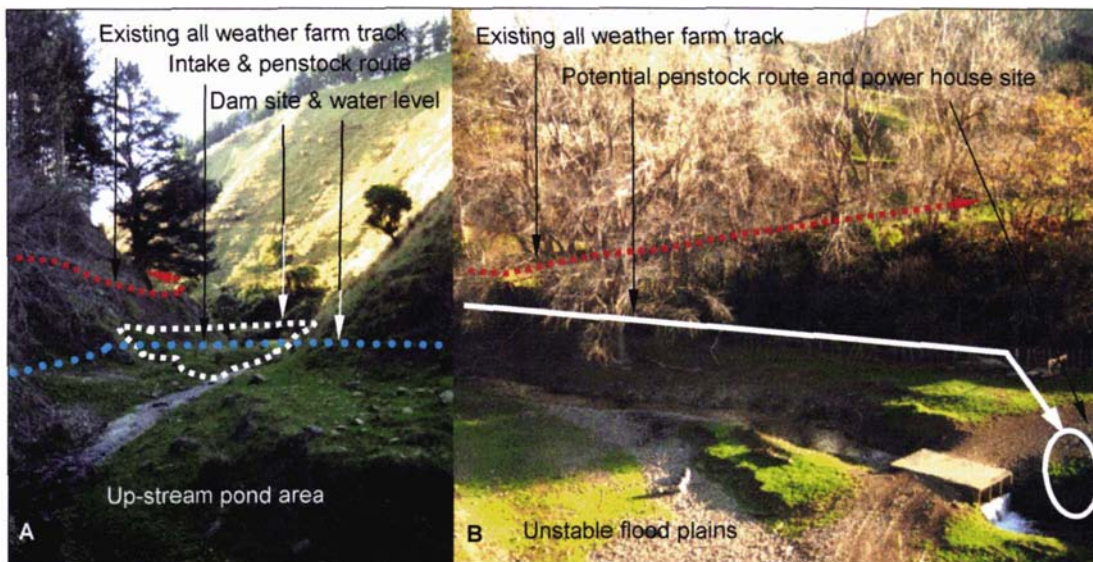


Figure 7.35 The Hydro Site 1 potential dam site (A) with supporting infrastructure locations (B).

Hydro Site 2

The results of hydrological resource assessment at Site 2 – Farm 3 (Figure 5.3) in January and March 2000 indicated a summer low-level flow rate in Totara Stream of approximately 47 l/s and 51 l/s respectively. Measurement details are provided in Appendix G – 19.1.

Site 2 on Farm 3 (Figure 5.3 & Figure 7.36) was situated at the site of a tight 'ox-bow' or switchback, a characteristic of which is the small distance between the stream flows of opposite direction (Figure 7.37). A nominal two-metre head of water would be available over a short horizontal distance. The diversion weir would divert water into a penstock that was either placed around the point of land as indicated or was 'bored' through the ground to the potential power house and draft tube two metres below the intake height.

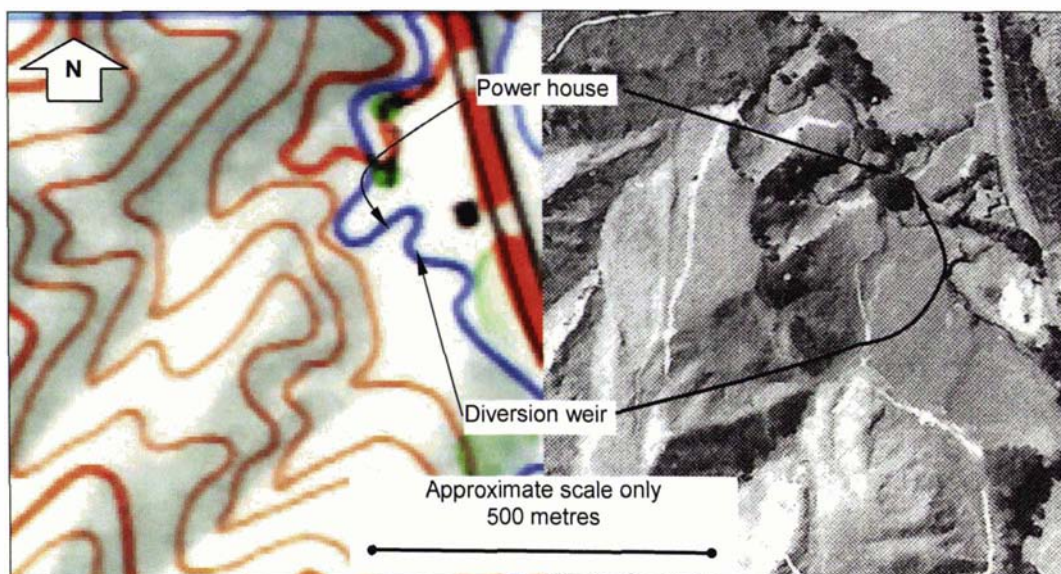


Figure 7.36 The Hydro Site 2 on Farm 3 location map and aerial photo illustrating infrastructure locations.

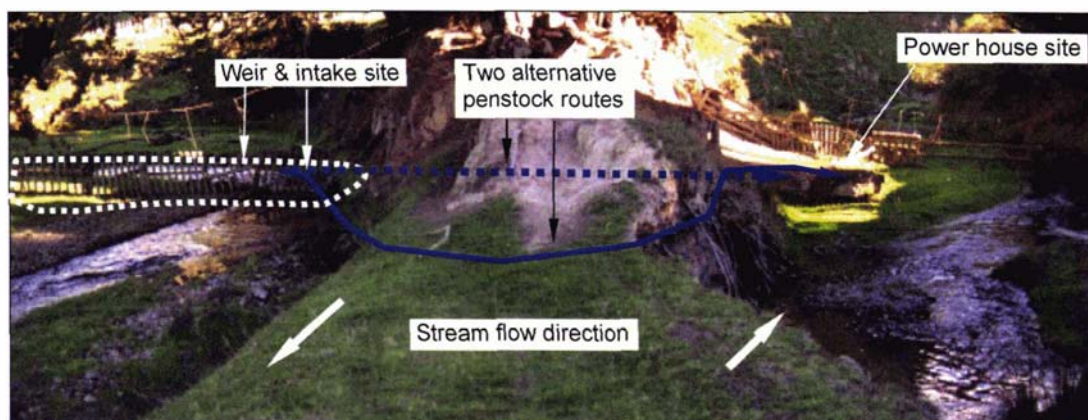


Figure 7.37 The Hydro Site 2 where the characteristic small 'neck' of the ox-bow means there was a small head difference over a short horizontal distance.

The potential diversion weir, intake, and penstock routes are indicated (Figure 7.37), as is the location of a powerhouse site. If the turbine used had a draft tube attached the powerhouse may be located above possible flood levels for security. The entire hydro infrastructure would be on the opposite side of the stream from any good wet weather access track so, providing the stream was not in flood, access would be good. Site 2 would have a nominal head of two metres available if a diversion weir was to be built on the upstream oxbow section. The approximate cable distance from the generation source to the load would be 70 metres.

Hydro Site 3

The results of hydrological resource assessment at Hydro Site 3 – Farm 3 (Figure 5.3) in January and March 2000 indicated a summer low-level flow rate of approximately 49 ℓ/s and 52 ℓ/s respectively. Measurement details are given in Appendix G – 19.1.

Site 3 would have a nominal head of 2 metres available if a diversion weir was built 50 metres upstream of the powerhouse site (Figure 7.38). The diversion weir and intake

infrastructure would not be accessible if the stream was flooded but the access to the powerhouse site would be good in all weather. The approximate cable distance from the generation source to the load would be 200 metres.

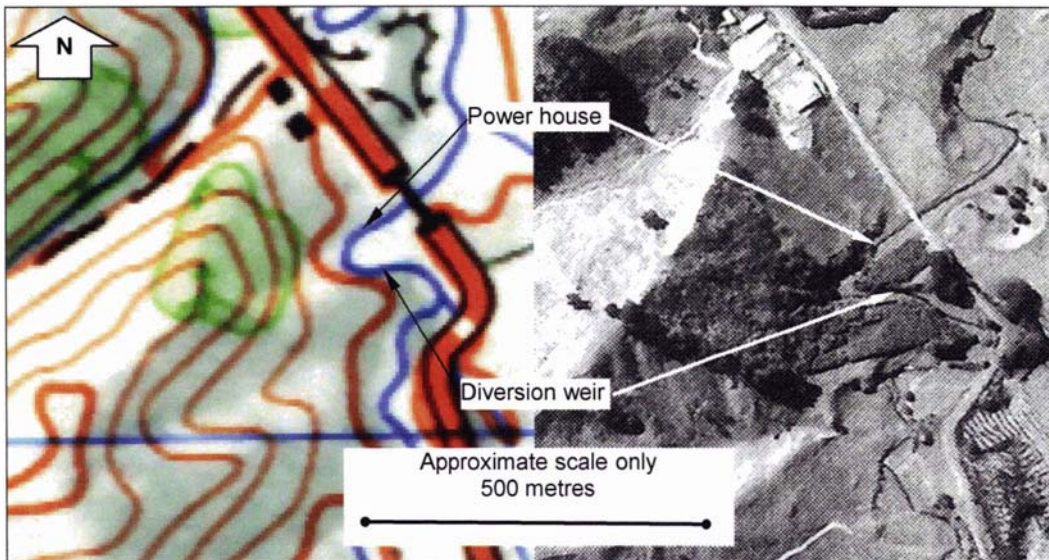


Figure 7.38 The Hydro Site 3 on Farm 3 location map and aerial photo illustrating infrastructure locations.

7.2.6 The Solar Energy Resource

The pyranometer of Solar Site 1 was located on the anemometer mast of Wind Site 1 (Figure 7.6). The mean solar resource plot of Solar Site 1 (Figure 7.39) indicated a typical seasonal solar insolation 'map' in shape if not in magnitude for many areas of New Zealand. Data was recorded in one-hour averaged values from 26th February 1999 to 2nd August 2000 and then ten-minute mean values to 9th June 2001. The data from January 2000 to December 2000 was used in the HOMER modelling.

The mean peak solar insolation of between 600 – 650 W/m² occurred in January (1300 to 1400 hours). The lowest mean winter peak was 200 – 250 W/m² and occurred in June and July (1200 to 1400 hours). Although the standard deviation was the usual measure of variation (Figure 7.40), the highest level of variation was in the morning and evening hours as indicated by the coefficient of variation (Figure 7.41).

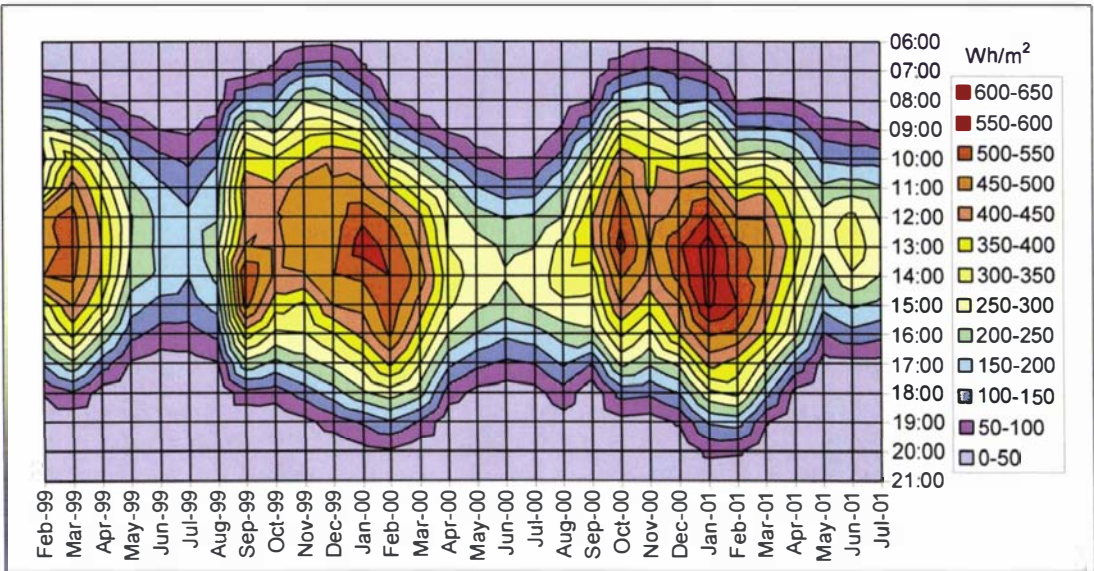


Figure 7.39 Mean solar resource levels through the duration of the monitoring.

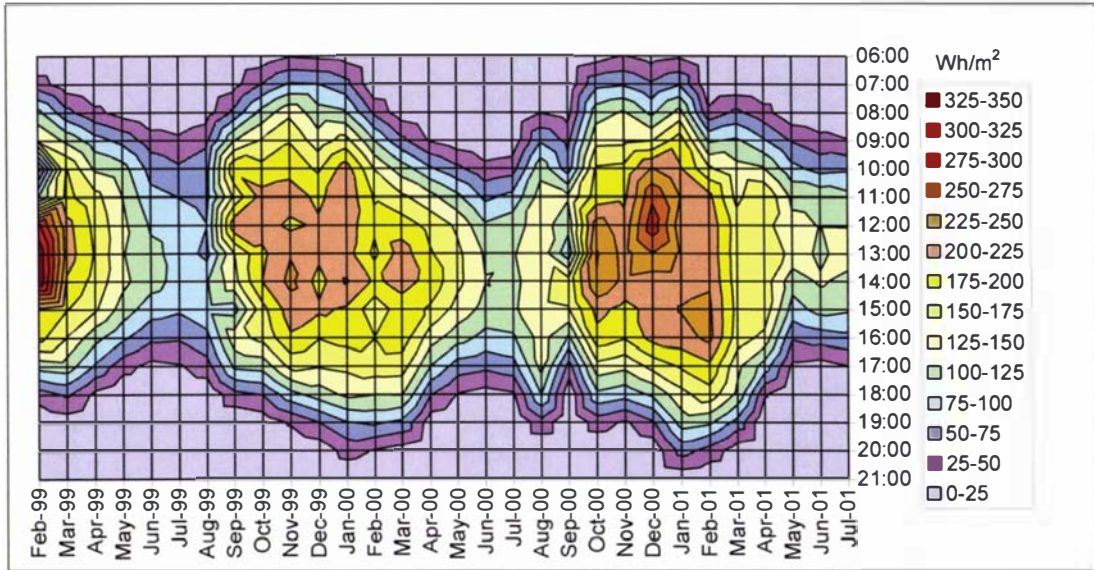


Figure 7.40 Standard deviation of the solar resource levels over the duration of the monitoring.

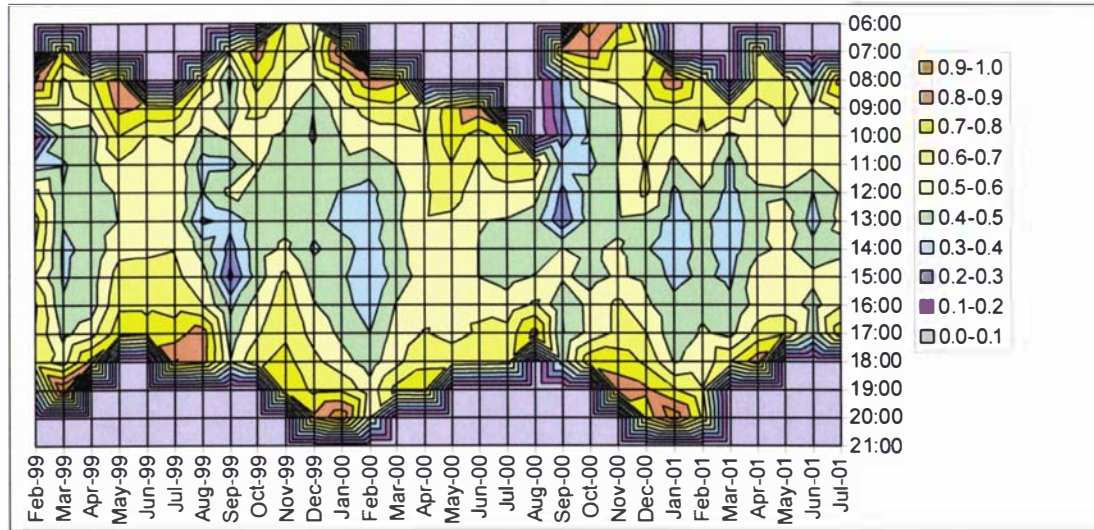


Figure 7.41 Coefficient of variation of the solar resource over the duration of the monitoring.

As Solar Site 1 was at a high altitude relative to the surrounding hills, it was unobstructed with only very early morning and very late evening shading from adjacent hills. However the Load Sites 1 – 6 in the valley floor where solar photovoltaic (PV) is likely to be used will remain shaded later in the morning and earlier in the afternoon/evening by the hills. The extent of this shading was estimated through anecdote and observation by the author (Figure 7.42). Valley shading may not be an issue as it depends greatly on the steepness of the surrounding terrain and the orientation of the valley relative to the solar geometry. Local shading from trees, neighbouring dwellings, and other restrictions to clear solar access may be greater issues in other locations.

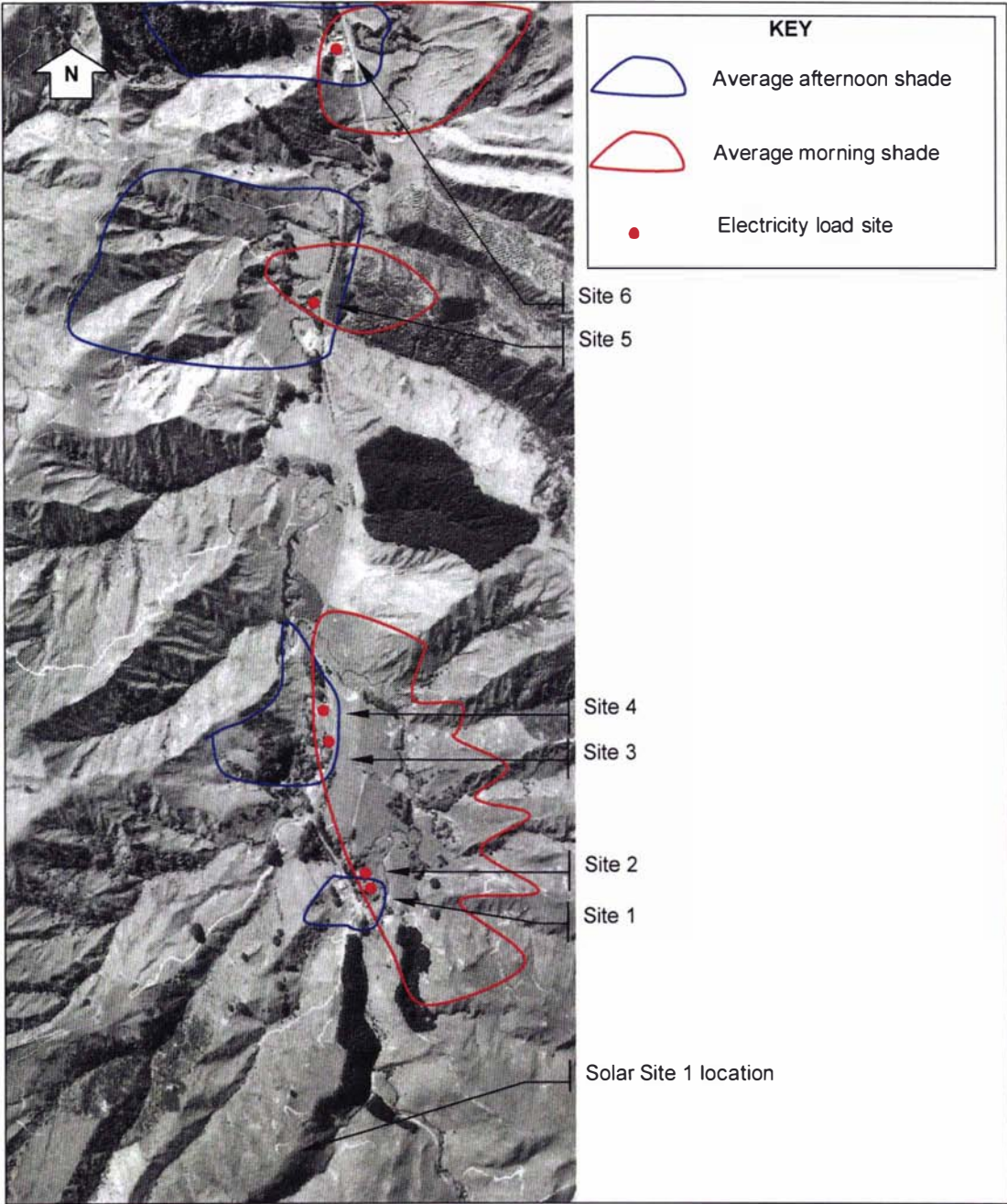


Figure 7.42 The Totara Valley electricity load sites and potential solar photovoltaic installation sites with the estimated mean 0900 hrs and 1600 hrs shading indicated.

Although the value of the early morning and late afternoon/evening sun is minimal for solar PV sourced electricity generation, it still has some energy input, so an allowance for the loss against the recorded data was made for the generation systems modelling stage. This was estimated to be around 5.6% (Table 7.3) and was to be applicable across all sites as it is a reduction of the resource.

Table 7.3 The estimated loss of solar radiation (Wh/m²/d) resulting from valley shading for the morning and evening, and the percentage of solar loss at the valley floor.

Month & year	Level of the morning and evening solar resource (Wh/m ²)								Mean <u>daily</u> solar (Wh/m ² /d)	Solar loss (Wh/m ² /d)	Percent difference	
	0600	0700	0800	0900		1700	1800	1900				2000
Feb-99	0	35	118	270		156	54	11	0	3,190	46	1.4
Mar-99	0	15	102	223		240	95	11	0	3,908	25	0.6
Apr-99	0	1	48	147		125	21	0	0	2,727	69	2.5
May-99	0	0	17	83		45	1	0	0	1,546	101	6.6
Jun-99	0	0	2	48		23	0	0	0	1,121	74	6.6
Jul-99	0	0	3	39		29	1	0	1	970	73	7.6
Aug-99	0	0	16	79		47	3	0	0	1,393	98	7.0
Sep-99	0	22	147	291		234	84	1	0	3,891	545	14.0
Oct-99	7	59	145	234		186	75	8	0	3,461	219	6.3
Nov-99	33	122	246	325		230	124	35	1	4,021	191	4.8
Dec-99	39	129	215	336		269	178	74	10	4,384	252	5.8
Jan-00	13	61	158	291		325	243	108	35	4,621	218	4.7
Feb-00	0	3	52	158		412	279	146	45	4,377	194	4.4
Mar-00	0	0	13	85		303	222	94	12	3,381	107	3.2
Apr-00	0	0	1	41		165	76	13	0	2,136	90	4.2
May-00	0	0	0	12		115	34	1	0	1,623	47	2.9
Jun-00	0	0	0	2		91	23	0	0	1,370	116	8.5
Jul-00	0	0	0	4		103	33	0	0	1,472	140	9.5
Aug-00	0	0	17	55		161	81	30	1	2,072	183	8.8
Sep-00	0	5	45	149		102	9	0	0	2,538	209	8.2
Oct-00	13	77	188	335		266	121	33	2	4,389	313	7.1
Nov-00	31	107	205	296		210	112	26	0	3,716	164	4.4
Dec-00	30	85	133	241		264	155	58	9	4,141	181	4.4
Jan-01	13	57	152	285		419	288	158	63	5,184	290	5.6
Feb-01	0	2	48	158		380	315	172	58	4,263	233	5.5
Mar-01	0	4	53	157		281	170	55	7	3,615	66	1.8
Apr-01	0	2	51	141		139	32	0	0	2,525	86	3.4
May-01	0	0	10	77		28	0	0	0	1,467	87	6.0
Jun-01	0	0	5	67		31	0	0	0	1,742	103	5.9
Jul-01	0	0	3	43		31	0	0	0	1,466	77	5.3
Mean solar loss											5.6	
Gray cells represent the morning hours of shade and blue cells represent the afternoon hours of shade												

The mean daily solar resource ($\text{Wh/m}^2/\text{d}$) (Table 7.3) was calculated as the mean summed daily insolation. The level of solar loss was estimated by subtracting the amount in the (morning and evening) shaded cells from the daily amount, and assessing the percentage of solar loss. This figure was estimated for use in the renewable energy based distributed generation system modelling (Chapter 9).

An alternative and more accurate method of calculating the shading loss of a valley solar resource would be the use of a Solar Pathfinder tool. This tool still uses visual inspection of the site, but requires the user to trace a line across a solar path chart that follows a reflected view of the skyline. From this chart, the amount of monthly solar shading loss can be calculated. Such a tool was unavailable at the time of monitoring the solar resource at Totara Valley, but one should be used where anecdotal evidence was unavailable, and yearlong observation was not possible.

Further comparison of the solar resources of locations in the southern hemisphere, locations in New Zealand and Totara Valley (Figure 7.43) reveal the level of differences attributable to geographical and local meteorological effects. The NASA-derived global solar resource data date from 1992 and the Totara Valley monitored data is noted for comparison purposes only (Figure 7.43).

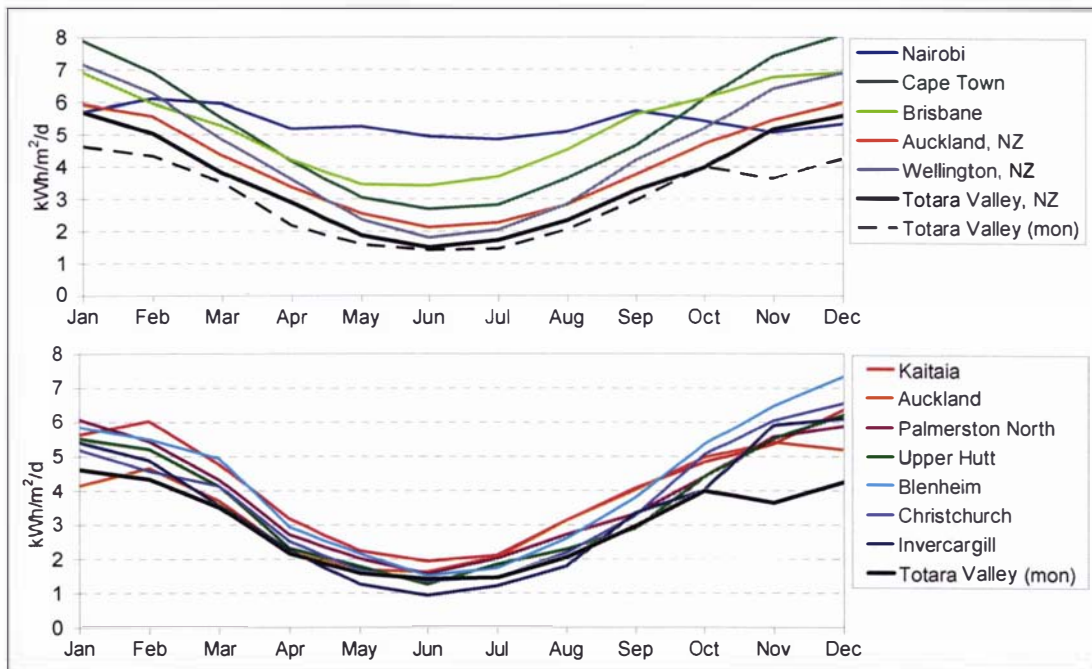


Figure 7.43 Comparative analysis between the 1992 NASA data from several Southern Hemisphere cities (top), the 1992 Totara Valley Data, and the monitored 2000 data for Totara Valley (top), and the NIWA 2000 data from several locations within New Zealand, and the monitored 2000 data for Totara Valley.

The NIWA-derived New Zealand solar resource data is for 2000 and the comparison with the monitored Totara Valley data reveals the differences between the locations. Interesting to note is the difference between Palmerston North and Totara Valley, a geographical distance of only 50 kilometres. This difference cannot be explained by this study, however it was not

known when the pyranometer was last calibrated and there may have been metering errors introduced into the Totara Valley data.

7.2.7 Short-Term Duration Analysis – Renewable Energy Resources

Wind Energy Resource Data

When modelling the wind in HOMER, the six modelling parameters required are the mean wind-speed, the Weibull 'k', the autocorrelation factor, the diurnal pattern strength factor (DPS), the hour of peak wind-speed, and a monthly wind speed profile (Figure 4.3). This section reports on the analysis of the monitoring duration required to obtain relatively settled levels of the mean wind-speed, the Weibull 'k', and the diurnal pattern strength parameters. This analysis was not required for the autocorrelation factor or the hour of peak wind-speed. It would become obvious within a very short period due to the inherent nature of the wind-speed at any one-hour being strongly correlated to the previous hour's mean wind-speed at the subject site. This would vary between sites however as each site would be affected in different ways by the complex terrain.

Hassan & Sykes (1990) found that the United Kingdom Weibull 'k' wind statistics were generally between 1.7 and 2.5, whereas Lilienthal *et al.* (2003) indicated that it was usually between 1.5 and 2.5. The autocorrelation factor was usually between 0.8 and 0.95, the diurnal pattern strength was usually between zero and 0.4, and the hour(s) of peak wind-speed usually occurred between 1400 and 1600 hours (*Ibid.*). The descriptive statistics of the monitored wind-speed data has been analysed (Table 7.4) and all the final measures were similar to those proposed by Lilienthal *et al.* (2003) except for the hour of peak wind-speed for Site 3.

Table 7.4 The descriptive statistics useful for wind modelling in HOMER at the end of the monitoring duration.

Site	Hours of data	Mean wind-speed (m/s)	Standard deviation (m/s)	Confidence interval (95%)(m/s)	Weibull 'k' shape factor	Auto-correlation factor	Diurnal pattern strength	Daily hour of peak wind-speed
1	16,319	5.61	3.07	0.047	1.77	0.91	0.13	1500
2	1,994	6.04	4.02	0.026	1.52	0.93	0.18	1600
3	1,340	6.27	3.78	0.202	1.65	0.94	0.20	1800
4	5,144	4.29	2.76	0.075	1.50	0.91	0.23	1400
5	7,002	5.95	3.51	0.071	1.66	0.93	0.12	1400

For the short-term duration modelling of the mean wind-speed in HOMER, an indication of the duration before a relatively stable mean wind speed was required. As a definition of stability for this study, a moving differential measure of the maximum mean wind speed minus the minimum mean wind speed over the previous 1,000 hours was calculated for each hour of the monitored duration (Figure 7.44 and Figure 7.45). This measure was intended to calculate the (maximum and minimum mean wind speed) range over a defined duration. The range differential over 1,000 hours was chosen because it represents a period of approximately six-weeks, therefore after the first 1,000 hours of monitoring, the difference between the maximum and minimum mean wind speed within the previous 1,000 should be calculated for

each succeeding hour of the monitoring duration until such time as the differential falls to an acceptable level. No defined differential was proposed, however it should be relatively small compared to the overall mean at that period.

This calculation process identified the duration of 2,177 hours (approximately 12 weeks) before the mean wind speed 1,000-hour differential dropped below 0.3 m/s, a figure that was approximately 5% of the mean wind speed at that time. This was deemed an acceptable level of differential and at 2,177 hours, the mean wind speed appeared to have settled (Figure 7.44).

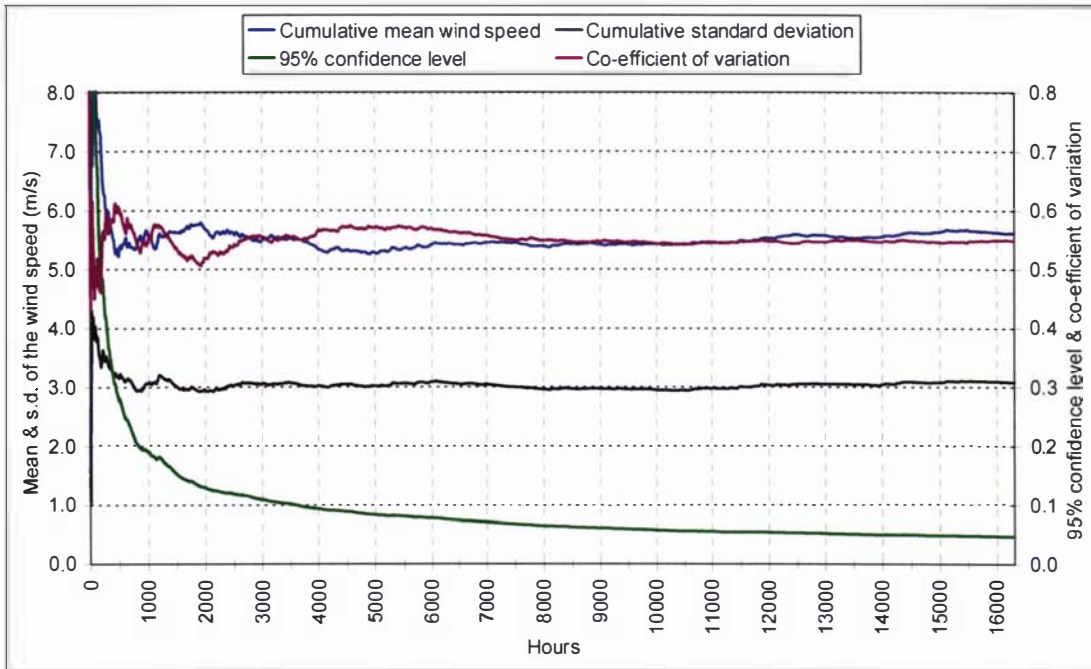


Figure 7.44 Cumulative mean, standard deviation, co-efficient of variation and 95% confidence interval of the wind speed at Site 1.

This 'settling' of the mean wind speed is indicated clearly in Figure 7.45 where the mean wind speed at various hours over the monitoring period is given as well as the differential value. However, as with any average value, the mean wind speed was prone to moving as climatic and seasonal influences impacted on it over time. This is indicated in Figure 7.44 (at approximately the 3,800 hour mark where the mean wind speed fall slightly due to a prolonged period of low winds. Therefore this requirement of a duration before an apparent settling of the wind speed, and the use of the method in this study, should be treated with caution as with any dynamic value, the mean wind speed is a changing value.

One further point should be noted from Figure 7.44 and Figure 7.45. The standard deviation did not clearly indicate any settling of the mean as evidenced in Figure 7.44, and nor did the co-efficient of variation. What did occur was the divergence of the calculated differentials for the mean wind speed and the standard deviation. Prior to the 2,177 hours, the differentials were very similar, but after this duration, they began to differ markedly.

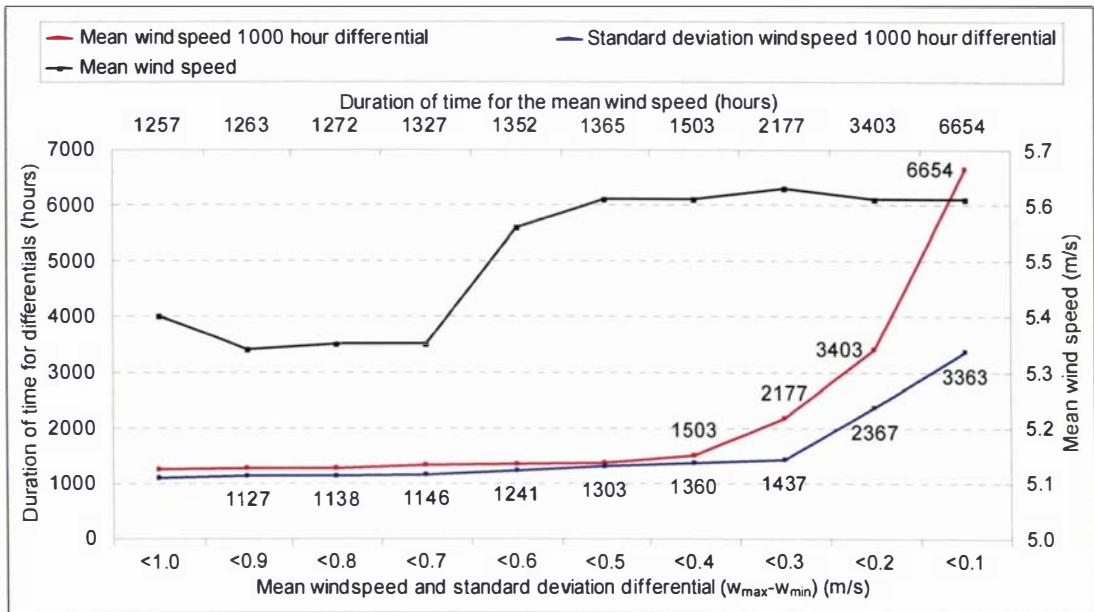


Figure 7.45 The 1,000 hour differential (Maximum wind speed minus the minimum wind speed over a moving 1000 hour duration) of the mean wind speed for Site 1.

The Weibull 'k' and 'C' values over this duration displays a variation between 1.69 – 1.80 (Figure 19.4) with the Weibull 'k' at approximately 1.80 at the 2,177 hour period. In the sensitivity analysis of wind parameters (Figure 4.5) the Weibull 'k' sensitivity appeared minor compared with the effects of wind speed variation.

The diurnal pattern strength factor (DPS) is a measure of how strongly the wind-speed tends to depend on the time of day. Although HOMER uses a complex fitted cosine function to calculate the DPS with the data set used, a simple manual calculation can be undertaken separately (Equation 7.3) in order to assess this parameter based on monitored data.

Equation 7.3 Simple calculation of the diurnal pattern strength factor.

$$DPS = \frac{(w_{max} - w_{min})}{2w_{mean}}$$

Where :

DPS = Diurnal pattern strength factor

w_{max} = maximum wind speed in an averaged 24 hr period

w_{min} = minimum wind speed in an averaged 24 hr period

w_{mean} = the mean wind speed in an averaged 24 hr period

Source: Lambert (2005).

This equation "gives a reasonable proxy for the diurnal pattern strength" (Lambert, 2005). The higher the DPS factor the more the maximum wind-speed is dependent on the time of the day. The DPS would be quite high if there were regular katabatic – anabatic cycles in favourable orographic settings, but if there was no dependence on the time of day (e.g. Antarctic winter) then there will be a DPS of zero (*Ibid.*). The DPS factor for the duration of 2,177 hours was 0.85.

The autocorrelation factor (Equation 7.4 and Table 7.4) is a measure of how strongly the wind-speed in one hour depends on the wind-speed from the previous hour. HOMER uses this to model the wind contiguously from one hour to the next. The higher the autocorrelation factor the greater the correlation of the wind-speed from one hour to the next.

Equation 7.4 The autocorrelation function used to determine the correlation of the wind-speed on the wind-speed of the previous hour.

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i-k} - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

Where :

r_k = the autocorrelation factor

i = the value at time i

k = the lag time

x = the value of x in the time - series

$\bar{x}$ = the mean value of the time - series

Source: Lilienthal *et al.* (2003).

The hour of peak wind-speed is a factor that appears to be seasonally dependant with the hour of peak wind-speed appearing to be later in the day over the warmer months of the year, and earlier in the day in the cooler months (Figure 19.11). 1500 hours would appear to be the mean time of peak wind-speed for Site 1, with Sites 2, 4, and 5 varying from this slightly. Site 3 had 1800 hours as the hour of peak wind-speed (Table 7.4).

Solar Energy Resource Data

The NASA website¹⁷ only had information for the years 1983 to 1992 and the data presented (Table 7.5) is from 1992. This data, when compared with the monitored data, revealed some large differences, presented as the percentage difference. Given that these data are from different years, there will obviously be differences and any comparison given here (Table 7.5) is for illustrative purposes only.

The clearness index, given alongside the monitored data (Table 7.5), was calculated in HOMER and was an indicative measure of the clearness of the atmosphere surrounding the subject site. As such, it is the (dimensionless) fraction of the solar radiation that radiated through the atmosphere to the subject site. It is thus, the surface radiation divided by the extraterrestrial radiation (Lilienthal *et al.*, 2003).

¹⁷ <http://eosweb.larc.nasa.gov/cgi-bin/sse/>

Table 7.5 A comparison between the monitored solar data and the data from the NASA database.

Month	Monitored data (2000)	HOMER derived data	NASA data (1992)		Data comparison	
	kWh/m ² /d	Clearness index	kWh/m ² /d	Clearness index	kWh/m ² /d % difference	Clearness index % difference
Jan	4.620	0.386	5.69	0.475	-18.8	-18.7
Feb	4.330	0.409	4.93	0.466	-12.2	-12.2
Mar	3.505	0.414	3.82	0.451	- 8.3	-8.2
Apr	2.170	0.354	2.93	0.478	-25.9	-25.9
May	1.585	0.366	1.94	0.448	-18.3	-18.3
Jun	1.418	0.402	1.57	0.445	- 9.7	-9.7
Jul	1.454	0.375	1.70	0.438	-14.5	-14.4
Aug	2.051	0.384	2.39	0.448	-14.2	-14.3
Sep	2.960	0.393	3.37	0.448	-12.2	-12.3
Oct	3.996	0.407	4.14	0.421	- 3.5	-3.3
Nov	3.641	0.315	5.13	0.443	-29.0	-28.9
Dec	4.244	0.344	5.47	0.443	-22.4	-22.3
Mean	2.998	0.379	3.59	0.450	-16.5	-15.8

7.3 Discussion

7.3.1 The Wind Energy Resource

There was a good readily usable wind energy resource at Wind Sites 1, 2, 3, and 5, with mean wind-speeds of 5.65 m/s, 6.04 m/s, 6.27 m/s, and 5.95 m/s respectively. The short duration of monitoring at Wind Sites 2 and 3 must be considered too short for any accurate assessment of the long-term wind-speed at these sites. All data however will be used in WAsP (Chapter 8) to model the wind energy resource of the Totara Valley area in order to identify the areas of high resource levels. The model will be validated using data from the intermediary Sites 2, 3, and 4. The results of this modelling will then be used in the HOMER model (Chapter 9).

The multi-mast method of wind resource assessment used to gather wind-speed and direction data from five sites produced an extensive data-set indicating a wide-ranging useful wind resource, as well as information about the effect the complex terrain had on this resource. With extensive wind channelling evident and consequent wind-speed increases because of this, it would be very difficult to accurately model using a conventional Measure-Correlate-Predict approach so by using the monitored data in the WAsP model (Chapter 8) the effects of the terrain on the wind will be modelled to produce a region-wide wind atlas.

Existing roads or track access to the prospective sites will be vital in the further development of the potential wind sites and of the four good wind-speed sites, only three were readily accessible in all weather by four-wheel-drive vehicle. The existing farm tracks are indicated in Figure 5.3 and serve Sites 1, 2, and 3. There was a reasonable dry-weather track

that served Sites 4 and 5, which would need further development in order to make them all weather suitable. The electricity transmission infrastructure would be laid across farmland consisting of downhill slopes, and valleys.

As outlined (Figure 4.1), the wind-monitoring programme consisted of a two-stage process. An initial period of wind monitoring to provide the WAsP model with data for a wind atlas (Wind Site 1), followed by subsequent data gathering for WAsP model validation. A second potential reference site was initiated at Wind Site 5.

The mean wind-speed and the Weibull 'k' value were deemed the most important modelling parameters in HOMER (Figure 4.5). Given the results of the analysis of the mean wind-speed (Figure 7.44, Figure 7.45 and Appendix G – 19.3), the mean wind-speed data could be assessed to be relatively stable after 2,177 hours (approximately 12 weeks) (Figure 7.45). Therefore, the likely duration of monitoring to estimate the mean wind-speeds (Figure 4.1), may need revision downward.

The Weibull 'k' was analysed for Wind Sites 1, 4 and, 5 only, at incremental duration of 1000-hours. Only these sites were calculated as they had the longest period of monitoring and therefore indicated the relative behaviour of the Weibull 'k' value over the duration of the monitoring¹⁸. The relatively short-term duration of the monitoring instilled a degree of uncertainty into the analyses of the Weibull 'k' and 'C' parameters. However, the range was quite small between the calculated incremental Weibull 'k' and 'C' parameters from the three sites, and the probability density curves indicated only small relative fluctuations (Figure 19.5, Figure 19.7, and Figure 19.9). It can therefore be assumed that any value used from the monitored data for modelling the wind-speed in HOMER would be a close approximation of reality. There currently is no facility in HOMER to model uncertainty of the Weibull 'k' value.

The autocorrelation factor can be used in HOMER to attribute the relative effect of the modelled mean wind-speed of an hour with the modelled mean of the next hour's wind-speed. This factor did not need a large amount of data as the lag time required was one-hour, and therefore easily assessed over a short-duration of monitoring. Lilienthal *et al.* (2003) indicated that the complexity of the terrain surrounding the subject site had significant effects on the magnitude of the autocorrelation factor and from the autocorrelation factors from Wind Sites 1-5 of 0.91 to 0.94, the effects of the consistency of the prevailing wind can be assumed. This finding differed from those of Lilienthal *et al.* (2003), who indicated that surroundings of varied terrain had lower autocorrelation factors (0.70 – 0.80), whereas flat or rolling surroundings had the opposite effect, increasing the level of the autocorrelation factor (0.90 – 0.97).

7.3.2 *The Hydrological Resources*

The seasonal difference in stream flow rates needs to be considered in any design for a hydro system, as does the allowable amount of water to be abstracted for use in electricity generation. The drought conditions that existed over the summer of 1999 – 2000 meant that

¹⁸ The duration of monitoring at Wind Sites 2 and 3 was too short to accurately assess the Weibull 'k' values if using the 1000 hour increments as was done with Sites 1, 4, and 5. Analyses at shorter increments were not undertaken.

the low flow conditions of the stream could be assessed. Thus, these low flow figures were used to establish a base flow rate below which, any water for a prospective hydroelectric system could not be utilised.

The stream flow rates of Hydro Site 1, 46 ℓ/s and 50 ℓ/s were considered dry year flow levels due to the drought conditions in effect at the time. The August 2000 flow rate of 195 ℓ/s (Appendix G – 19.1) was assessed after a winter period of two weeks of little or no rain and was therefore considered a stable winter flow. The flow rate differed between sites as side-streams and tributaries contributed to the flow. Hydro Site 2 had a low flow rate of between 47 ℓ/s and 51 ℓ/s and Hydro Site 3 had a low flow of between 49 ℓ/s and 52 ℓ/s . Therefore, the recommended minimum amount of stream flow to be diverted for use in the hydro generation system would be approximately 40 ℓ/s thus allowing a small maintenance level flow to remain in the streambed.

7.3.3 *The Solar Resource*

The mean diurnal – monthly solar resource plot shape was as expected in the magnitude of the profile (Figure 7.39). The plateau of midday (1100 hours to 1400 hours) of October, November and to some extent, December 1999, and November 2000 was an interesting feature of the mean profile but the standard deviation of the mean (Figure 7.40), and the coefficient of variation (Figure 7.41) indicated these months had a high level of variation. December 2000 had the highest level of variation over the monitoring duration.

As Solar Site 1 was at a higher altitude relative to the surrounding hills, it was unobstructed with only very early morning and very late evening shading from adjacent hills. However the Load Sites 1 – 6 in the valley floor where solar photovoltaic (PV) is likely to be used will remain shaded later in the morning and earlier in the afternoon/evening by the hills, the extent of which was estimated through anecdote and observation by the author.

The indication of shading in the valley (Figure 7.42) was estimated based on anecdote and visual inspection over the duration of monitoring by the author. This method may not be 'safe' at any other location where the short-term involvement of the research precludes an all-year view of the seasonal variation of shade and subsequent energy loss at the solar PV array. Other methods would be better suited for this analysis. Options include the simple method of using a 'Solar pathfinder' which accurately traces the potential shading of a site year-round and enables a calculation of energy loss due to shading.

The use of the NASA data for modelling other locations in HOMER was a distinct possibility unless monitored data was available. An allowance would need to be given for the potential variation from this data from site-specific parameters such as shading, and the clearness of the site due to cloudiness.

7.4 Summary

There were readily exploitable renewable energy resources evident in and around the Totara Valley area. These included mean wind-speeds of around 6 m/s, nominal minimum useful stream flow around 40 ℓ/s with a stable winter time stream flow around 195 ℓ/s . The solar

resource indicated a peak summer time resource of approximately 600 Wh/m², while over winter the resource ranged between 150 – 200 Wh/m².

Consideration will need to be given at the modelling stage to the wind for inaccuracies involving stronger channelled wind-speeds as influenced by the local terrain and to the solar resources to allow for valley shading at low sun angle times.

There may be a need to revise the duration over which the HOMER modelling parameters are sought from short-term data, especially the more important parameters of mean wind-speed, and the associated Weibull 'k' value. It was possible six weeks would be the minimum duration and 12-weeks the most likely duration required from which any useful estimate could be calculated. The other parameters, although also necessary for accurate modelling, have a smaller impact on the resultant output from HOMER, and therefore are not as important.

Part three: the framework applied

Wind energy resource modelling

Distributed generation system modelling

Multiple criteria decision analysis

8 Wind Energy Resource Modelling

This chapter reports on the use of the wind-energy resource model, WAsP, and follows on from the wind-monitoring study (Chapter 7). Mortensen *et al.* (2002) described in detail, WAsP version 7.2, which was in use by up to 800 users worldwide in 2002 to model their wind energy resources. The literature indicated the WAsP model has been increasingly used in the micro siting of wind turbines and assessment of potential wind turbine and wind farm outputs since the first version was released in 1987.

In this section, details are given of some applications of WAsP and some of the limitations inherent in the design and use of this model. Section 8.2 details the assessment of which of two reference sites would be most suitable to form the basis of the regional wind atlas model. These assessments include a correlation and regression analysis between the wind data, and an assessment of the terrain differences between sites through an analysis of the Ruggedness Index (RIX) numbers (section 8.2.1). The next stage of the modelling was the setting of the model parameters of inversion scale length, and the level of forcing needed (section 8.2.2).

The results are given in Section 8.3 which includes sections on comparisons between the observed wind climate and that modelled (section 8.3.1), regional wind atlases for wind-speed and wind power density (section 8.3.2), and a comparison between the RIX number and the prediction error (section 8.3.3). These results are discussed (Section 8.4) and then summarised (Section 8.5).

8.1 Applications of WAsP

Accurate predictions of wind-speed data at other sites can be made if both the predictor and predicted sites are subject to the same weather regime, prevailing weather conditions are close to being neutrally stable, the surrounding terrain is sufficiently similar, and that the reference data were reliable (Bowen & Mortensen, 1996; Reid *et al.*, 1998; Reid, 1997; Bajić, 1999). If the terrain was very steep, then separating flows usually occurred and these flows were not treated correctly by the calculations used by WAsP. WAsP cannot consider any potential large-scale atmospheric stratification due to thermally driven wind flow systems (Farrugia & Scerri, 1999), and in acknowledging this limitation, they still considered that using WAsP saved money and avoided time-consuming monitoring programmes for site prospecting. This was confirmed by Hansen & Mortensen (1999) who used WAsP modelling for micro-siting and wind farm layout optimisation over a five month period of measurements using calibrated site monitoring parameters and reference data.

Reid (1997) used an early version of the WAsP model to determine the mean wind-speed and direction frequencies at ten anemometer stations in high wind areas within the Manawatu region of New Zealand. Only one of the sites modelled displayed closeness to reality. The other sites were highly channelled by the surrounding terrain and WAsP under-

predicted both the mean wind-speed and the predominance of the channelled directions. However, Reid (1997) also found that the results from a standard WAsP run were not overly affected by contours more than a few kilometres away from the grid centre of the zooming grid area. Only adjustment of the inversion and softness parameters to encourage channelling did the outer ranges have an impact on the wind flow. This point has been noted with respect to this study where localised channelling effects were found at Wind Sites 2 and 3 (Chapter 2). The adjustment of the inversion and softness parameters will be undertaken in order to encourage this channelling behaviour in the model.

8.2 Modelling with WAsP in the SPiRAL Framework

The WAsP model normalises a wind-speed and direction data set by removing the effects of the roughness and site obstacles at the subject site and this data is then used to estimate the wind regime at other sites re-initiating the effects of the new site-specific roughness and obstacle inputs and assumptions (Figure 8.1).

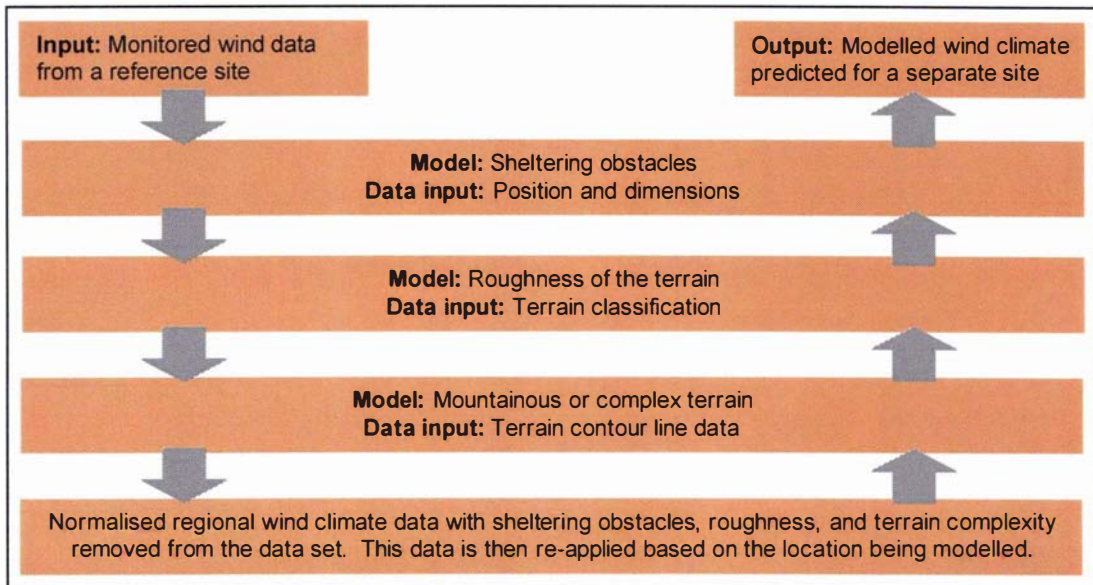


Figure 8.1 A schematic diagram of the WAsP wind energy resource modelling process.

Figure 8.1adapted from Mortensen *et al.* (2002).

The modelling process of WAsP was prescribed in the literature (Mortensen *et al.*, 2002) and this study has adhered to these modelling precepts as required to produce suitable output from this study (Figure 8.2). The results of the modelling will be used to 'prospect' for potential wind sites using the initial wind atlas mapping outputs. This output will subsequently be validated using the results from the intermediary sites. This will produce the required short-term duration data pertaining to the modelling of the wind resource in HOMER, the short-term duration mean wind-speed and Weibull 'k' values.

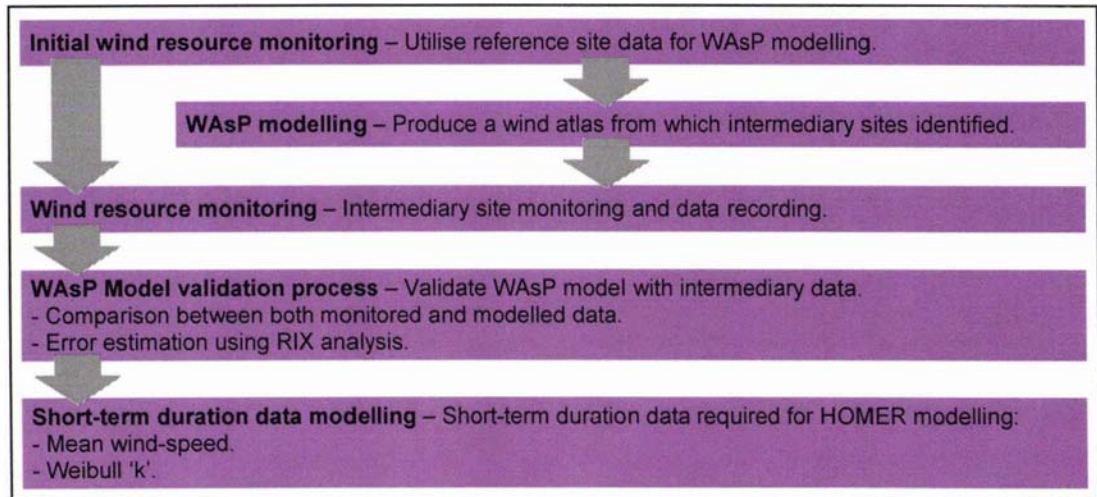


Figure 8.2 The WAsP wind energy resource modelling process within the SPiRAL decision framework outlining the interaction with resource monitoring.

Due to the sequence of progress in the study, much wind data from Wind Site 1 already existed prior to the purchase and use of WAsP in December 2000 (Irving, 2000; Murray & Sims, 2001c; and Murray & Sims, 2002). The chronological sequence is documented in Figure 7.29. This indicates the full extent of the data set available for use in the WAsP process in SPiRAL.

The wind data from Wind Site 1 was therefore used to produce an initial wind atlas of the Totara Valley region (Figure 14.1). From this, further potential wind monitoring sites were identified. An alternative potential reference site (Site 5) was identified. This was considered necessary due to the complexity of the terrain around the existing Wind Site 1. An analysis between the potential reference sites would indicate which one to use for modelling. The reference site will then be used to assess the short-term duration before a wind atlas could be produced, and from this duration, the WAsP model will be used to produce the data required for the short-term duration data required by HOMER (Chapter 9).

8.2.1 Reference Site Analysis

In order to assess which of reference Wind Sites 1 or 5 to use to model a regional wind atlas, an assessment needs to be made on the similarity of the terrain and the data between the reference sites 1 and 5, and Sites 2, 3, and 4. WAsP uses a data set from one location to predict the wind climate of another location, and if there are data from the predicted site, this can be used to validate the WAsP predicted results.

Reference site selection can be done with a RIX analysis or comparison between wind data with regression or correlation analysis. This type of reference site analysis is only necessary due to there being two reference sites for this study. Most other analyses would only have one site and the analysis would only be required when assessing this site with the intermediary sites.

Ruggedness Index Analysis

The ruggedness index (RIX) number was defined as the percentage fraction of the terrain within a user-defined radial distance from a specific site that is steeper than some nominated critical slope (Mortensen *et al.*, 2002). There was no indication in the literature of what radial distance was best to use in a RIX analysis, but figures of 250 and 1500 to 3500 metres were used in reported studies (Bowen & Mortensen, 1996; Bajić, 1999; Mortensen *et al.*, 2002). In WAsP however, the default radius was 3500 metres (Mortensen *et al.*, 2002) has been used in this study.

The RIX number is to be used in the following manner:

“If the RIX is $\sim 0\%$ the slopes of the terrain are less steep than 0.3^{24} and the flow is likely to be attached, i.e. follow the terrain surface. This situation is generally within the performance envelope of WAsP.

If the RIX is $>0\%$ parts of the terrain are steeper than 0.3 and flow separation may occur in some sectors. This situation is generally outside the performance envelope of WAsP and prediction errors may be expected. Large RIX values will lead to large errors in the flow modelling. The accuracy of prediction, however, will depend on the relation between the two sites.” Mortensen *et al.* (2002).

The relation between the sites Mortensen *et al.* (2002) referred to is between the RIX value of the predictor and predicted sites is as follows.

- If the predictor and predicted sites have approximately the same RIX value then the modelling errors could be significant but similar in magnitude.
- If the RIX value of the reference site is larger than that of the predicted site then the modelling errors are significant and unequal. The overall prediction will be underestimated with a significant negative error.
- If the RIX value of the reference site is smaller than that of the predicted site then the modelling errors are significant and unequal. The overall prediction will be overestimated with a significant positive error.

The RIX values of the wind sites 1 to 5 (Table 8.1) represent the percentage of terrain over the critical 0.3 slope within the defined sector. The ‘All’ column is the mean overall RIX value of the total area assessed. When viewing these RIX values and considering predictor sites the ‘All’ column is as important as the predominant wind direction sector of the individual sites. In Site 1 the predominant direction was 270 degrees (blue shaded cells), whereas the predominant direction of Site 5 was 293 degrees (grey shaded cells). Scrutiny of the RIX value differences between the potential predictor sites to that of predicted sites show that Site 5 was closer topographically to all the predicted sites than Site 1.

²⁴ A slope of 0.3 equates to a 17-degree slope angle.

Table 8.1 The calculated RIX values within a 3500-metre radius area for each 22-degree sector for all Wind Sites.

	RIX value (%) of terrain over the critical slope by direction sector																
Site	0	23	45	68	90	113	135	158	180	203	225	248	270	293	315	338	All
1	45	27	23	30	23	31	32	31	27	16	14	28	41	51	51	39	32
2	36	21	16	28	21	21	19	26	18	28	20	26	31	36	31	41	26
3	19	19	33	20	27	21	19	23	31	34	36	26	23	31	49	37	28
4	29	17	24	28	20	12	21	20	21	38	36	35	34	27	26	25	26
5	21	27	37	22	13	11	19	17	19	23	45	44	33	34	22	29	26

Correlation and Regression Analysis

A high correlation coefficient and high regression r^2 and adjusted r^2 values between sites could indicate similar weather regimes. However, Bowen & Mortensen (1996) warned that this does not imply both sites were in neutrally stable conditions, which is a key assumption of the WAsP model (Mortensen *et al.*, 2002). The strong effects of the terrain on the wind-speeds would show up as differences in the correlation and regression statistics (Table 8.2) between Site 1 reference data and Sites 2 – 5, and between the Site 5 reference data and Sites 1 – 4 (

Table 8.3). Data point sample size was the number of the simultaneous data points available between the comparison sites for use in the correlation and regression analyses. Only periods of simultaneous data were used in these analyses between sites. The data set sample size varies because of this.

Table 8.2 The correlation and regression statistics for Wind Sites 2, 3, 4, and 5 relative to Wind Site 1.

Site	Data set sample size	Correlation coefficient	Regression analysis linear equation	r^2	Adjusted r^2
2	7,595	0.82	$y = 0.9903x + 0.5954$	0.668	0.668
3	8,048	0.87	$y = 1.1260x + 0.2585$	0.760	0.760
4	10,364	0.76	$y = 0.6275x + 0.6920$	0.574	0.574
5	7,306	0.83	$y = 1.0249x + 0.9924$	0.687	0.687

Table 8.3 The correlation and regression statistics for Wind Sites 1, 2, 3, and 4 relative to Wind Site 5.

Site	Data set sample size	Correlation coefficient	Regression analysis linear equation	r^2	Adjusted r^2
1	7,306	0.85	$y = 1.0249x + 0.9924$	0.724	0.724
2	5,409	0.63	$y = 0.6892x + 1.9828$	0.391	0.388
3	7,983	0.86	$y = 0.9674x + 0.6347$	0.740	0.740
4	28,880	0.28	$y = 0.2138x + 2.8460$	0.076	0.076

By comparing the results of these analyses, it can be noted that the Site 1 data correlates better with the data of Sites 2, 3, and 4 than does Site 5 though the difference is relatively small for Site 3. Regression analysis results indicated that Site 1 data when compared with simultaneous data from other sites had a better fit than that of Site 5 as noted by the r^2 and adjusted r^2 values.

The Predictor Site

Sites 1 and 5 were potential reference (predictor) sites for the rest of the wind sites in this WAsP modelling study. Data from Sites 2 to 4 correlated better to Site 1 data than to Site 5 data. However, the RIX analysis indicated the topography of Site 5 had the most similarity to that of the predicted Sites 2, 3, and 4, especially from the angle of predominant wind, 293-degrees, and hence Site 5 was chosen as the main reference predictor site for WAsP modelling.

8.2.2 Setting the WAsP Wind Climate Prediction Parameters

To alter the behaviour of the default WAsP model to channel the wind certain model parameters need adjustment. When done successfully, WAsP can predict the wind climate at another site in relatively complex terrain. The two key parameters that were used to achieve this were the height of the modelled inversion level and the softness of the enforcement of this level.

The purpose of the height of inversion and the softness parameter in the WAsP model is to "enable an (admittedly, extremely simple) modelling of the climatological effect of the stably stratified atmosphere above the boundary layer" (Mortensen *et al.*, 2002). The height of inversion in the WAsP model is set to 1000 metres by default but can be set to values between 100 – 5000 metres. The softness of inversion in the WAsP model is set to 1 (no forcing) by default but can be set to values between 0 – 1 (maximum forcing – no forcing). Mortensen *et al.* (2002) explained that by changing the inversion height within the WAsP model any velocity 'distortions' or disturbances larger than the inversion height are 'squeezed' to make the calculated velocity perturbations more horizontal and thus intensify vertical motion back along the horizontal, thus enabling the modelled wind to speed up over a hill as in reality.

The best combination of inversion setting and relevant softness parameter can be chosen by a sensitivity analysis of predicted wind-speeds against observed wind-speeds (Reid, 1997). Using the data from Site 5 as the reference site, such a sensitivity analysis was conducted using inversion levels of 1000, 800, 600, 400 and 200 metre heights and softness levels of 0.5, 0.25 and 0.1 to see which combination of parameters modelled the wind-speed at Sites 1 – 4 closest to the recorded mean wind-speed. The results of the sensitivity of five inversion heights at three softness levels can be seen in Figure 8.3 (softness 0.1), and in Appendix B – 14.3.

The parameters that produced modelled results most closely resembling the observed data were an inversion level of 600 metres and softness of 0.1. The results (Figure 8.3) depicted the observed monitored mean wind-speed for each site (solid line) and the modelled mean wind-speed (dashed line) for each site at each of the inversion heights and a softness

level of 0.1. For Site 1 an inversion level of 600 metres brought the predicted mean wind-speed closest to the actual monitored wind-speed. Site 2 showed the greatest discrepancy between modelled and monitored wind-speeds throughout the modelling and 200 metres of inversion is the closest the model would go to the observed wind climate under the set parameters. An inversion level of 600 metres was seen as being the best for Site 3, and for Site 4 the best level was assessed as 1000 metres.

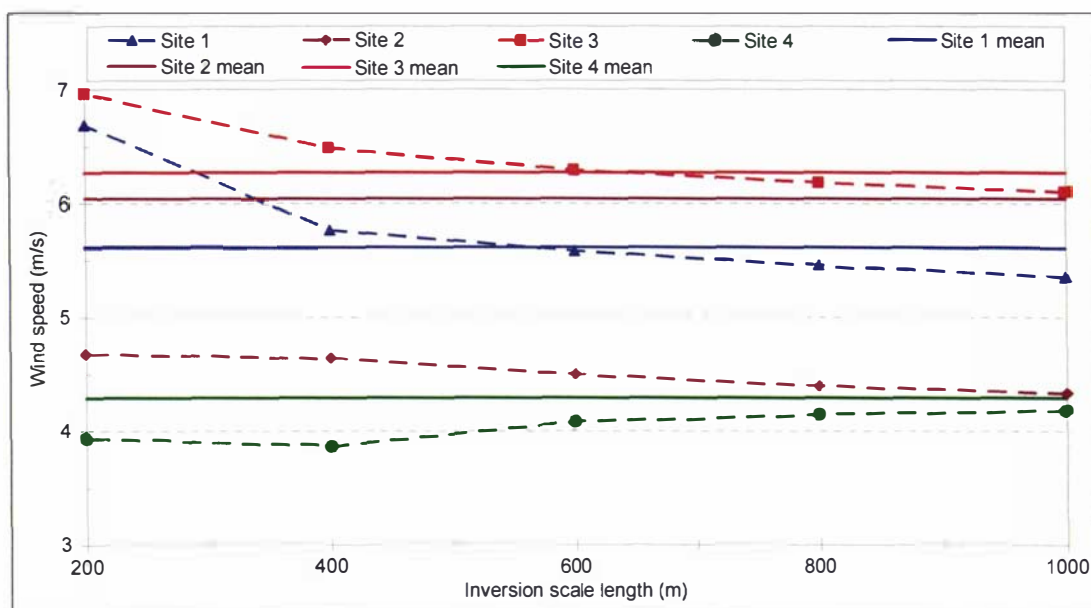


Figure 8.3 The WAsP model inversion scale length parameter testing results using scale lengths of 200 to 1000 metres and a softness of 0.1.

8.3 Results

8.3.1 Observed and Modelled Data

The observed wind climates (Figure 8.4 to Figure 8.7) were from monitored data that WAsP had 'normalised' to remove roughness and obstacle affects where appropriate, and derived the Weibull statistical data shown in each plot. The peak wind-speed frequency percentage was given as was the minimum wind-speed and the percentage this represented. The Weibull 'k' and 'A' parameters²⁵ were in the body of the plotted graph.

The predicted wind climates (Figure 8.4 to Figure 8.7) were modelled using a 600-metre inversion scale length and 0.1 softness on the normalised data. All the Weibull statistical data shown was generated by the WAsP model. In each predicted wind climate plot, the peak wind-speed frequency and the minimum frequency bin wind-speed is given in the diagram key, along with the frequency of occurrence at this wind-speed range and the percentage this represents. The predicted Weibull 'k' and 'C' parameters are given in the body of the plotted graph. A comparison between the observed and predicted wind climate on the peak wind-speed frequency, minimum frequency bin, and the Weibull statistical data highlighted any apparent differences between the modelled results and the measured data.

²⁵ The Weibull statistic 'C' as referred to in this study, was given as 'A' in the WAsP results, and was not user definable.

The predicted wind climate of Site 1 indicated the predominant direction of the predicted wind was incorrect but the predicted mean wind-speed was very close to that observed (Figure 8.4). The Weibull 'k' and 'C' were also very close but the predicted peak wind-speed frequency of 12.1% at 2.9 m/s was very different from the observed peak wind-speed frequency of 12.8% at 4 – 5 m/s.

In the predicted wind climate of Site 2, the predominant direction of the predicted wind was correct but the predicted windrose displayed a more fragmented distribution. The predicted mean wind-speed was very different to what was observed (Figure 8.5). The Weibull 'k' and 'C' were also very different but the predicted peak wind-speed frequency of 15.1% at 2.5 m/s was similar to the observed peak wind-speed frequency of 12.1% at 2 – 3 m/s.

The wind climate of Site 3 indicated the predominant direction of the predicted wind was very similar to the predictor site but the windrose displayed only a slightly fragmented direction distribution. The predicted mean wind-speed was virtually the same to that observed (Figure 8.6). The Weibull 'k' and 'C' were also very close but the predicted peak wind-speed frequency of 10.9% at 3.7 – 4.1 m/s was very different from the observed peak wind-speed frequency of 11.6% at 5 – 6 m/s.

In the predicted wind climate of Site 4 the direction and the distribution of the predicted predominant wind is similar but the predicted mean wind-speed was slightly different to that observed (Figure 8.7). The Weibull 'A' and 'k' were also close but the predicted peak wind-speed frequency of 17.2% at 2.7 m/s was very different from the observed peak wind-speed frequency of 11.5% at 3 – 4 m/s.

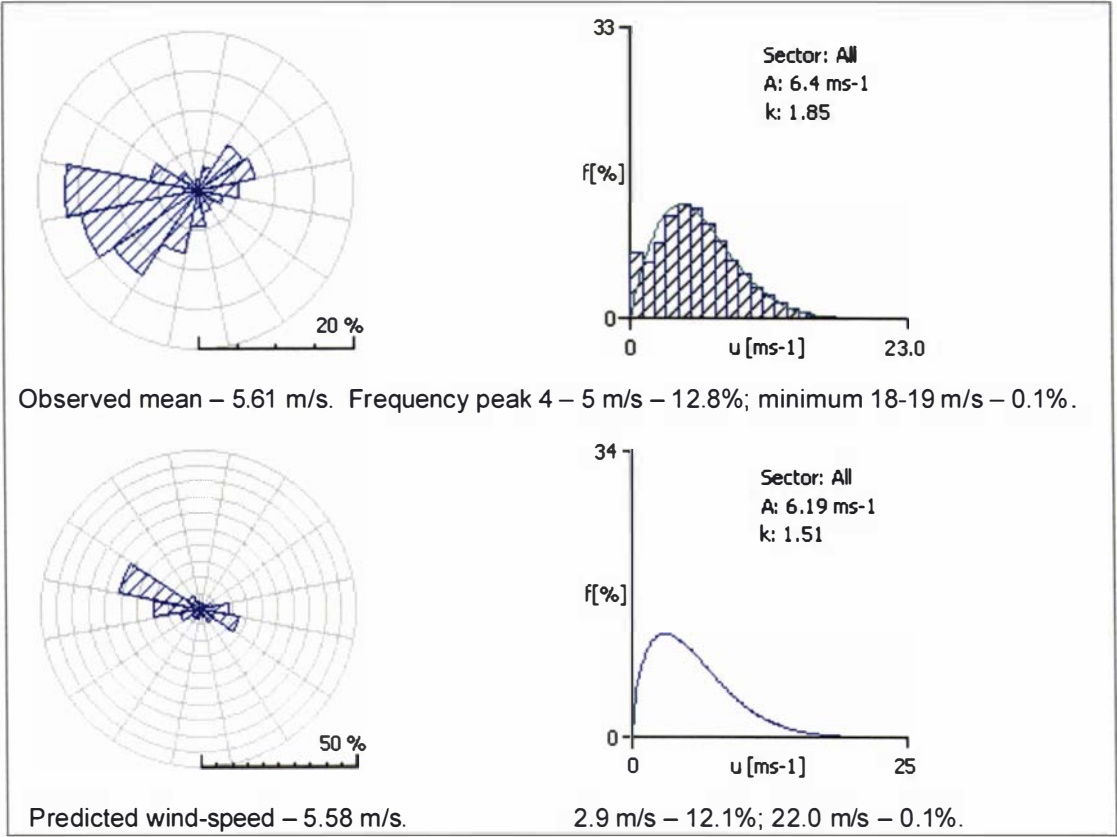


Figure 8.4 The observed and predicted wind climate through WAsP modelling for Site 1 using Wind Site 5 as the predictor site.

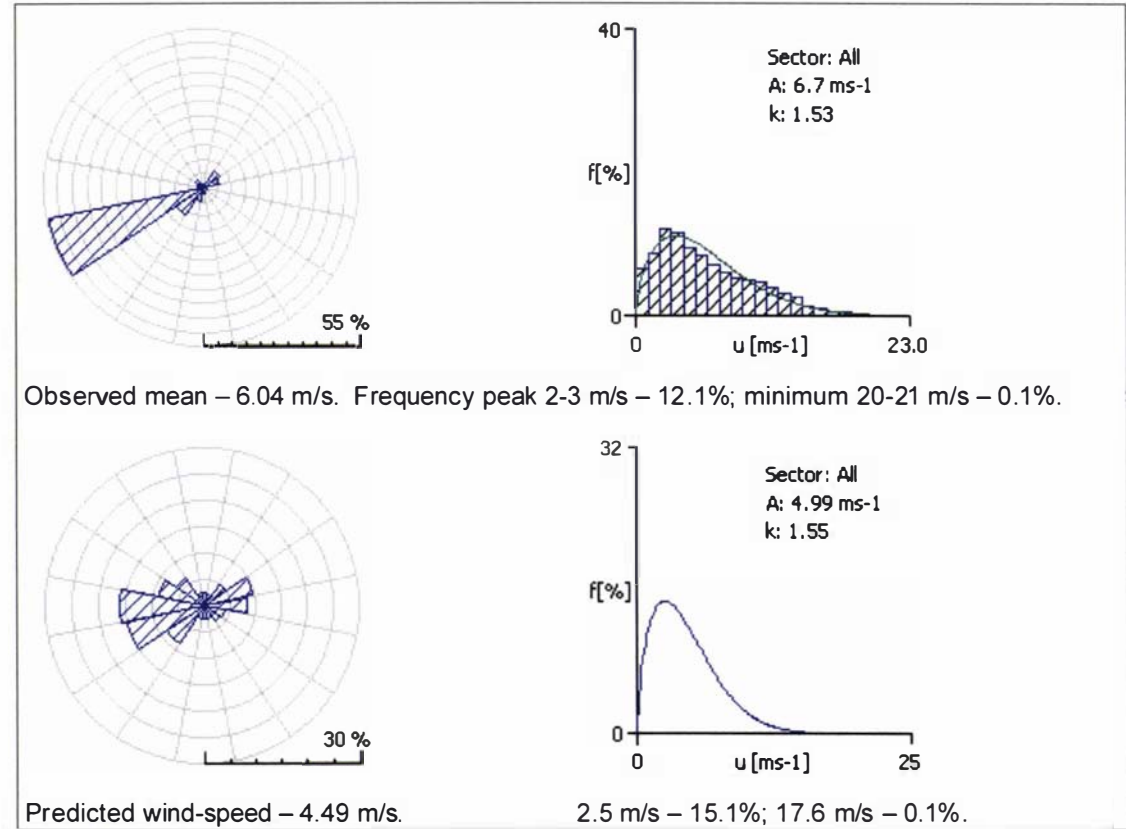


Figure 8.5 The observed and predicted wind climate through WAsP modelling for Site 2 using Wind Site 5 as the predictor site.

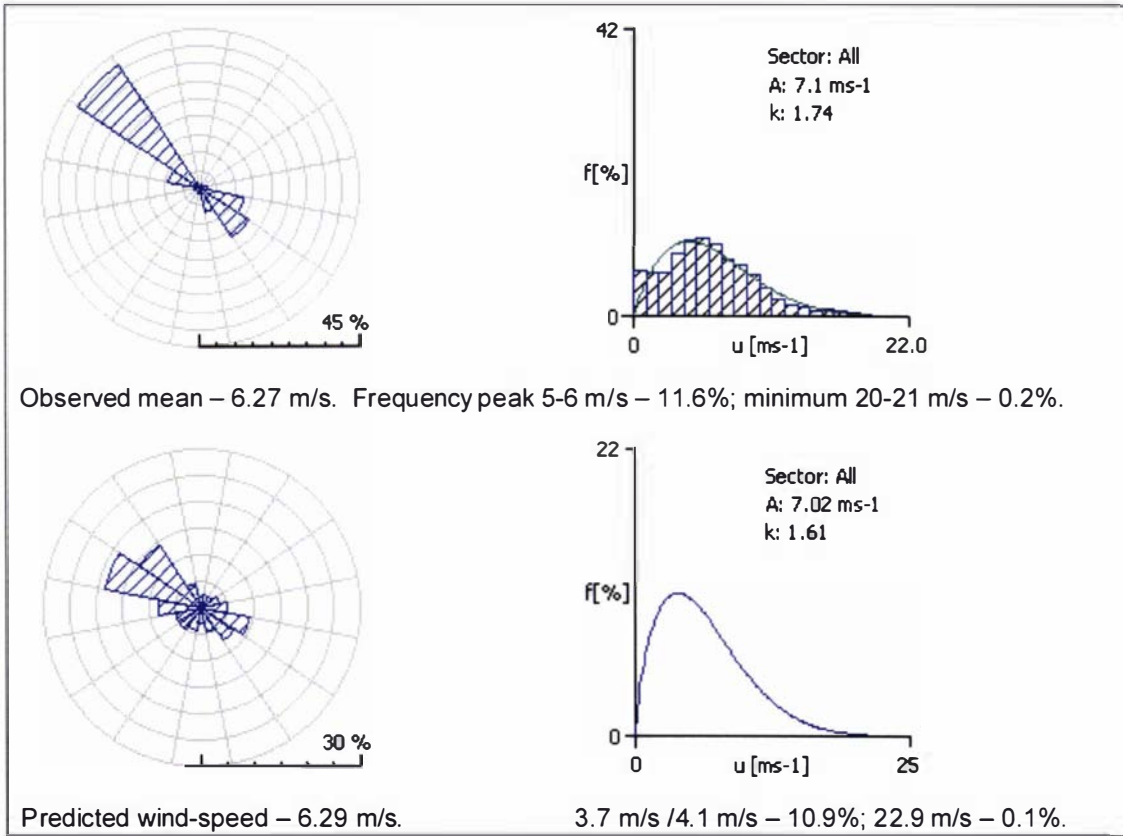


Figure 8.6 The observed and predicted wind climate through WAsP modelling for Site 3 using Wind Site 5 as the predictor site.

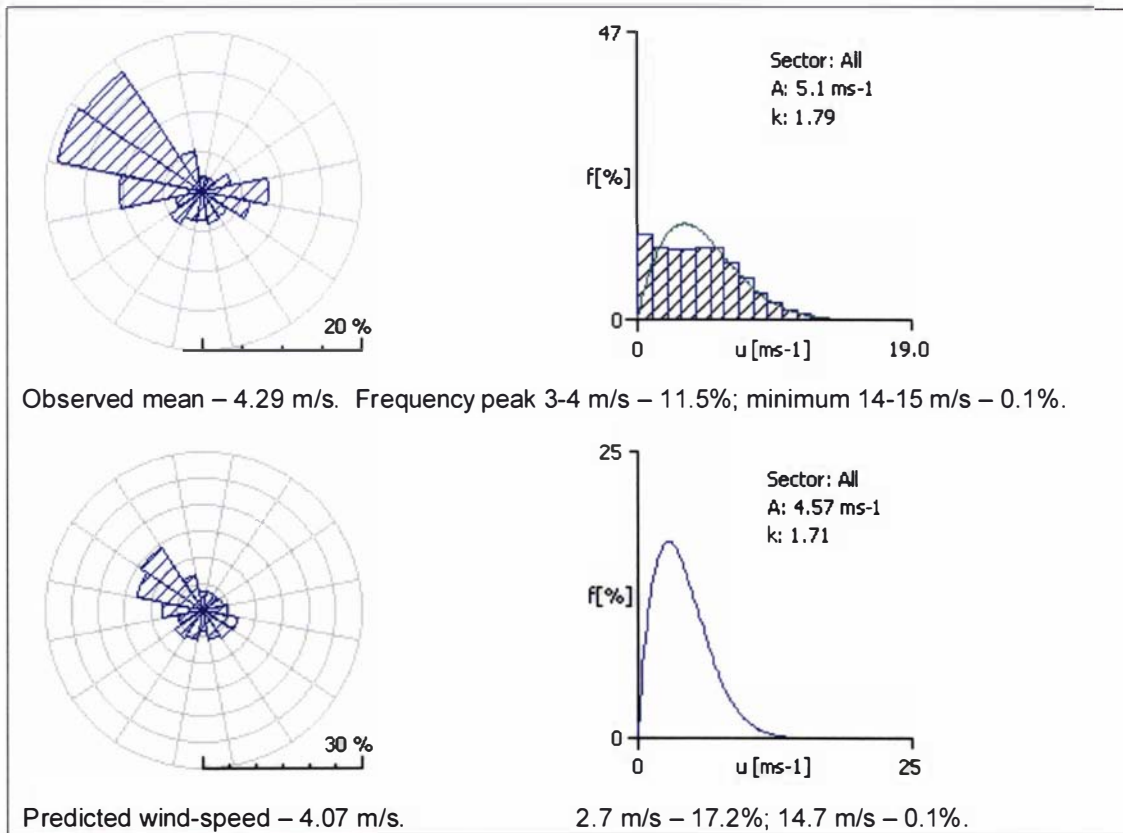


Figure 8.7 The observed and predicted wind climate through WAsP modelling for Site 4 using Wind Site 5 as the predictor site.

8.3.2 Totara Valley Wind Atlases

The two wind atlases of Totara Valley (Figure 8.8 and Figure 8.9) were modelled on Wind Site 5 data, and the relative wind-speeds and locations of relatively higher wind power density in the Totara Valley region are indicated. The WAsP parameters of 600 metres inversion and softness of 0.1 were used to model these atlases. The brighter red areas indicate the areas of higher relative wind-speed in Figure 8.8.

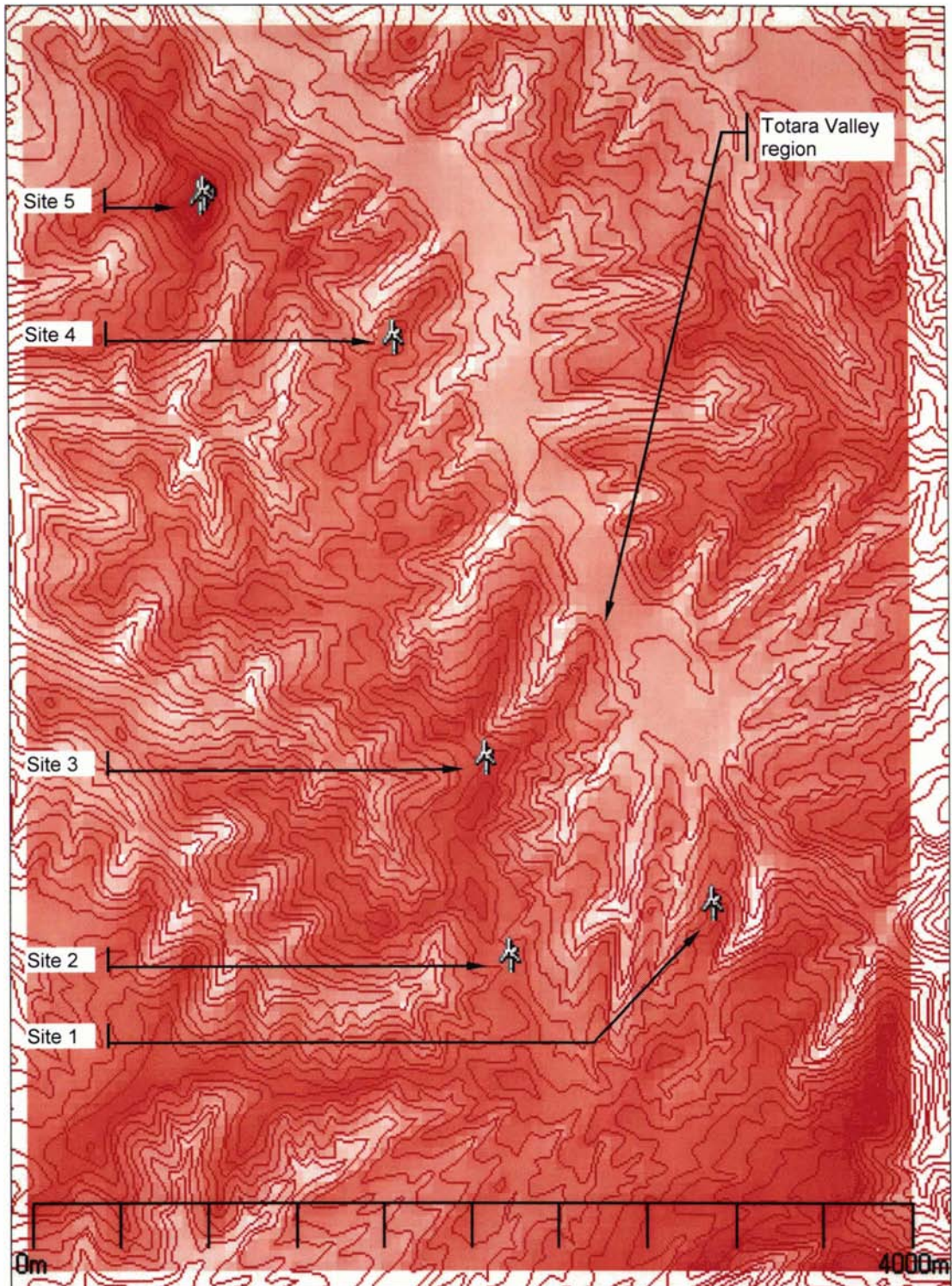


Figure 8.8 The WAsP modelled relative wind-speed wind atlas for the Totara Valley region.

The relative levels of wind power density (W/m^2) in the second wind atlas (Figure 8.9) are indicated by the colour gradient of white to purple. The bright purple areas indicate areas of relatively higher wind power density and the white areas relatively low power density. Wind Site 5 clearly had the highest level and Sites 3 and 4 appeared to be just to one side of areas of relatively higher power density.

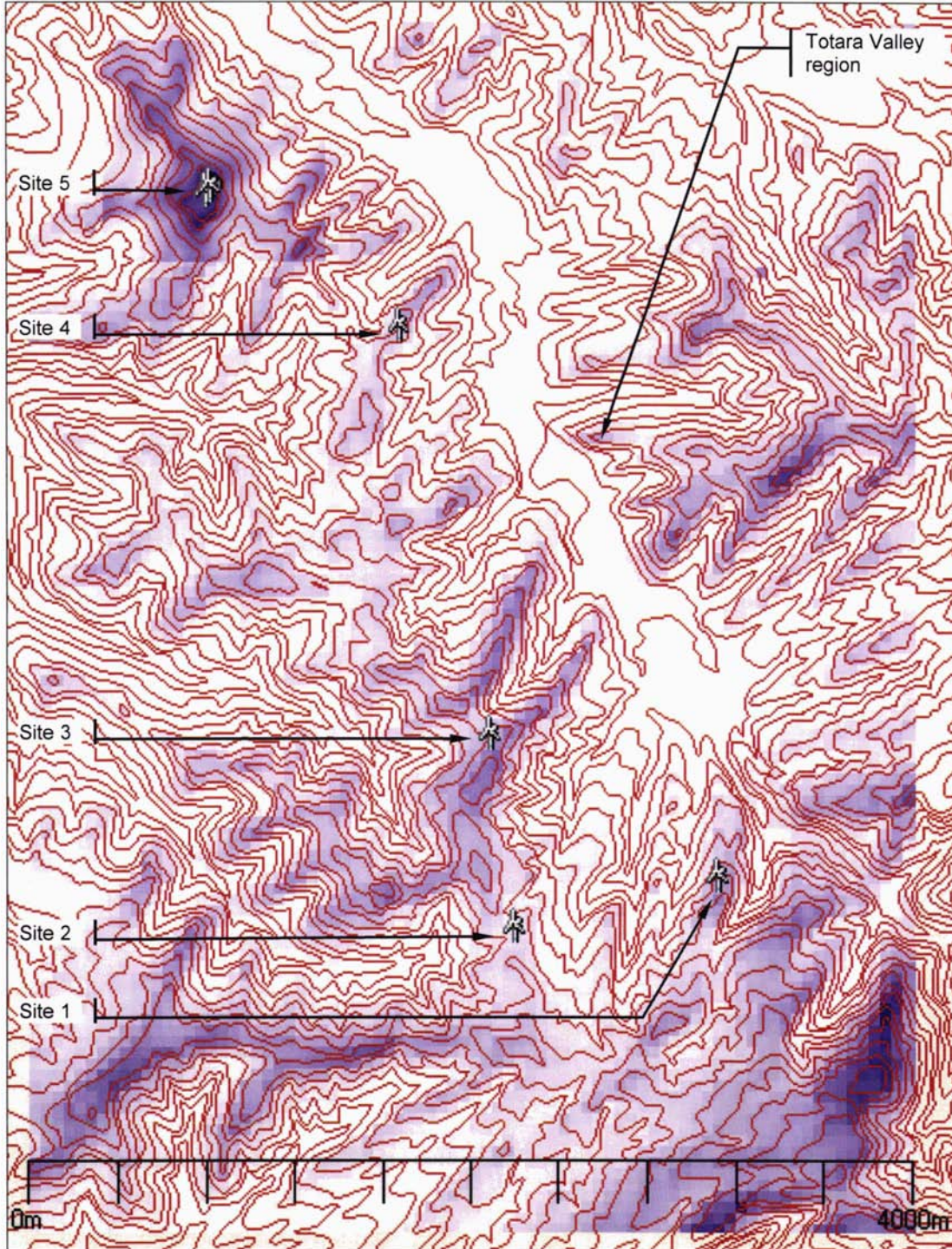


Figure 8.9 The WAsP modelled relative power density (W/m^2) wind atlas for the Totara Valley region.

8.3.3 Ruggedness Index Number – Prediction Error Analysis

As a test of the extent of the error in the WAsP modelled results relative to the terrain complexity, the ruggedness index (RIX) number differences between the reference Site 5, and Sites 1 to 4, and prediction error from the modelled results were compared. The overall RIX number difference (i.e. RIX of the predictor Site 5 minus the RIX of the predicted site – Table 8.1) was compared with the overall prediction error of the Weibull 'k' and 'C' parameters (Figure 8.10).

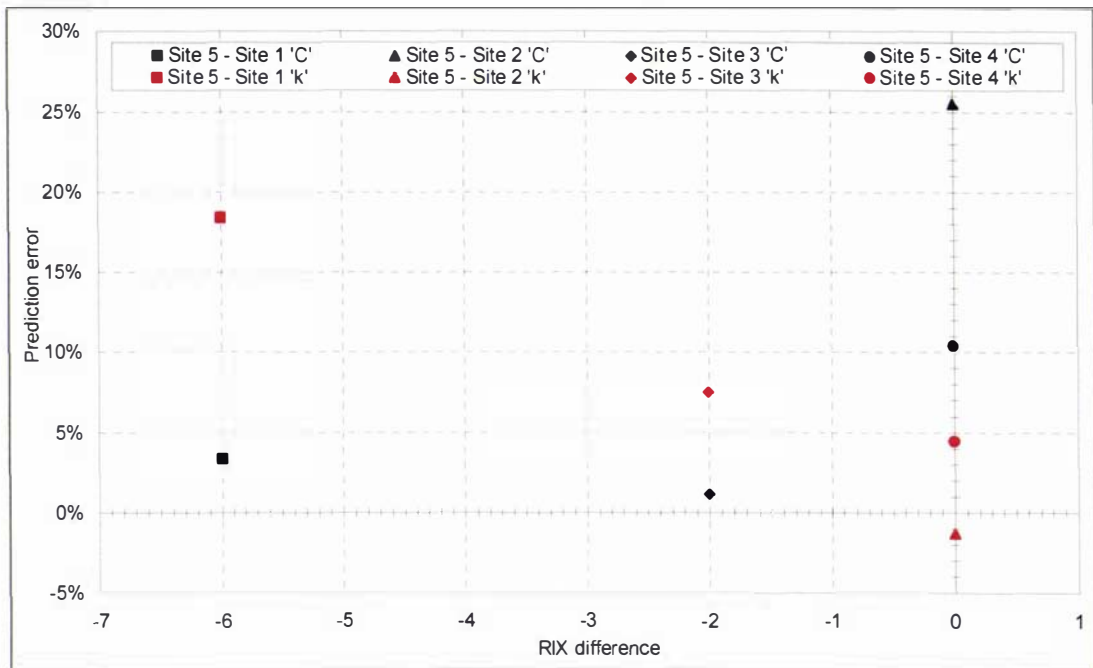


Figure 8.10 A comparison analysis of the Wind Site 5 RIX number and prediction error for the Weibull 'k' and 'C' values for Sites 2, 3, and 4.

A key result of this error analysis was that when using Site 5 as the predictor site the modelled results of Site 1 and 3 had a smaller prediction error of 3% and 1% respectively, which was relatively close to the RIX difference of -6 and -2 (Figure 8.10). The negative value of the RIX difference indicated that the RIX values of Site 5 were smaller than the values of the predicted sites and therefore the modelling errors were significant and unequal. The overall prediction was over-estimated with a significant positive error. The prediction error was supposed to be proportional to the difference in RIX values, and in this study, for Sites 1 and 3 this was true. For Sites 2 and 4 with a prediction error of 26% and 10% respectively and a RIX number difference of 0, the use of the difference was not considered an accurate portrayal of model accuracy for these sites.

8.3.4 Short-Term Duration Analysis – WAsP Modelling

An analysis of a wind atlas map utilising data obtained from 2100 hours of monitoring identified slightly different locations of the high relative wind-speed shown in Figure 8.8. The Weibull 'k', and mean wind-speed from the 2100-hour duration WAsP predicted wind climate for Site 3 would be used for HOMER wind modelling (Figure 8.11).

The predicted mean wind-speed for Site 3 was 6.80 m/s, slightly higher than the final measured wind-speed of 6.27 m/s, after 1340 hours of monitoring. The 2100-hour duration Weibull 'k' was 2.07.

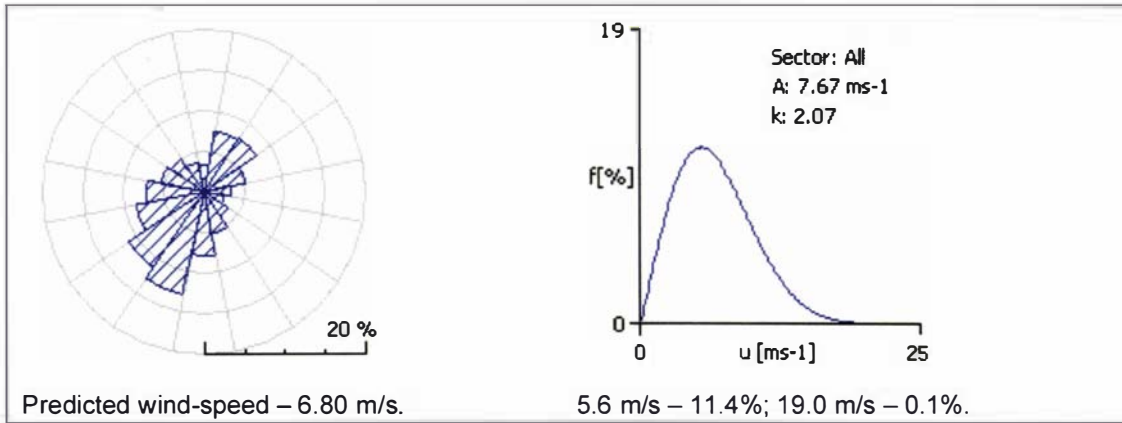


Figure 8.11 The observed and predicted wind climate through WAsP modelling for Site 3 using Wind Site 1 as the predictor site.

8.4 Discussion

The assessment of which reference site to use resulted from having two sites to choose from. In a short-term duration project, this would probably not be the case and therefore the reference site would be chosen initially from anecdotal evidence, intuition, or the location previous data monitoring indicating the presence of a good wind energy resource. The data coming in from this reference site would then be assessed for a stable mean in conjunction with the wind data being used to produce a regional wind atlas. If the wind atlas identifies any sites of interest, then intermediary monitoring can be undertaken in order to provide data for WAsP model validation. This validation process would provide the required modelled mean wind-speed and Weibull 'k' for HOMER wind energy resource modelling. However, if no further sites are identified through this analysis, then monitoring can continue until other SPIRAL model inputs are obtained (electricity load data, solar resource data, and hydrological data etc). In this case, the final mean wind-speed and Weibull 'k' data from the initial reference site can be used in the HOMER model.

In this study, data from Wind Sites 1 and 5 were assessed for their suitability as reference sites for modelling the wind atlases for the Totara Valley region. Because Wind Site 1 was in place before the commencement of this study (Irving, 2000), there was already a data set to use. However, the author had doubts as to the usefulness of this data for this purpose due to the complexity of the surrounding terrain and the consequent potential for distortion of data. An initial wind atlas was produced from this data and it identified sites of interest, in particular the site that became Wind Site 5 (Figure 14.1).

Site 5 was used as the reference site after a ruggedness index (RIX) analysis established that the surrounding terrain of Site 5 was similar to Sites 2, 3, and 4, more so than was the terrain surrounding Site 1. A correlation and regression analysis indicated perhaps an obvious fact, that because of the close proximity of all the sites, there was a similar wind regime between them (Table 8.2 & Table 8.3).

The more important method of assessing site similarity was a spatial comparison between site RIX numbers. This involved comparing the percentage of terrain over the nominated critical 0.3 slope within defined sectors between sites. Site 5 had more similarities with Sites 2, 3, and 4 than did Site 1. Since WAsP uses terrain slope data as the determinant of the terrain effects on the wind climate between sites, the findings of the RIX analysis of differences between sites was deemed more important than the correlation and regression analysis of wind-speed between sites. To this end, Site 5 was chosen as the predictor wind climate as opposed to Site 1.

An analysis was then undertaken to determine the best WAsP modelling parameters to use in modelling the Totara Valley region. Section 8.2.2 detailed the results of a sensitivity analysis to determine the appropriate inversion level and the required level of 'enforcing' this effect, the softness factor. From this analysis, the closest the modelled data came to resembling the observed data for the wind sites was produced using a 600-metre inversion scale length, with a softness of 0.1 equal to a severe forcing of the effect of inversion. The required severity in the forcing reflected the degree of complexity of the terrain of the modelled locations, and was in keeping with the findings of Reid (1997) in the study of the channelling effects in the Manawatu area.

Using these modelling parameters, two wind atlases were produced for the Totara Valley area depicting the relative mean wind-speeds and the energy densities of the area. These illustrate in relative terms, the level of level of the mean wind-speeds (Figure 8.8) and the energy densities (Figure 8.9) about the region. Sites 3 and 5 were located at the optimum sites for relative energy densities. Overall, the modelled results conformed well to the data from Sites 1 and 3 but relatively poorly against Sites 2 and 4.

All WAsP modelled mean wind-speed errors were compared against the results of the RIX analysis, and it became clear that the wind resource of Sites 1 and 3 was over-estimated reflecting the RIX difference where an over-estimated prediction error similar to the magnitude of the RIX difference was evident (Figure 8.10). Sites 2 and 4 had an over-estimated prediction error far higher than the zero RIX difference calculated. From the analysis of the RIX number difference – prediction error WAsP would appear to have modelled Sites 1 and 3 satisfactorily. In New Zealand there would be few applications of WAsP in which extensive systems of hills and mountain ranges can be excluded (Reid, 1997) so for the RIX analysis to have indicated the magnitude and direction of the prediction error successfully was a satisfactory result.

In the short-term duration analysis, the Totara Valley wind atlases for 1000-hour incremental durations were calculated based on Site 5 data, and compared. There was no difference in any of the wind-speed mapping. Given that the initial wind atlas was to be used at the early stage of wind resource monitoring for identifying potential intermediary sites for monitoring, the duration of 1000 to 2000-hours ($\approx 6 - 12$ weeks) appeared to be sufficient for this purpose.

The modelled mean wind-speed and the Weibull 'k' value were modelled for Wind Site 3 to use in the short-term duration analysis in HOMER modelling (Chapter 9).

8.5 Summary

A modelling error was evident in the results when compared with observed data from the modelled sites. The use of the WAsP RIX tool satisfactorily indicated the magnitude and sign of this error at Sites 1 and 3, both of which will be used in the next section of this study with a suitable allowance for over-estimation of the wind resource.

The monitoring duration and hence, data set length of 1000 – 2000-hour duration appeared to be sufficient to provide WAsP with initial data to produce a wind atlas to be used in identification of other potential sites. Consequently, the WAsP model was used to produce the mean wind-speed and the Weibull 'k' data for inclusion in the short-term duration HOMER modelling of the wind.

9 Distributed Generation System Modelling

This section of the study used HOMER to simulate various configurations of wind turbines, solar photovoltaic (PV), and hydro systems to assess the economically optimal combination and capacity of technologies for the Totara Valley community in a renewable energy based distributed generation system. A full one-year time-series data set was used based on the results of the electricity load and renewable energy resource monitoring undertaken (Chapter 6 and 7).

The HOMER simulation and optimisation processes used in this study are described in Section 9.1. The use of HOMER within the SPiRAL framework is outlined (section 9.1.1). The settings and inputs for the HOMER simulations and optimisations were outlined for the full-term duration data (section 9.1.2) and the short-term duration data (section 9.1.3). These include a description of all the scenarios modelled, and the sensitivity values used. The results of the HOMER modelling and optimisation process using the assumptions and values outlined above are then given (Section 9.2). The results are given first as a ranked list based on lowest to highest NPC, and then as a series of tables showing the values and sensitivity variables needed in the decision modelling section of this study (Chapter 10). These results are discussed (Section 9.3) and followed by a summary (Section 9.4).

9.1 HOMER – The Method of Simulation and Optimisation

9.1.1 *HOMER within the SPiRAL Modelling Procedure*

Given that the Totara Valley is grid connected, all the simulation and optimisation modelling was undertaken assuming that any renewable energy generation system would also be grid connected. No modelling of stand-alone power supply systems was undertaken under the presumption that this option would be too expensive to contemplate replacing the existing grid-connection in conjunction with distributed generation systems. In previous studies the cost of stand-alone systems for the whole community were assessed as having a net present cost of over \$1,195,000 and a cost of energy of around 1.00 \$/kWh depending on the water heating arrangements (Irving, 2000).

The simulation procedure used to obtain the results required for the SPiRAL process comprised of five steps (Figure 9.1). First, the required data was gathered in the correct format. If data was unavailable, it was modelled using the listed parameters. Secondly, an overall simulation that included all combinations of the solar, wind and hydro technologies was undertaken²⁶. From these results, the different configurations from HOMER were then simulated individually to include the single technologies or the hybrid combinations only.

²⁶ A diesel generator was not modelled because using conventional fuel would not be sustainable, and there is currently no bio-fuel infrastructure in New Zealand and so this is not a mainstream renewable energy technology. In reality, a diesel generator may be required for use with non-dispatchable generation sources such as solar and wind, however, it was not modelled in this study.

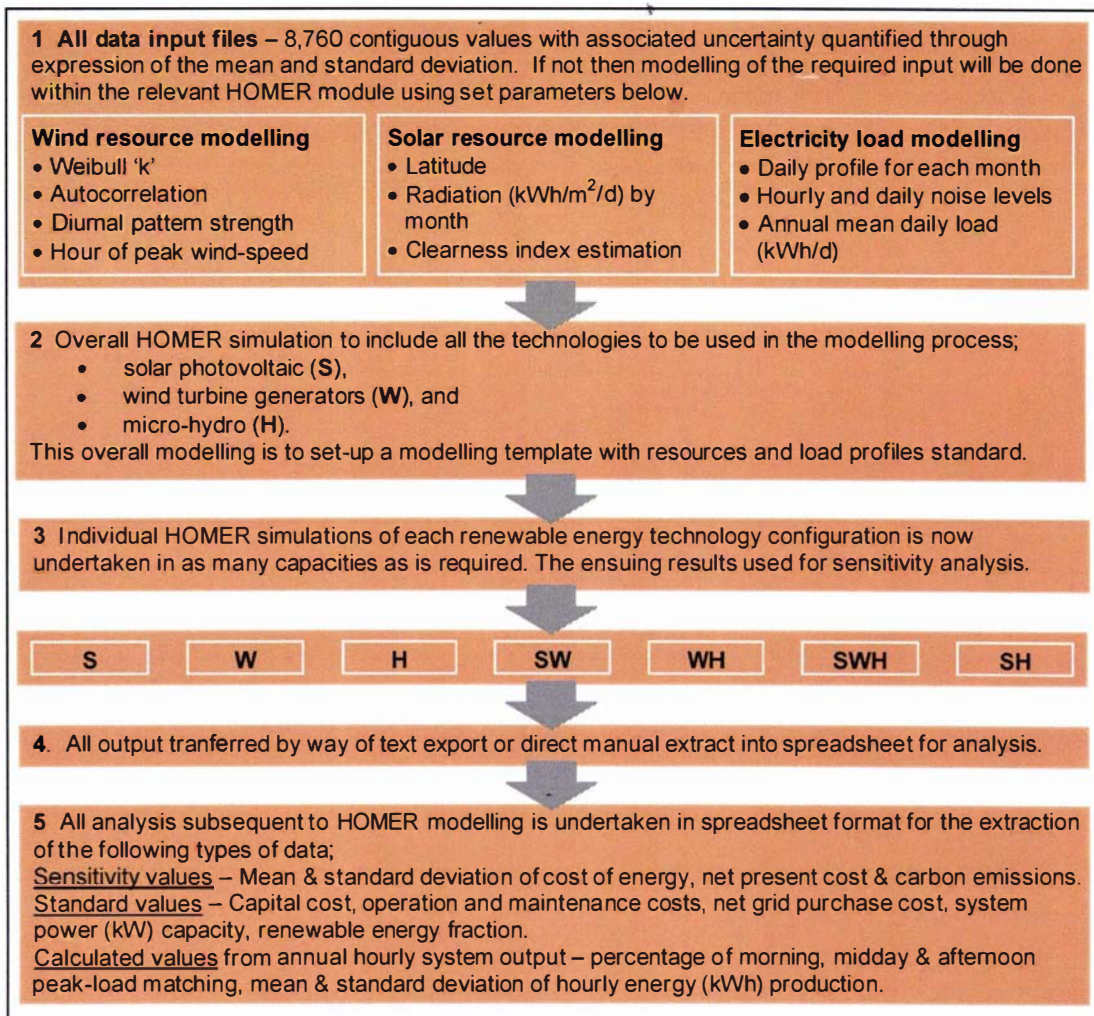


Figure 9.1 The five-stage simulation procedure used to obtain outputs from HOMER useful to the Logical Decisions for Windows process.

Due to data export limitations, the fourth and fifth stages required some manual data extractions and manipulation. The final stage involved preparation of data for use in the decision analysis model (Chapter 10). The extraction and analysis of the sensitivity variables was undertaken and a mean and standard deviation value derived for each, whereas non-sensitivity values were left as they were. Further analysis in a spreadsheet was required on some of the HOMER output to derive the required calculated values of morning, midday, and evening peak-load matching and the level of mean hourly energy generated.

Although only singular technology capacities were modelled in this study, instead of multiple capacities, this modelling format could be used to model multiple capacities of technologies. The resultant singular technology capacity format was a natural outcome from the HOMER economic optimisation process where the lowest net present cost was the optimising factor.

The net present cost as calculated by HOMER includes all the costs (as entered by the user) and any ensuing revenues occurring within the prescribed project lifetime. As with any calculation such as this, these are discounted to the present value of the costs (Equation 9.1).

The net present cost as used by HOMER was defined as follows:

Equation 9.1 The formula used to calculate the net present cost in HOMER

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})}$$

Where :

C_{NPC} = the net present cost (\$)

$C_{ann,tot}$ = total annualised costs of the system (\$/yr)

R_{proj} = project lifetime (yrs)

i = real interest rate (%)

CRF = the capital recovery factor

Source: Lilienthal *et al.* (2003).

The cost recovery factor is calculated as follows:

Equation 9.2 The cost recovery factor calculations used in HOMER.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$

Where :

N = the project lifetime (yrs)

$$i = \frac{i' - f}{1 + f}$$

i' = nominal interest rate

f = inflation rate

Source: Lilienthal *et al.* (2003).

Another output of HOMER used in the decision analysis process is the levelised cost of energy (COE), expressed as \$/kWh. This is defined as the average cost per kWh of useful electrical energy produced by the system (Equation 9.3).

Equation 9.3 The levelised cost of energy (COE) calculations used in HOMER

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{grid}}$$

Where :

$C_{ann,tot}$ = the total annualised cost of the system (\$/yr)

E_{prim} = the amount of the primary load served (kWh)

E_{grid} = the amount of energy exported to the grid (kWh)

Source: Lilienthal *et al.* (2003).

The total annualised cost of the system is the sum of the annualised capital costs, replacement costs, and the annual operation and maintenance costs (Lilienthal, *et al.*, 2003).

9.1.2 Full-Term Duration – Settings and Inputs

The load profiles used in HOMER (Figure 6.7 and Figure 6.8) were based on the monitored data and have had all the data gaps modelled using Equation 6.1. The wind data used in the HOMER modelling was profiled (Figure 7.7), and the period of January to December 2000 has been re-scaled to match the modelled mean wind-speed of Site 3, 6.27 m/s. The

solar data used in HOMER modelling was profiled (Figure 7.39), and the period of January to December 2000 was used. The hydro data used in HOMER (Figure 9.2) was based on the findings of the hydro monitoring (section 7.2.5). A residual flow of 30 ℓ/s will be allowed for in the modelling of the hydro systems.

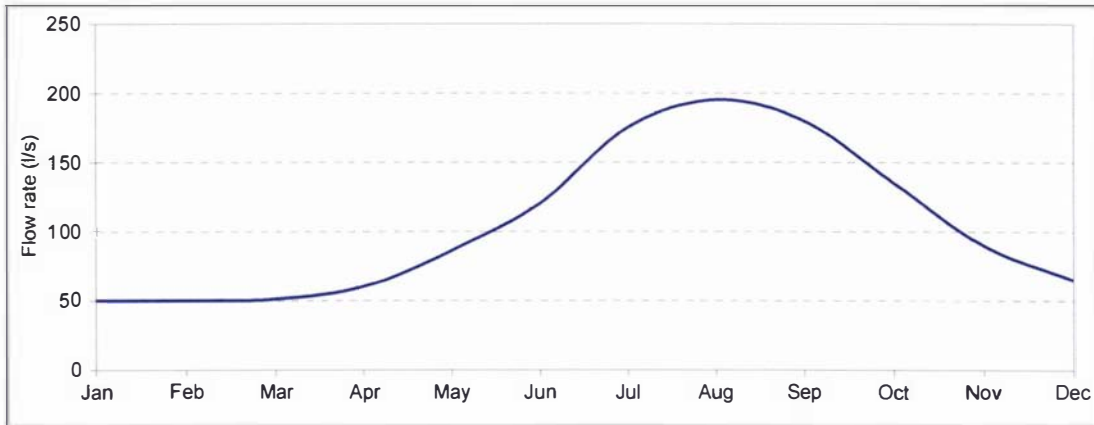


Figure 9.2 The annual stream flow of Totara Stream used in the HOMER modelling based on measured data.

Sensitivity Values

HOMER simulations can involve any number of sensitivity variables as required. The inputs that have sensitivity variables in this study are annual mean daily electricity load (kWh/d), mean annual solar insolation ($\text{kWh/m}^2/\text{d}$), and mean annual wind-speed (m/s) inputs. The values entered were used by HOMER to re-scale the original data to match the sensitivity value. The sensitivity values in HOMER each comprise one part of a parametric analysis and therefore, each has an equal probability of occurrence. There was no way of indicating that one sensitivity value had more chance of occurring than any other value.

The mean electricity used per day (kWh/d) summary load data used in the HOMER model is listed in Table 9.1. The 'monitored load' figure is a mean kWh/d value derived from the load data used (Chapter 6). The 'reduced load -10%' and the 'increased load +25%' figures were intended to assess the affect of decreasing the mean daily load by 10% due to energy efficiency uptake or increasing the mean daily load by 25% due to the potential for future growth.

Table 9.1 The electricity load inputs to be used in a sensitivity analysis in HOMER.

Site	Load type	Gap-filled load profile (kWh/d)	Reduced load -10% (kWh/d)	Increased load +25% (kWh/d)
1 – 9	Domestic & Farm	122	109.8	152.5
	Water heating	75	67.5	93.8

A figure of 10% was used as the lower limit partially because as a nation this is representative of the amount we could collectively reduce our electricity use during the recent electricity shortages (MED, 2002). The value of 25% has been used to account for load increases in the future.

The wind energy resource at Totara Valley was monitored and recorded at five locations (Figure 5.3). The monthly wind-speed profile used in the HOMER modelling was compiled from the time-series profile of Wind Site 1, and was re-scaled to the modelled mean wind-speed of Wind Site 3, 6.29 m/s (Figure 8.6). The wind-speed profile from Wind Site 1 was used because of the close proximity to Wind Site 3, and it was assumed that the profile would not differ much.

A figure of $\pm 15\%$ was used as the uncertainty level for the sensitivity analysis values, and was based on reported long-term annual average wind-speed variation of between 5% to 10% (Reid, 1991), 10%, (Van Lieshout, 1997), and 6% (Raftery *et al.*, 1999), and an analysis of the long-term wind-speed data from Grasslands, Palmerston North (Figure 9.3). A figure of 15% has been used as the upper and lower uncertainty value, thus the sensitivity figures of 7.21 m/s and 5.33 m/s were used.

The Weibull 'k' used was derived from the modelling (Figure 8.6), but the autocorrelation factor, diurnal pattern strength, and the hour of peak wind-speed were set at the Site 1 levels because the monitoring period at Wind Site 3 was too short to assess them, and the sites were close enough for these modelling values to be relatively similar.

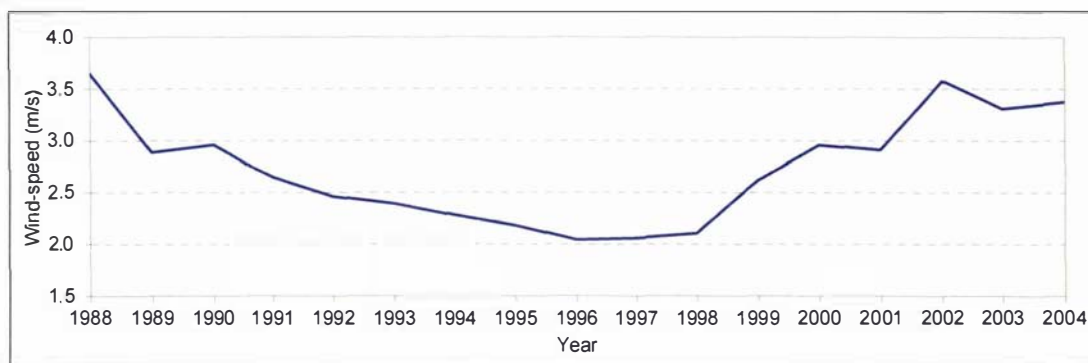


Figure 9.3 The annual mean wind-speeds for Grasslands Research Centre, Palmerston North over a 17-year period.

The solar resource at Totara Valley was monitored and the mean annual value of 2.99 kWh/m²/d for the period January to December 2000 was calculated from this time series. Given the location of the solar monitoring site at a higher-altitude relative to the houses in the valley floor (Figure 5.3) there will be shading at these sites (Figure 7.42). The estimated losses from this shading and the fluctuation of the solar resource from year to year were used to estimate a lower sensitivity analysis value. This has been estimated as being approximately 5% for actual shading loss (Table 7.3), and 15% for annual year-to-year differences (Table 7.5). The solar sensitivity value for the community has therefore been estimated at up to 15% less (15% being the greater of the two figures) than the monitored value for Sites 1 – 9. Therefore, 2.54 kWh/m²/d will be used as a sensitivity variable in the HOMER simulations. A higher level of sensitivity value was not used because it was considered unlikely that the resource at the valley floor would be much higher than that monitored at the higher altitude.

The parametric effects of all the sensitivity variables on the simulation results will be used in an analysis of renewable energy generation system performance under both load and

resource uncertainty. The use of these sensitivity values in this way will produce results based on the assumption of equal probability of occurrence, that is, a drop in load is as likely as a rise in consumption etc.

Fixed Values

Fixed value inputs into HOMER are values not used in sensitivity analyses. These were the economic inputs, grid-connected values, constraints, and the system technologies (wind turbines, solar photovoltaic arrays, micro-hydro systems and all other equipment). All renewable energy technology costs have been derived from surveying the retail costs of several suppliers and averaging these back to a unit cost (\$/kW) for each of the technologies.

The Economic Settings were set as follows:

- The annual real interest rate of 3.8% was used, and was based on Equation 9.4 (Lilienthal *et al.*, 2003), with the 2001 nominal loan interest rate of 6.8%²⁷ and a rate of inflation of 3%.

Equation 9.4 The formula used to calculate the real interest rate used in the HOMER economic model.

$$i_{real} = \frac{i_{nom} - f}{1 + f}$$

Where :

i_{real} = the real interest rate

i_{nom} = the nominal interest rate (at which loans are calculated)

f = the inflation rate

Source: Lilienthal *et al.* (2003).

- System fixed operation and maintenance cost was based on the daily charge paid by the Totara Valley residents for electricity line maintenance amounting to \$182.50 per year for each connection.
- An overall project lifetime of 25 years.
- Unmet load costs and fixed capital costs are set to zero.

The project lifetime was been set to 25 years. This length of time was set to match the long-time commitment that investment in distributed generation represents. Technology lifetimes vary within this time duration and for this study, the assumption is that wind turbines will last 15 years; solar photovoltaic, 20 years; hydro equipment, 25 years; and the DC to AC inverter equipment, 10 years. As the technology lifetime passes, the HOMER model will incur new costs associated with new equipment installation.

Fixed capital costs could include the costs associated gaining resource consent for the modelled systems and ongoing compliance costs but because these costs are varied, it has not been included in this assessment. Resource consent application costs are allocated after consent has been granted and can include staff costs, as they were required, ongoing

²⁷ These figures are based on the December 2001 interest rates and are simple interest rates. Interest rate data was obtained from the Reserve Bank of New Zealand (www.rbnz.govt.nz). A weighted average cost of capital was not used.

compliance costs, any third-party reporting costs, advertising costs, pre-hearing costs, document preparation and circulation, and any associated travel time.

Costs of resource monitoring and electricity load profile work could also be included in the associated system fixed capital costs; however, they have not been. Such costs of resource and electricity monitoring were separated from the cost of renewable energy system design. The decision analysis system is about assessing renewable energy design decision options, and not detailed system design and implementation (although costs should reflect reality as closely as possible). Such costs would be considered sunk costs and be incurred prior to detailed system design. They would be expected to be invoiced and paid for after the decision analysis and therefore prior to any detailed design and implementation work once a system was decided upon.

The settings used to determine the economics of the interaction of the DG system with the grid network were:

- grid power price (\$0.132 kWh), based on current pricing,
- sellback rate (\$0.08 kWh), based on a premium wholesale rate,

The net-metering calculations are calculated monthly in this study. Annual calculation was an option. When the amount of electricity 'sold' to the grid is less than the amount 'purchased' the electricity is 'sold' at the retail cost, in this case, \$0.132 kWh. When the amount of electricity 'sold' to the grid is more than the amount 'purchased' the difference is 'sold' at the sellback rate, in this case, \$0.08 kWh. Any monetary return from the electricity sold was accounted for in the operation and maintenance figure of the HOMER results.

The carbon content of a kilowatt-hour of electricity for this study was set to the New Zealand Climate Change Office marginal rate of 0.6 kgC/kWh (Anon, 2003).

Certain constraints can be placed on the renewable energy generation system in HOMER if required. Such constraints include the maximum allowable capacity shortage (%), minimum renewable energy fraction (%), and operating reserve as a percentage of the mean hourly load, annual peak-load (%), solar output (%), and wind output (%). The only constraint imposed on simulations in this study was on the setting of the minimum renewable energy fraction option at 1%. This 'forced' the removal of the grid-alone option from the resultant optimisation mix at stage 2 of the modelling (Figure 9.1).

The annual flow used in the micro-hydro modelling was estimated based on three separate monitoring periods (Chapter 7) and was plotted in Figure 9.2. This flow was used to model a combination of three hydro systems. Due to the limitation in HOMER of only being able to model a single hydro system, all three scenarios were modelled in a combined manner in the HOMER simulation. This was done by summing the head to seven metres, the penstock length to 170 metres, and using a design nominal flow-rate of 40 l/s, and a turbine efficiency of 75%, giving a combined nominal capacity of 2.06 kW. The hydro system has been set to be able to operate within the range of 35% to 150% of the nominal flow rate.

The three different hydro scenarios modelled were:

- Hydro Site 1 – a cross-flow turbine or a Turgo turbine installed at the culvert area at Farm 1 with an earth dam and 100 metres of 300²⁸ mm diameter penstock, a nominal design flow rate of 40 l/s, and a 3-metre head.
- Hydro Site 2 – a cross-flow turbine at the oxbow area at Farm 3 below Site 5 with a diversion weir and 20 metres of 300 mm diameter penstock, a nominal design flow rate of 40 l/s, and a 2-metre head.
- Hydro Site 3 – a cross-flow turbine in the stream below Site 8 shearing shed on Farm 3 after a diversion weir and 50 metres of 300 mm diameter penstock, a nominal design flow rate of 40 l/s, and a 2-metre head.

The cost data used in this simulation (Table 9.2) assume the costs:

- earth works at \$10,000 for a dam, and \$5,000 for a diversion weir;
- a penstock of 300 mm diameter PVC pipe at \$142/m;
- electricity transmission line costs at \$15,000 per kilometre over flat terrain, and
- three different hydro turbines and generation plant calculated at \$13,616 per kW.

Table 9.2 The estimated hydro system construction cost data for the dam and two weir scenario in Totara Valley (2001 \$NZ).

Construction	Earthworks (\$)	Penstock (\$)	Transmission (\$)	Total costs (\$)
Dam	10,000	14,200	50m = 750	38,566
Weir	2 x 5,000	2 x 840	2x50m = 1,500	33,604
				72,170

HOMER can simulate the performance of two separate wind turbines (i.e. a 3 kW or a 10 kW turbine) in any renewable energy system configuration. However, the two different turbines cannot be in the one system (i.e. a 3 kW and a 10 kW turbine). HOMER will choose the optimal wind turbine size for inclusion in the system based on cost and performance. The wind turbine costs used in this study were based on site-specific characteristics such as transmission, wind turbine tower size, and associated rigging costs. The two wind turbine capacities made available for consideration, and the assumed costs of the wind turbines, towers, and transmission are shown in Table 9.3.

Table 9.3 The wind turbine options and the estimated costs per site (2001 \$NZ).

	WTG sizes (kW)	WTG costs (\$)	Transmission costs (\$/km)	Tower costs (\$)	Total costs
Cost parameters per WTG	3 10	10,910 39,000	\$15,000 / km	3,500 15,400	1 WTG (\$)
Sites 1 – 9	3 10	10,910 39,000	12,000	3,500 15,400	26,410 66,400

²⁸ 300 mm diameter pipe will lead to a low absolute head-loss of 157 mm (2.25%) over the total length of the penstock.

These assumed costs were derived from average technology retailer cost lists and are intended to reflect general costs per kW rather than accurate figures for particular wind turbines. The cost of transmission infrastructure was assumed to be \$15,000 per kilometre and this was incorporated into the final wind turbine cost. Tower costs were assumed to include any foundation work and rigging required.

The interface between the DC bus bar and the AC grid network requires an inverter connection and cost data was required for HOMER to calculate this cost. The total cost of the inverter connection comprises an estimate of the wiring costs of \$2,500 per connection. This has been used in this study instead of the complex and costly process of costing each individual site. For the combined sites 1 – 9, this is equal to \$22,500.

Solar PV costs were set to \$11,964/kW_p and array assumptions were: \$300 annual operation and maintenance costs; a derating factor of 10% to allow for aging, heat and dust issues over time; fixed (non-tracking) array systems; slope of 40 degrees from the horizontal; facing solar north; and a ground reflectance of 20%.

9.1.3 Short-Term Duration – Settings and Input Sensitivity Values

The short-term duration electricity load data was synthesised based on the January 2000 load from the 'gap-filled' community load data (Figure 6.11). The load parameters of daily and hourly noise were set to 8% and 15 % respectively. The mean daily load was 207 kWh/d and the two sensitivity values were set to 186 and 259 kWh/d respectively. Only one load was modelled as a combined domestic, water heating, and farm load.

The solar data used was from the NASA collated data and had an annual average of 3.58 kWh/m²/d (Table 7.5). Twenty percent variability was allowed for given the additional uncertainty of using non-monitored data. Therefore, the lower sensitivity value of 2.86 kWh/m²/d was used.

The wind profile used was based on the mean wind speed profile of Palmerston North (Figure 7.32), with the mean wind-speed set to the modelled wind-speed of 6.80 m/s (Figure 8.11). The wind-speed variation was set to $\pm 15\%$, 5.78 m/s and 7.82 m/s respectively. The Weibull 'k' value used was the WAsP modelled value of 2.07 (Figure 8.11); the autocorrelation factor, 0.91; the diurnal pattern strength, 0.13; and the hour of peak wind-speed was to 1500 hours (section 7.2.7).

There were no changes made to the hydro resource, and all settings were left as for the full-term duration model (section 9.1.2). For the analysis using short-term duration data, all cost data and technology capacity (Figure 9.1) remained the same as that set in section 9.1.2.

Fixed Values

All fixed values used in the short-term duration study remain the same as used in the full-term duration study.

9.2 Results

The modelling process was undertaken in the manner indicated in Figure 9.1, where overall modelling revealed the optimum combinations of the technologies and then these combinations were simulated and optimised separately such that sensitivity variables and other required data was obtained from the model.

The use of HOMER within the SPiRAL framework revealed limitations (section 9.2.1). Despite these limitations, HOMER produced data for use in the next stage of the SPiRAL model. The results are presented, ranked by the net present costs (section 9.2.2), with the sensitivity analysis results (section 9.2.3), peak load reduction for each system (section 9.2.4), and various miscellaneous values required for the decision analysis process (section 9.2.5). All the results as outlined have been calculated for the short-term duration, and these are given in section 9.2.6.

9.2.1 *Limitations of HOMER 2.19 within the SPiRAL Framework*

HOMER version 2.19 was used in this study and all results depicted are from this release. The beta release of this version was 'beta' tested using data in this study, with feedback given to the programme developers based at the National Renewable Energy Laboratory, Colorado. Development of the current version was to be on going and the version as used in this study (14th June 2005) had the following limitations:

1. The default HOMER time resolution of one hour led to results lacking the detail of performance that a smaller resolution would show. The monitoring of both electricity load and renewable energy resources indicated that much variation exists within an hour and this was missed by using this level of input data resolution.
2. Only one hydro system could be simulated and optimised at any one time. In some locations, there may be the option of two or more potential hydro systems. Any combined hydro systems were only possible if the flows were equal. Locations where high head/low flow systems and high flow/low head systems were possible cannot be simulated in the same file.
3. Even though two wind turbine capacities could be simulated in the same operation HOMER could not combine the two different capacities into an optimised configuration.
4. There was no ability to model sensitivity in the wind resource modelling dialog box thus restricting the ability to model sensitivity to variation or uncertainty in the Weibull 'k' value, the autocorrelation factor, the diurnal pattern strength, and the hour of peak wind-speed.
5. There was no facility for modelling a multi-tariff grid-connection for separate loads in a combined load site model (domestic and water heating tariffs). Only one rate of electricity charge (\$/kWh) and daily use charge (\$/d) was executable in the model.

9.2.2 *Ranked by Net Present Cost*

The default optimisation of all the alternatives in HOMER was on the basis of ranking the alternatives from the lowest to the highest NPC (Table 9.4). Although all renewable energy

systems were modelled as grid connected, the grid – alone option had the lowest NPC and was therefore ranked number 1.

Table 9.4 The full-term duration ranked results of the HOMER modelling.

Rank	System components and abbreviated label	PV (kW)	WTG (kW)	Hydro (kW)	Inverter (kW)
1 st	Grid alone	G	-	-	-
2 nd	Wind turbine	W	-	10 (AC)	-
3 rd	Microhydro	H	-	2.06 (AC)	-
4 th	Wind turbine & microhydro	WH	-	10 (AC)	2.06 (AC)
5 th	Solar PV	S	4.50 (DC)	-	4.50
6 th	Solar PV & wind turbine	SW	4.50 (DC)	3 (DC)	7.50
7 th	Solar PV & microhydro	SH	4.50 (DC)	2.06 (AC)	4.50
8 th	Solar PV, wind turbine, & microhydro	SWH	4.50 (DC)	3 (DC)	2.06 (AC)

PV is photovoltaic, WTG is wind turbine generator, and Hydro is the combination of three sites.

9.2.3 Sensitivity Analysis

Sensitivity analyses yielded a range of values based on the sensitivity variables used in the model. From these values, a mean and standard deviation (SD) were calculated (Table 9.5). The mean and standard deviation values of the cost of energy (\$), net present cost (\$), carbon emissions from the consumption of grid-based electricity (t/y), and the mean hourly energy from the system (kWh/h) can be compared with the status quo grid option.

Table 9.5 The full-term duration mean and standard deviation values for levelised cost of energy, net present cost, carbon emissions, and hourly delivered energy.

Alternative	Levelised cost of energy (\$)		Net present cost (\$)		Carbon emissions (t/y)		Mean hourly energy (kWh/h)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G	0.153	0.002	184,658	16,262	45,275	4,613	-	-
W	0.190	0.015	236,346	21,762	28,664	6,172	3.19	3.38
H	0.202	0.007	242,953	16,270	33,140	4,615	2.31	0.88
WH	0.226	0.018	294,686	21,681	16,528	6,173	5.50	3.57
S	0.251	0.012	302,478	16,276	43,052	4,616	0.46	0.77
SW	0.287	0.016	344,679	16,727	38,815	4,744	1.27	1.20
SH	0.300	0.017	360,773	16,283	30,917	4,619	2.77	1.13
SWH	0.334	0.020	402,972	16,730	26,679	4,745	3.58	1.50

A graphical presentation of the level of sensitivity of each of the options to extreme changes ($\pm 50\%$ in 12.5% increments) of load and resource variables are given below (Figure 9.4 to Figure 9.9) for changes in the net present cost, levelised cost of energy, grid sales (where applicable), and carbon dioxide emissions.

For the grid-only (G) option, the sensitivity to extreme changes in the loads for the net present cost, levelised cost of energy, and carbon emissions is given (Figure 9.4). This option appears to be quite sensitive to variability of the loads with reductions of load having a positive effect on both the net present cost and the level of carbon emissions but a negative effect on the levelised cost of energy.

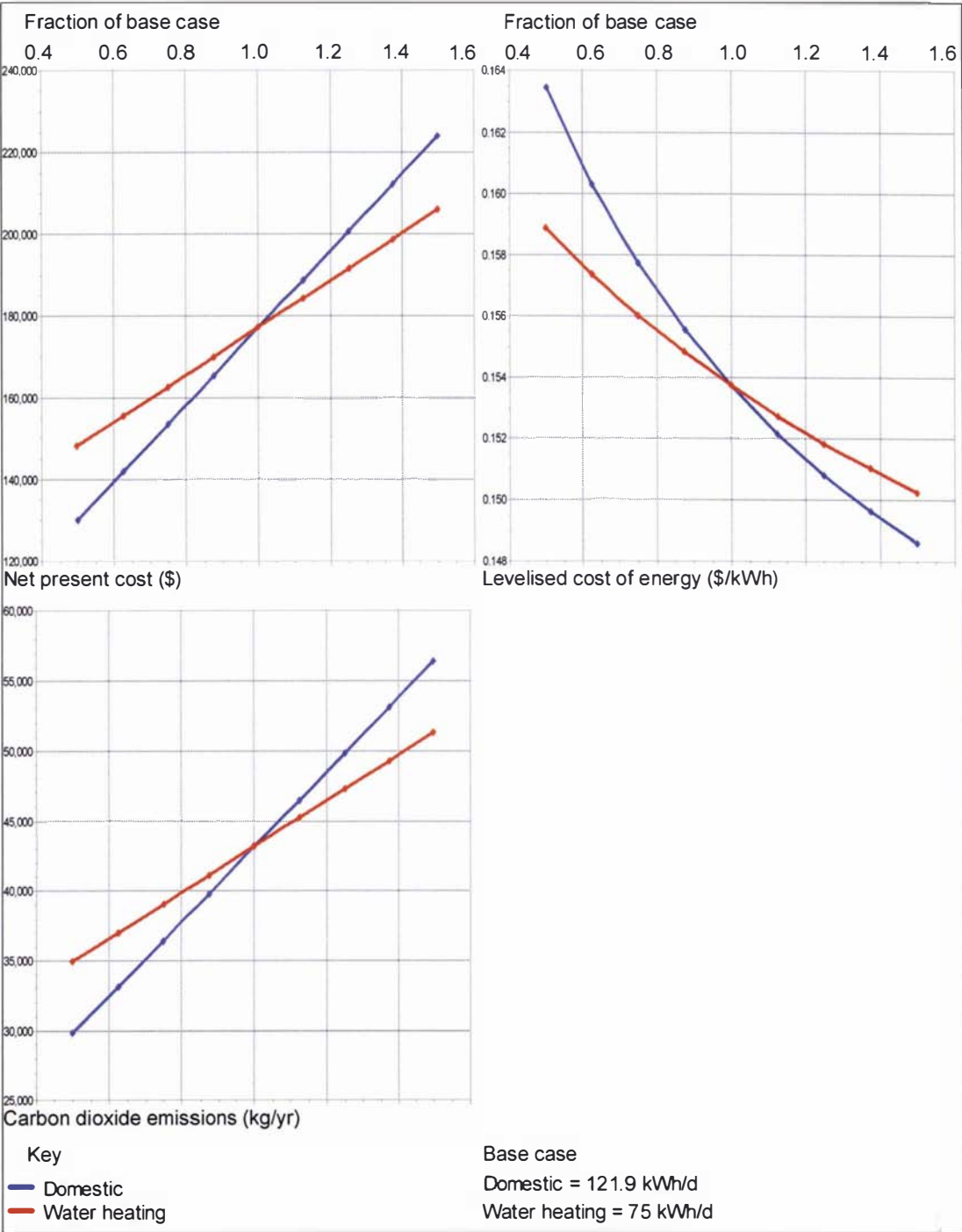


Figure 9.4 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), and carbon dioxide emissions (kg/yr) of the grid-only option.

For the grid-wind (W) option, the sensitivity to extreme changes in the loads and the wind speed for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.5). This option utilises the 10 kW wind turbine generator. This option appears to be quite sensitive to variability of the wind speed with small changes having large effects on all measured parameters.

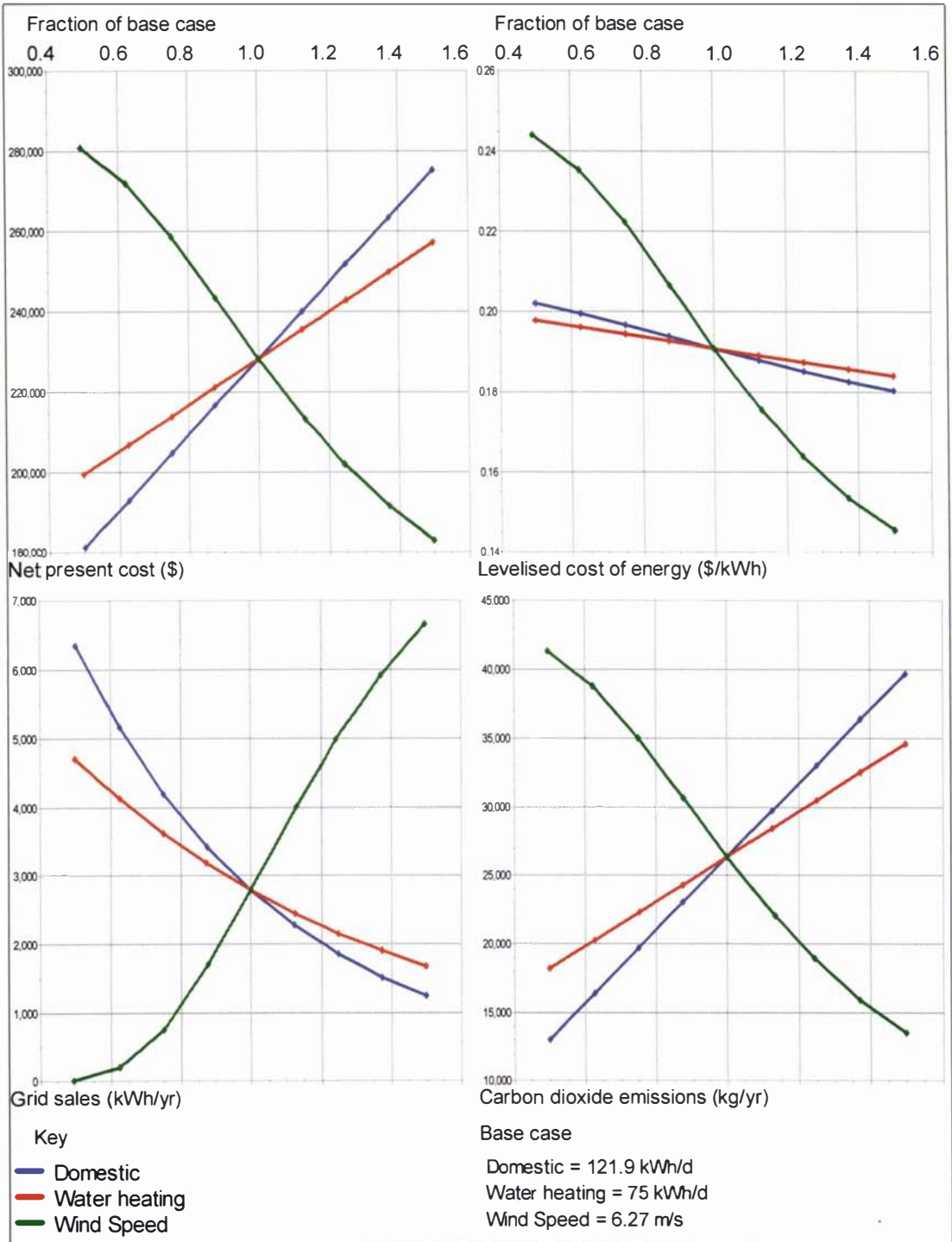


Figure 9.5 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-wind option.

For the grid-hydro (H) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.6). This option utilises the 2.06 kW combined hydro systems. This option appears to be sensitive to variability of the loads with reductions of load having a positive effect on both the net present cost and the level of carbon emissions but a negative effect on the levelised cost of energy. Grid sales are not overly sensitive to any changes.

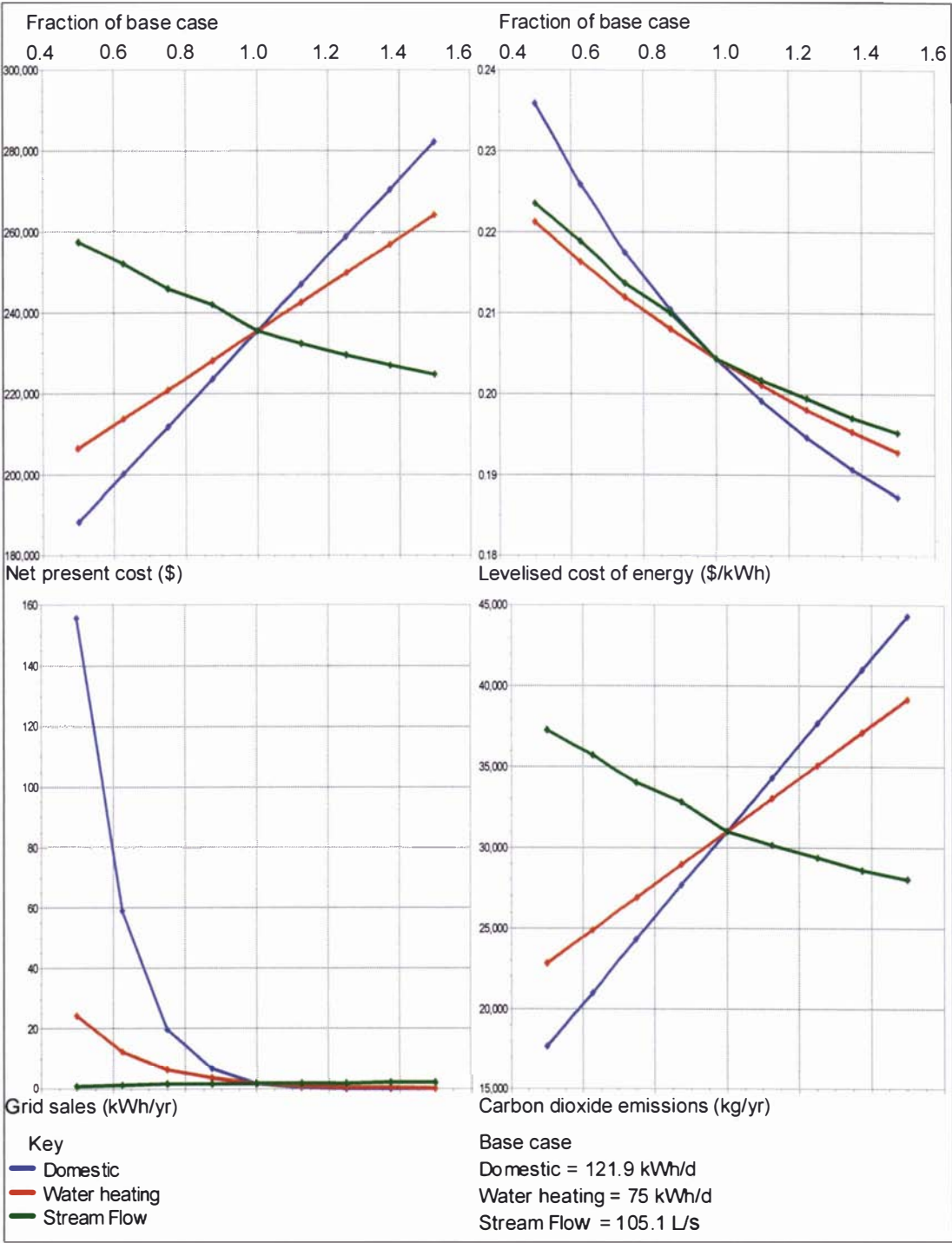


Figure 9.6 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-hydro option.

For the grid-wind-hydro (WH) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.7). This option utilises the 10 kW wind turbine generator and the 2.06 kW combined hydro systems. This option appears to be quite sensitive to variability of the wind speed with small changes having large effects on all measured parameters. Sensitivity to variability of the loads is also evident. A change to the stream flow has the smallest impact.

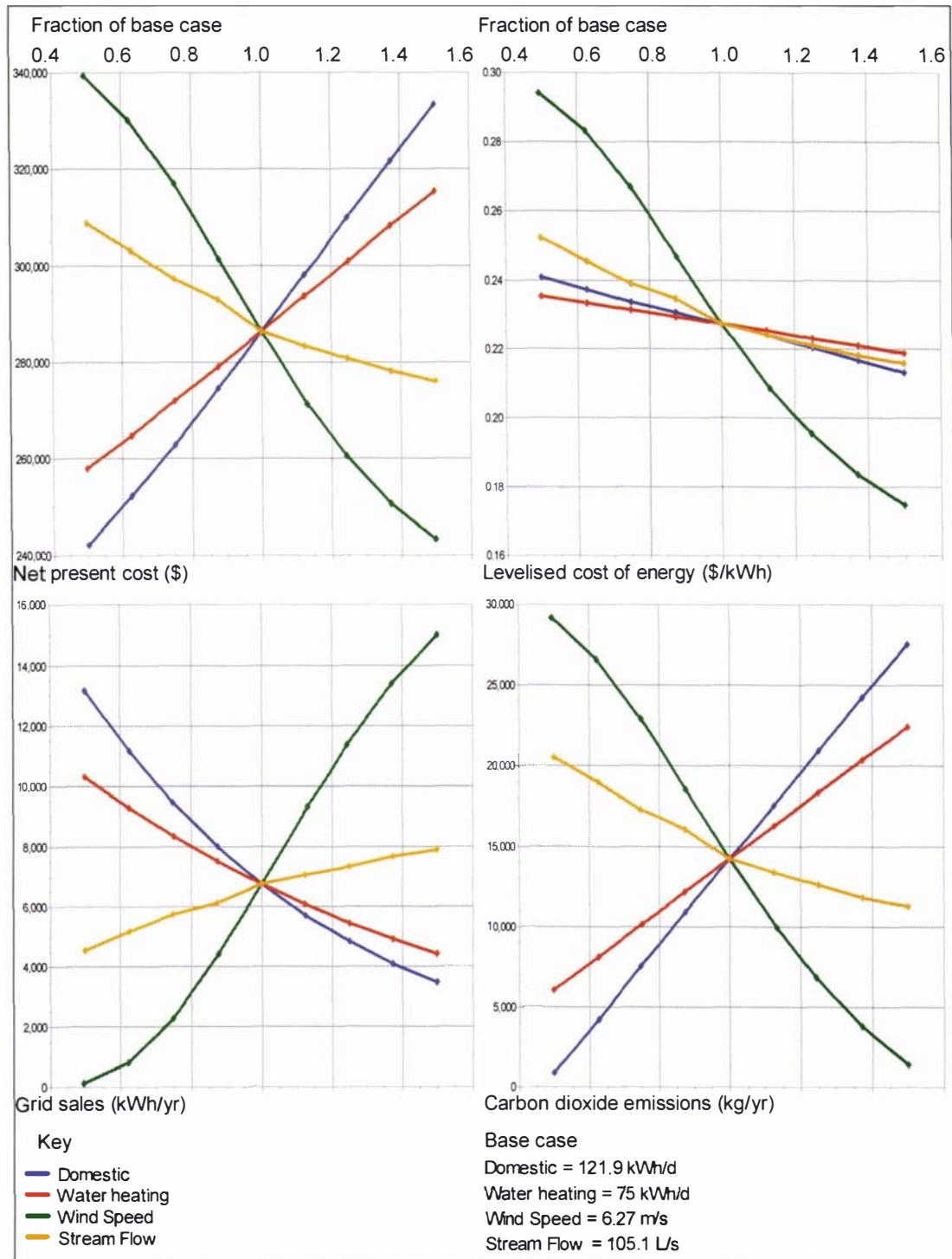


Figure 9.7 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-wind-hydro option.

For the grid-solar PV (S) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.8). This option utilises the 4.5 kW solar photovoltaic array systems. This option appears to be quite sensitive the loads. A change to the solar resource has a relatively small impact.

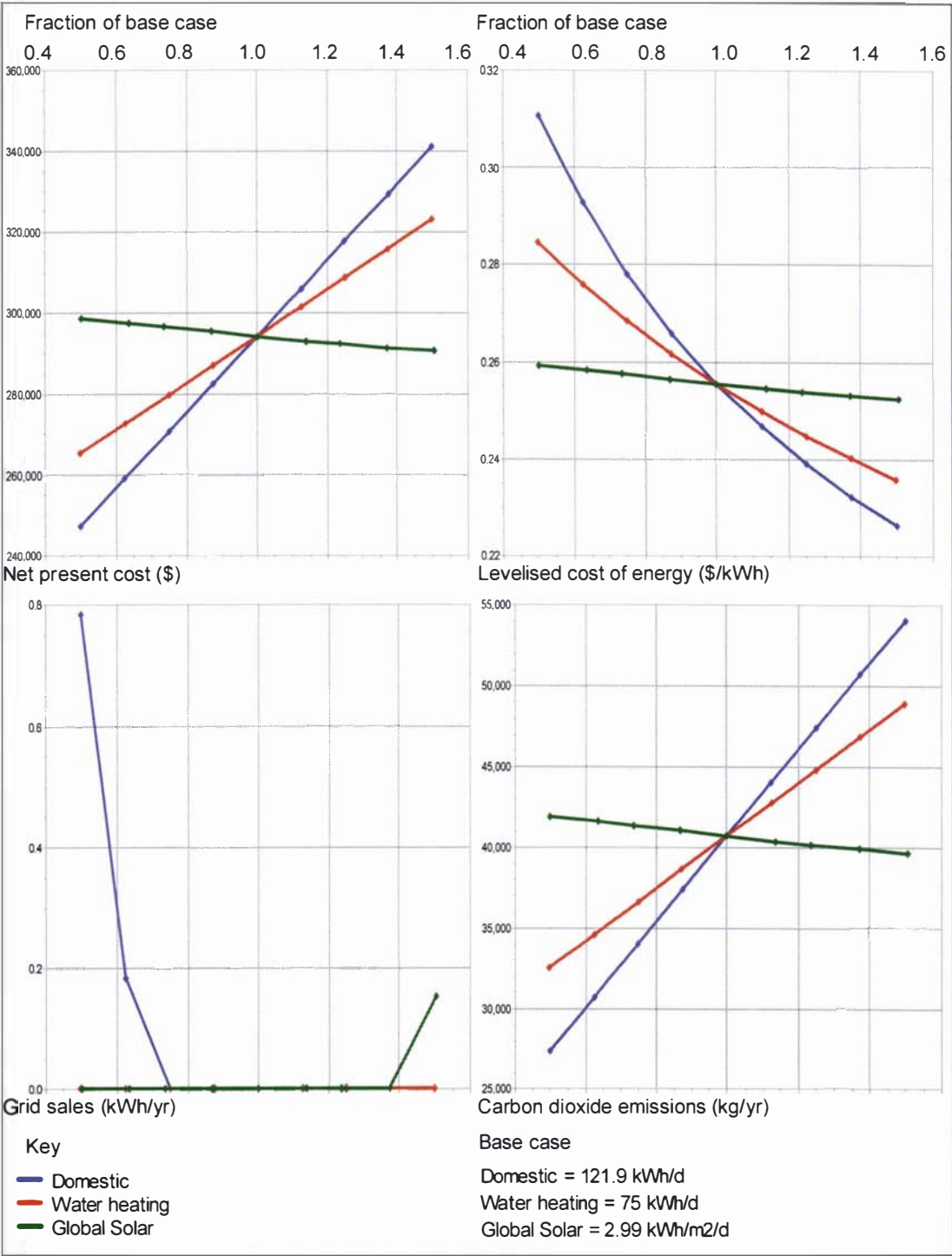


Figure 9.8 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-solar PV option.

For the grid-solar PV-wind (SW) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.9). This option utilises the 4.5 kW solar photovoltaic array system and a 3 kW wind turbine generator. This option appears to be quite sensitive the loads. Changes to both the solar resource and the wind speed have a relatively small impact.

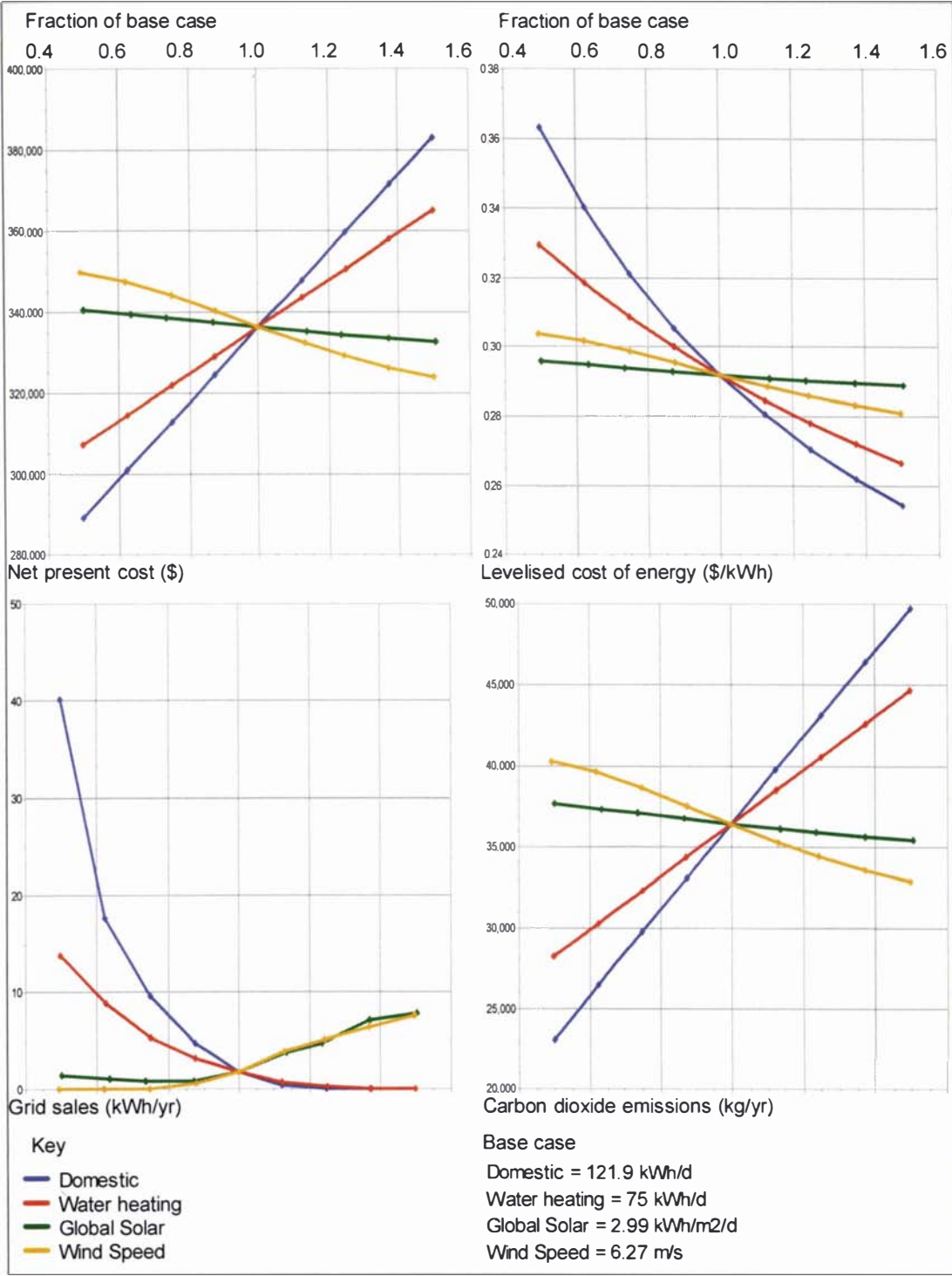


Figure 9.9 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-solar PV-wind option.

For the grid-solar PV-hydro (SH) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.10). This option utilises the 4.5 kW solar photovoltaic array system and the 2.06 kW combined hydro systems. This option appears to be quite sensitive the loads. Changes to both the solar resource and the stream flow have relatively small impacts.

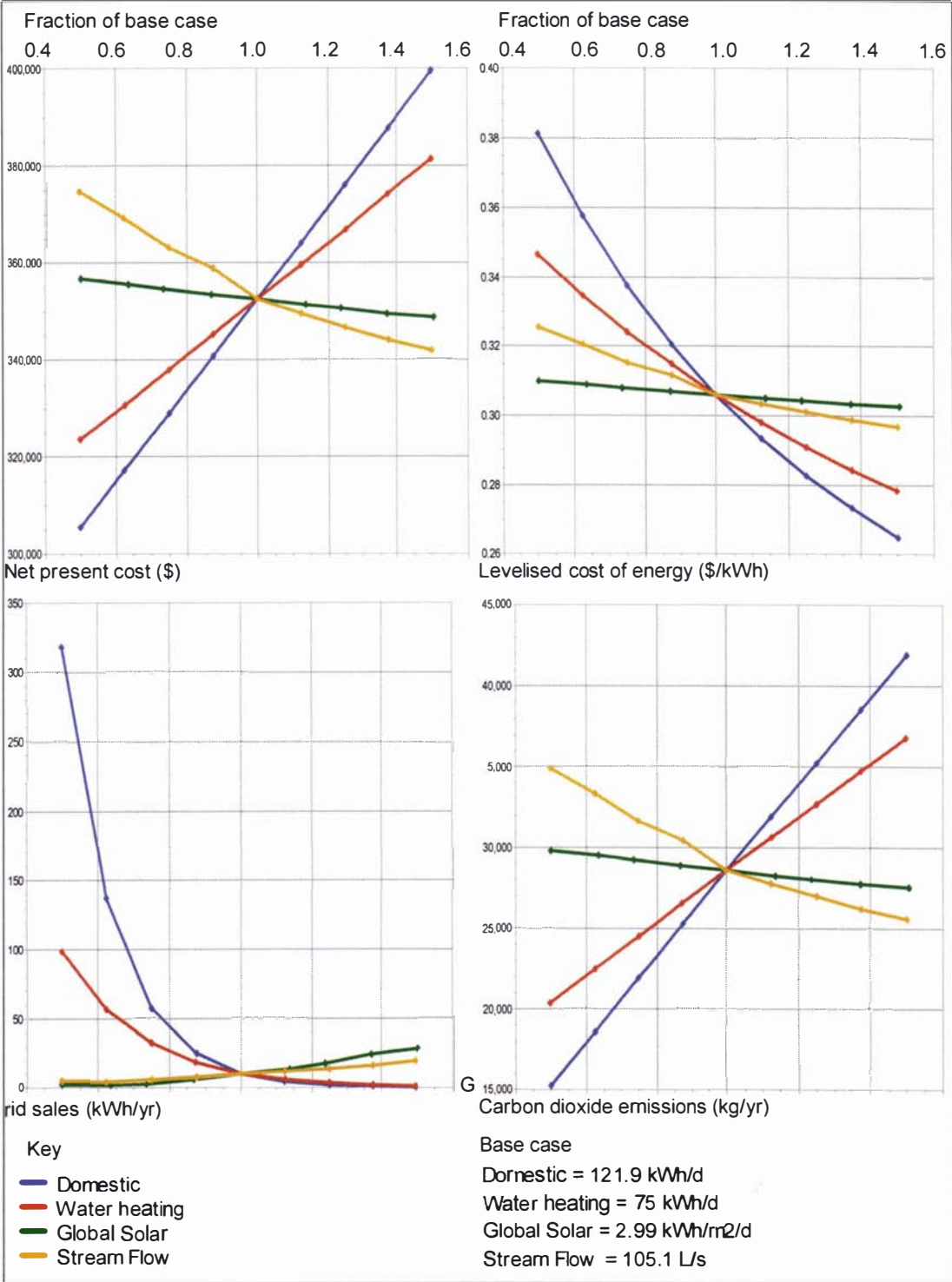


Figure 9.10 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-solar PV-hydro option.

For the grid-solar PV-wind-hydro (SWH) option, the sensitivity to extreme changes in the loads and the available stream flow for the net present cost, levelised cost of energy, grid sales, and carbon emissions is given (Figure 9.11). This option utilises a combined 4.5 kW solar photovoltaic array system, a 3 kW wind turbine generator, and the 2.06 kW combined hydro systems. This option appears to be quite sensitive the loads. Changes to the solar resource, wind speed, and the stream flow have relatively small impacts.

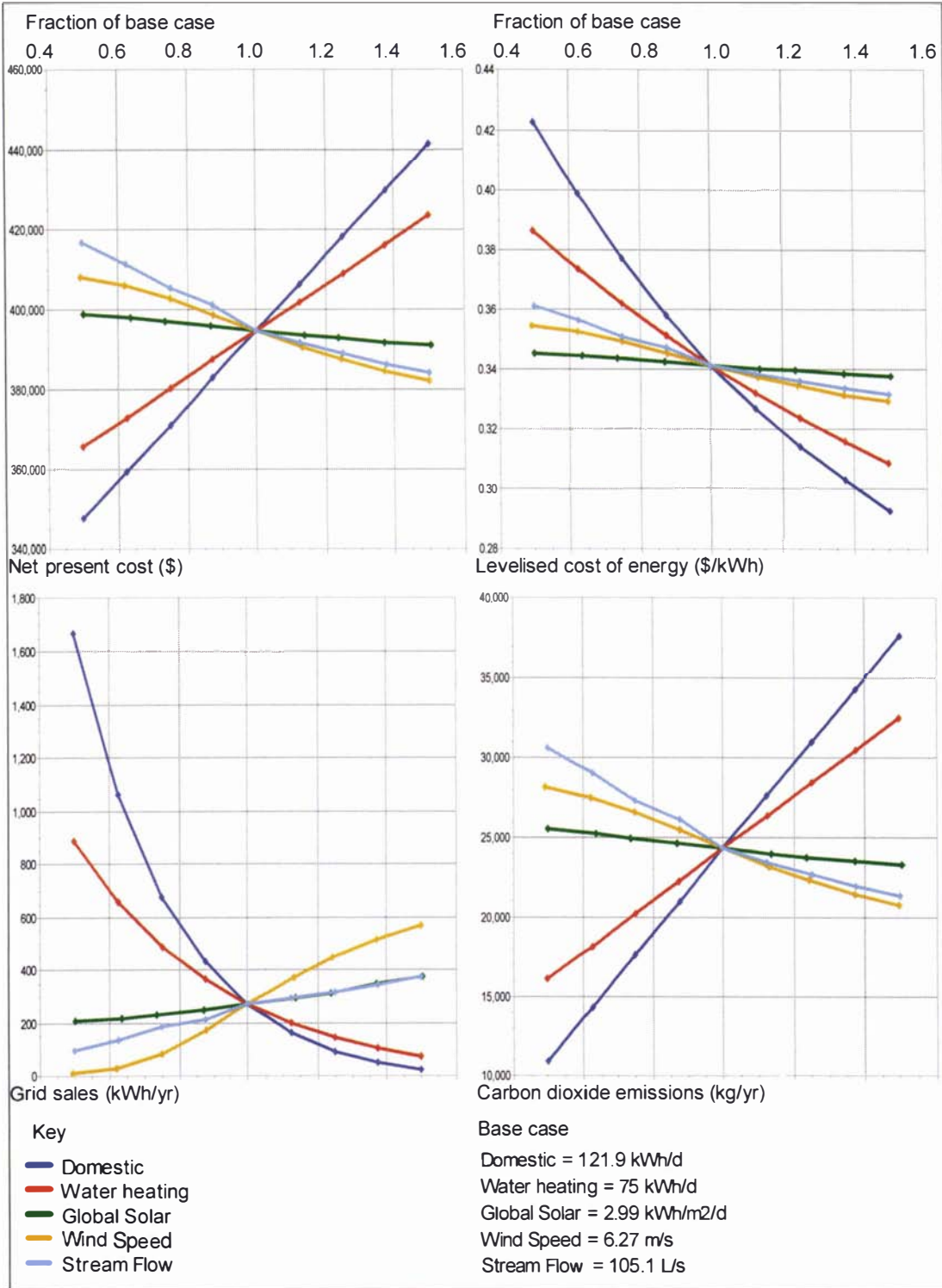


Figure 9.11 The sensitivity analyses of net present cost (\$), levelised cost of energy (\$/kWh), grid sales (kWh/yr), and carbon dioxide emissions (kg/yr) of the grid-solar PV-wind-hydro option.

An assessment of the single sensitivity values that would effect ranking changes within the overall rankings indicated a variety of possible results (Table 9.6). The sensitivity values used were mean daily load (kWh/d) magnitude changes (50%-200%), mean wind speed (m/s) changes (50%-175%), mean stream flow rate (l/s) changes (50%-175%), electricity cost changes (\$/kWh & \$/d), and technology cost changes (\$).

Electricity costs had the largest single impact on the overall rankings with a 250% increase in costs leading to the *WH* option being ranked highest with the singular technologies second and third. The grid only option became the fourth ranked option under this scenario. The wind speed variation had an impact on not only ranking but also combinations of technologies with the 3 kW wind turbine becoming an option in combinations where it was not previously considered.

Changes to the daily loads (kWh/d) did not impact on any of the top three rankings so was not included in an analysis of the single variable changes (Table 9.6), it is however included in the analysis of two sensitivity variables (Table 9.7).

Table 9.6 A single value sensitivity analysis table indicating the changes to the overall rankings resulting from fractional changes to the sensitivity variable.

Original rankings	Tech costs				Electricity costs							Stream flow						Wind speed					
	0.25	0.50	0.75	1.00	1.00	1.25	1.50	1.75	2.00	2.25	2.50	0.50	0.75	1.00	1.25	1.50	1.75	0.50	0.75	1.00	1.25	1.50	1.75
Values	Variable depending on the technologies				0.132 / 1.562	0.170 / 1.952	0.200 / 2.343	0.230 / 2.733	0.260 / 3.124	0.300 / 3.514	0.330 / 3.905	52.50	78.80	105.10	131.40	157.60	183.90	3.14	4.70	6.27	7.84	9.41	10.97
G	W	W	G	G	G	G	G	G	W	W	WH	G	G	G	G	G	G	G	G	G	G	G	W
W	G	G	H	W	W	W	W	W	G	WH	W	W	W	W	W	H	H	H	H	W	W	W	G
H	WH	WH	W	H	H	H	H	H	WH	G	H	H	H	H	H	W	W	W	W	H	H	H	WH
WH	SW	H	WH	WH	WH	WH	WH	WH	H	H	G	S	S	WH	WH	WH	WH	S	S	WH	WH	WH	H
S	H	SW	S	S	S	S	S	S	SW	SW	SWH	WH	WH	S	S	S	S	WH	WH	S	S	S	SW
SW	S	S	SH	SW	SW	SW	SW	SW	S	SWH	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	S
SH	SWH	SWH	SW	SH	SH	SH	SH	SH	SWH	S	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
SWH	SH	SH	SWH	SWH	SWH	SWH	SWH	SH	SH	S	S	SWH	SWH	SWH	SWH	SWH	SWH	SWH	SWH	SWH	SWH	SWH	SWH

W = 3 kW wind turbine generator; WH = 10 kW wind turbine generator

An assessment of what two combined sensitivity values would effect ranking changes within the first three rankings indicated a variety of possible results (Table 9.7). The original rankings are in the grey-shaded cells. The largest ranges of changes are when technology costs reduce, and electricity costs, wind speed, and stream flow increase. Again, changes in the load levels do not have a large impact on the rankings. The electricity costs were not included in the results to go to the decision analysis stage of this study because they were not forecast to increase anywhere near the levels modelled in this sensitivity analysis (MED, 2004a).

Table 9.7 A two-way value sensitivity analysis table indicating the changes to the first three ranks resulting from fractional changes to the sensitivity variable.

	Tech costs				Electricity costs							Stream flow						Wind speed					
	0.25	0.50	0.75	1.00	1.00	1.25	1.50	1.75	2.00	2.25	2.50	0.50	0.75	1.00	1.25	1.50	1.75	0.50	0.75	1.00	1.25	1.50	1.75
Load changes	W	W	G	G	G	G	G	W	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	H	W	W	W	W	W	G	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	WH	H	W	H	H	H	H	H	H	H	H	H	H	H	H	W	W	W	W	W	W	W	W
	W	W	G	G	G	G	G	G	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	H	W	H	H	H	H	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	W	W	WH	G	H	H	H	W	W	W	W	W	W	W	W
	G	G	H	W	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	WH	WH	W	H	H	H	H	H	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	G	G	G	G	G	G	W	W	WH	G	H	H	H	G	G	W	W	W	W	W	W
	G	G	H	W	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	G	G	G	G	G	G	W	W	WH	G	H	H	H	G	G	W	W	W	W	W	W
	G	G	H	W	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	G	G	G	G	G	G	W	W	WH	G	H	H	H	G	G	W	W	W	W	W	W
	G	G	H	W	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
Wind speed	G	G	G	G	G	G	G	G	G	H	H	G	G	G	G	G	G	G	G	G	G	G	G
	W	H	H	H	W	W	W	W	W	WH	W	W	W	W	W	W	W	W	W	W	W	W	W
	W	G	G	G	G	G	G	G	G	H	G	G	G	G	G	G	G	G	G	G	G	G	G
	WH	H	H	H	W	W	W	W	W	WH	W	W	W	W	W	W	W	W	W	W	W	W	W
	W	W	G	G	G	G	G	G	W	W	WH	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	H	W	W	W	W	W	G	WH	W	W	W	W	W	H	H	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	SW	G	WH	H	W	W	W	W	G	G	H	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	W	G	G	W	W	W	W	W	W	G	G	G	G	G	G	W	W	W	W	W	W
	WH	WH	WH	W	W	W	W	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
	SW	G	G	H	W	W	W	W	G	SW	SW	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	WH	WH	WH	G	W	W	W	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
	SW	G	G	WH	W	W	W	W	G	SW	SW	W	W	W	W	H	H	W	W	W	W	W	W
	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	WH	WH	WH	W	W	W	W	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
Stream flow	W	W	G	G	G	G	G	W	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	W	W	W	W	W	G	G	G	G	W	W	W	W	W	W	W	W	W	W	W	W
	SW	WH	H	H	H	H	H	WH	WH	WH	WH	G	G	G	G	G	G	G	G	G	G	G	G
	W	W	G	G	G	G	G	W	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	WH	WH	W	H	W	W	W	W	W	W	WH	G	G	G	G	G	G	G	G	G	G	G	G
	W	W	G	H	W	W	W	W	G	WH	W	W	W	W	W	W	W	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	W	W	W	W	W	W	W	W
	G	G	H	W	W	W	W	W	G	WH	G	H	W	W	W	W	W	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	WH	G	H	W	W	W	W	W	W	W	W	W	W	W	W
	W	W	H	G	G	G	G	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
	G	G	G	W	W	W	W	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
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	WH	G	G	H	W	W	W	W	WH	WH	WH	G	G	G	G	G	G	G	G	G	G	G	G
	G	WH	WH	W	W	W	W	H	H	H	H	W	W	W	W	W	W	W	W	W	W	W	W
	W	W	H	G	G	G	G	W	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W
	WH	G	G	H	W	W	W	W	WH	WH	WH	G	G	G	G	G	G	G	G	G	G	G	G
Electricity costs	W	W	G	G	G	G	G	W	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	H	W	W	W	W	W	G	WH	W	W	W	W	W	H	H	W	W	W	W	W	W
	WH	WH	W	H	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	W	W	H	G	G	G	G	W	W	W	W	G	G	G	G	G	G	G	G	G	G	G	G
	WH	WH	WH	W	W	W	W	W	W	W	WH	G	G	G	G	G	G	G	G	G	G	G	G
	G	G	G	H	W	W	W	W	G	WH	G	H	H	H	H	W	W	W	W	W	W	W	W
	W	W	WH	G	G	G	G	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
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	WH	WH	WH	WH	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	SWH	SWH	H	H	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W

W = 3 kW wind turbine generator; WH = 10 kW wind turbine generator

9.2.4 Peak-load Reduction

The capabilities of peak-load reduction of a grid-connected renewable energy system would be important if the grid-network capacity was potentially under pressure during times of peak loading. For this study, durations of peak-load occurrence were considered to be, morning (0600 – 1000 hrs), midday (1100 – 1500 hrs), and evening (1700 – 2200 hrs). These times reflected the peak-load times observed in the monitored load profiles (Figure 6.3) and the individual load profiles (Appendix F).

The values indicated in Table 9.8 were the mean percentage of the peak-load met during the indicated periods and include the standard deviation (SD). Although the values portrayed are annual, a monthly or seasonal mean could have been used instead, but was not for the sake of SPiRAL modelling simplicity in this formative study. However, the mean daily seasonal profile of fraction of the load met is given in Figure 9.12 to Figure 9.18.

The peak-load reduction capability of the *WH* option was better overall than any other option but had a larger relative variation (Table 9.8). The *H* option had a good overall load matching capability and had a lower relative standard deviation. The *W* option and the *S* option had the highest relative standard deviations of all the options.

Table 9.8 The full-term duration mean and standard deviation of the percentage of peak-load met by each option.

Alternative	Morning Mean (%)	Morning SD (%)	Midday mean (%)	Midday SD (%)	Evening Mean (%)	Evening SD (%)
	0600 – 1000 hours		1100 – 1500 hours		1700 – 2200 hours	
G	-	-	-	-	-	-
W	45	60	41	42	39	40
H	50	17	34	9	30	9
WH	85	67	68	45	62	43
S	2	4	16	12	4	8
SW	13	16	27	16	14	14
SH	41	20	43	17	27	14
SWH	53	28	54	21	37	19

The fractional proportion of the loads met for each of the options is given in Figure 9.12 to Figure 9.18. The analysis of the *W*, *H*, *WH*, *SH* and *SWH* options indicate a higher proportional level of load met in the early morning hours (Figure 9.12, Figure 9.13, Figure 9.14, Figure 9.17, and Figure 9.18). The wind turbine systems appeared to meet more of the load in the winter followed by spring. The *WH* option indicated a period of net electricity export capability in the early hours of the day over winter and spring (Figure 9.14). This is reflected in the larger scale (greater than 1.0) required to incorporate the level of load met.

The *S* option indicated relatively lower levels of load met due to the small size of the solar array, and the availability of the resource. Both the wind and hydro resources had a full daily impact to varying levels on the load.

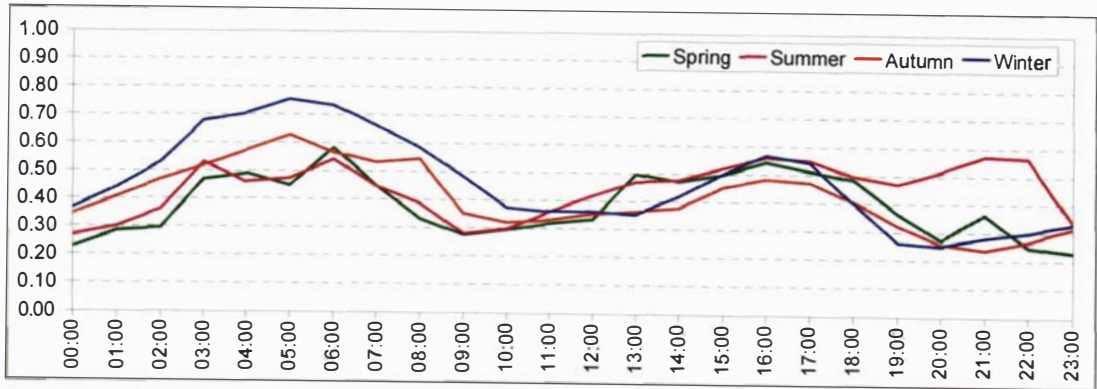


Figure 9.12 The fractional proportion of the seasonal electricity load met by the wind (W) option in the full-term study.

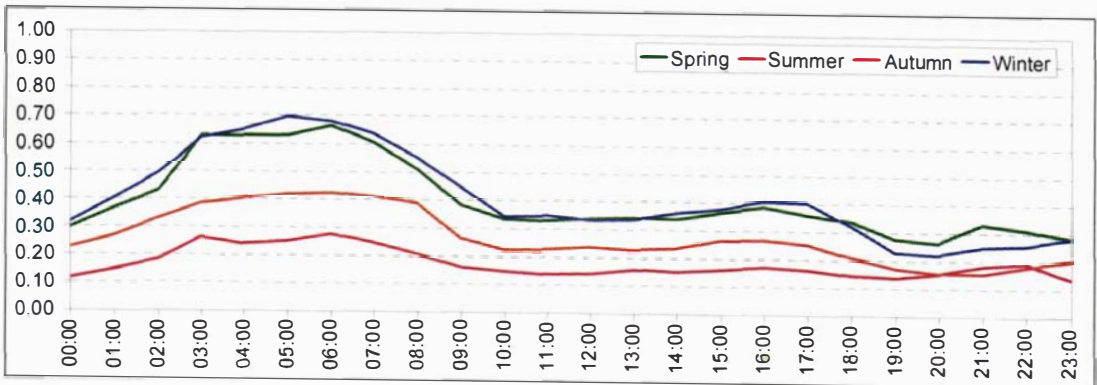


Figure 9.13 The fractional proportion of the seasonal electricity load met by the hydro (H) option in the full-term study.

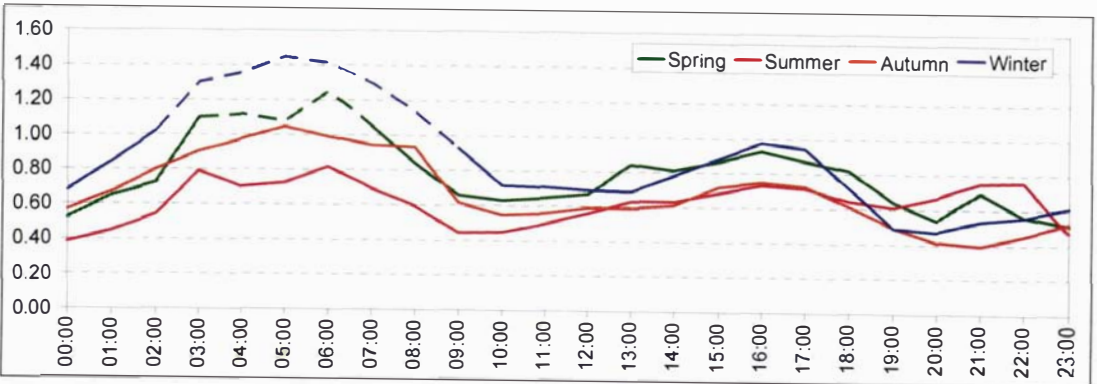


Figure 9.14 The fractional proportion of the seasonal electricity load met by the wind – hydro (WH) option in the full-term study (note: the net export in the winter and spring).

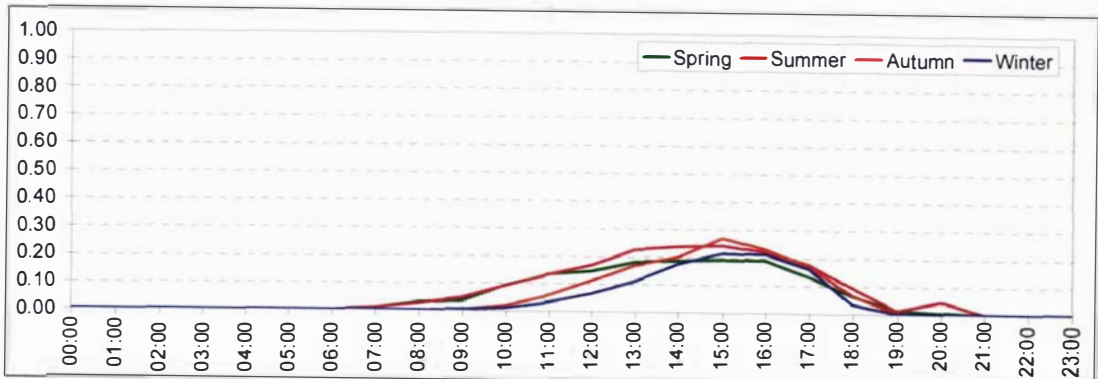


Figure 9.15 The fractional proportion of the seasonal electricity load met by the solar PV (S) option in the full-term study.

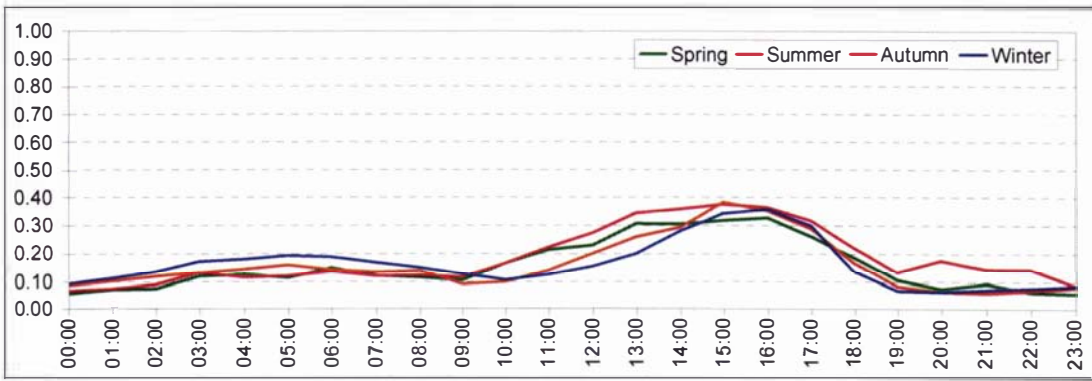


Figure 9.16 The fractional proportion of the seasonal electricity load met by the solar PV – wind (SW) option in the full-term study.

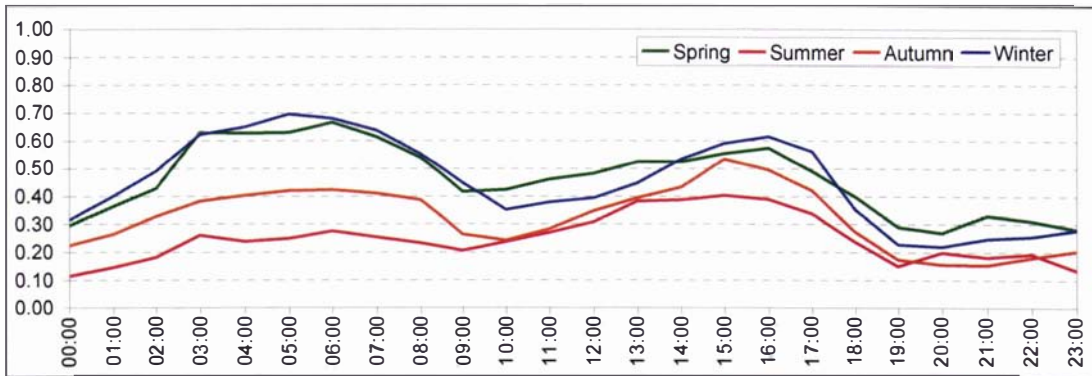


Figure 9.17 The fractional proportion of the seasonal electricity load met by the solar PV – hydro (SH) option in the full-term study.

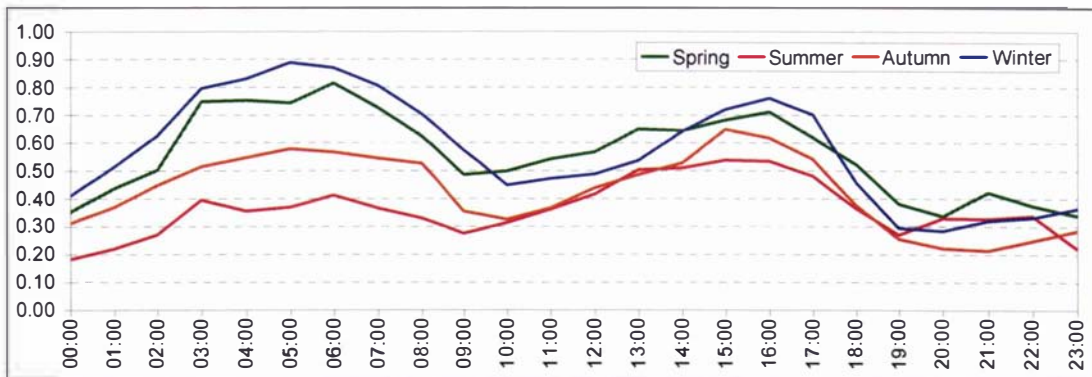


Figure 9.18 The fractional proportion of the seasonal electricity load met by the solar PV – wind – hydro (SWH) option in the full-term study.

9.2.5 Miscellaneous Values

Values that were also required for the decision analysis included total system capacity (kW), Grid capacity displacement capacity (kW), initial capital required for system implementation (\$), annual operation and maintenance costs (\$) (includes a return on electricity sold), net grid purchases required (\$), and the renewable energy fraction (%) (Table 9.9).

Initial capital cost was the total capital required for initial system purchase and implementation (section 9.1.2). Annual operation and maintenance cost included all costs related to the operation and maintenance of the system including the return on exported electricity as a credit against cost. The operation and maintenance costs of the grid-only option

set the base for the others to equal or better. The net grid purchase was the total amount to be paid for imported electricity. The renewable energy fraction was the percentage of electricity that met the load that was generated by the renewable energy components of the system.

Table 9.9 The full-term duration miscellaneous values that were not outputs from HOMER modelling.

Alternative	Total system capacity (kW)	Grid capacity displacement (kW)	Initial capital (\$)	Annual O&M (\$/yr)	Net grid purchases (\$)	RE fraction (%)
G	-	-	-	11,048	9,487	0
W	10.00	10.00	66,400	9,023	5,801	37.4
H	2.06	2.06	72,170	10,182	6,817	28.1
WH	12.06	12.06	138,570	8,157	3,131	61.2
S	4.50	4.50	76,036	12,423	8,957	6.2
SW	7.50	7.50	102,446	12,306	8,018	16.9
SH	6.56	6.56	148,206	11,557	6,286	34.1
SWH	9.56	9.56	174,616	11,440	5,348	44.4

9.2.6 Short-Term Duration Analysis – HOMER

The short-term duration results were ranked according to the lowest net present cost (Table 9.10) which indicated there were no changes from the full-term duration ranked results (Table 9.4). The sensitivity analysis results (Table 9.11) indicated an increased cost of energy, a decreased net present costs, large reductions in the level of carbon emissions, and only negligible differences in the mean energy produced from the full-term duration data (Table 9.5). The peak-load reduction data (Table 9.12) indicated lower net grid purchases and higher renewable energy fraction levels (Table 9.9). All other values were unchanged due to the same levels of technology capacity.

Table 9.10 The short-term duration ranked results of the HOMER modelling.

Rank	System components and abbreviated label		PV (kW)	WTG (kW)	Hydro (kW)	Inverter (kW)
1 st	Grid alone	G	-	-	-	-
2 nd	Wind turbine	W	-	10 (AC)	-	-
3 rd	Microhydro	H	-	-	2.06 (AC)	-
4 th	Wind turbine & microhydro	WH	-	10 (AC)	2.06 (AC)	-
5 th	Solar PV	S	4.50 (DC)	-	-	4.50
6 th	Solar PV & wind turbine	SW	4.50 (DC)	3 (DC)	-	7.50
7 th	Solar PV & microhydro	SH	4.50 (DC)	-	2.06 (AC)	4.50
8 th	Solar PV, wind turbine, & microhydro	SWH	4.50 (DC)	3 (DC)	2.06 (AC)	7.50

PV is photovoltaic, WTG is wind turbine generator, and Hydro is the combination of three sites.

Table 9.11 The short-term duration mean and standard deviation values for levelised cost of energy, net present cost, carbon emissions, and hourly delivered energy.

Alternative	Levelised cost of energy (\$)		Net present cost (\$)		Carbon emissions (t)		Hourly energy (kWh/h)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G	0.152	0.002	192,852	23,525	47,599	6,672	-	-
W	0.180	0.015	236,359	27,685	28,668	7,852	3.65	3.57
H	0.199	0.009	251,143	23,526	35,463	6,673	2.31	0.88
WH	0.215	0.017	294,966	27,302	16,531	7,852	5.96	3.67
S	0.245	0.015	308,485	23,569	44,756	6,685	0.62	0.99
SW	0.277	0.020	349,052	24,470	39,895	6,778	1.55	1.44
SH	0.291	0.021	366,776	23,570	32,619	6,685	2.93	1.27
SWH	0.322	0.025	406,776	23,896	27,758	6,778	3.86	1.65

Table 9.12 The short-term duration mean and standard deviation of the percentage of peak-load met by each option.

Alternative	Morning Mean (%)	Morning SD (%)	Midday mean (%)	Midday SD (%)	Evening Mean (%)	Evening SD (%)
	0600 – 1000 hours		1100 – 1500 hours		1700 – 2200 hours	
G	-	-	-	-	-	-
W	52	59	47	44	38	38
H	35	19	26	11	22	10
WH	87	66	73	47	61	41
S	7	9	21	14	2	4
SW	21	18	33	20	12	12
SH	42	19	46	18	25	11
SWH	56	27	58	24	34	17

Table 9.13 The short-term duration miscellaneous values that were not otherwise outputs from HOMER modelling.

Alternative	Total system capacity (kW)	Grid capacity displacement (kW)	Initial capital (\$)	Annual O&M (\$/yr)	Net grid purchases (\$)	RE fraction (%)
G	-	-	-	11,535	9,973	-
W	10.00	10.00	66,400	8,971	5,749	40.8
H	2.06	2.06	72,170	10,669	7,303	26.8
WH	12.06	12.06	138,570	8,110	3,048	63.0
S	4.50	4.50	76,036	12,725	9,258	7.9
SW	7.50	7.50	102,446	12,463	8,175	19.6
SH	6.56	6.56	148,206	11,859	6,588	34.5
SWH	9.56	9.56	174,616	11,597	5,055	45.7

The fractional proportion of the loads met for each of the options is given in Figure 9.19 to Figure 9.25. The analysis of the *W*, *H*, *WH*, *SH* and *SWH* options indicate a higher proportional level of load met in the early morning hours (Figure 9.19, Figure 9.20, Figure 9.21, Figure 9.24, and Figure 9.25). The wind turbine systems appeared to meet more of the load in the winter followed by spring. The *WH* option indicated a period of net electricity export capability in the early hours of the day over winter and spring (Figure 9.21). This is reflected in the larger scale (greater than 1.0) required to incorporate the level of load met.

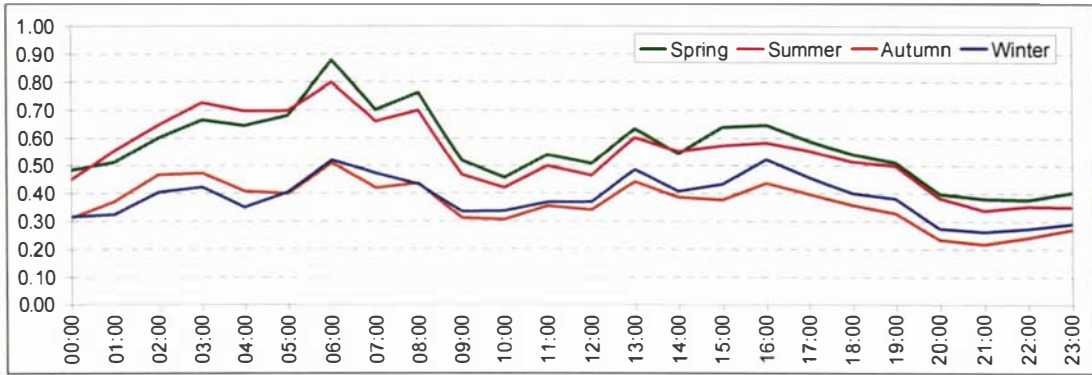


Figure 9.19 The fractional proportion of the seasonal electricity load met by the wind (*W*) option in the short-term study.

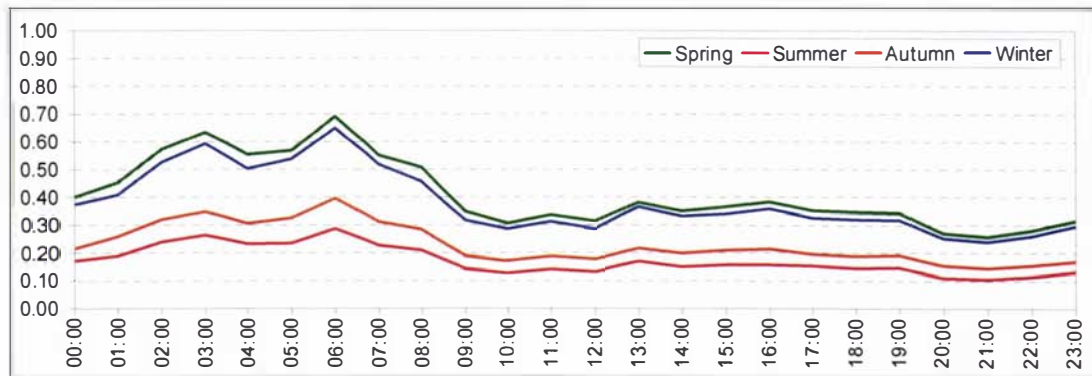


Figure 9.20 The fractional proportion of the seasonal electricity load met by the hydro (*H*) option in the short-term study.

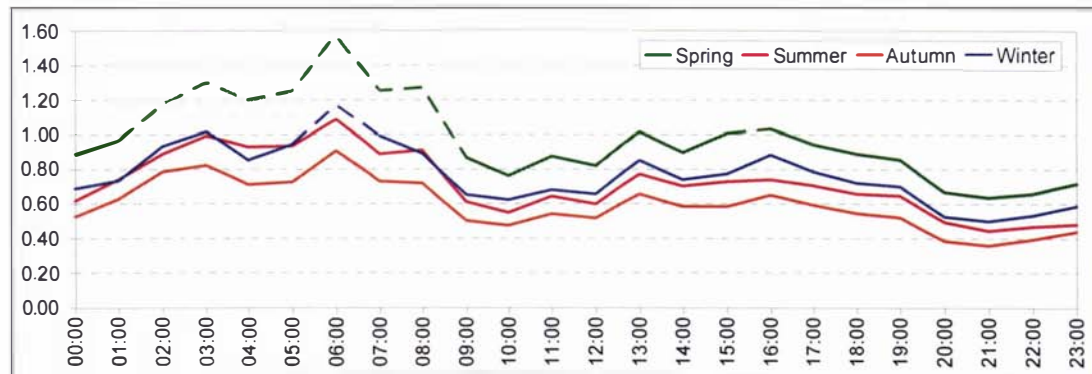


Figure 9.21 The fractional proportion of the seasonal electricity load met by the wind – hydro (*WH*) option in the short-term study (note: the net export in the winter and spring).

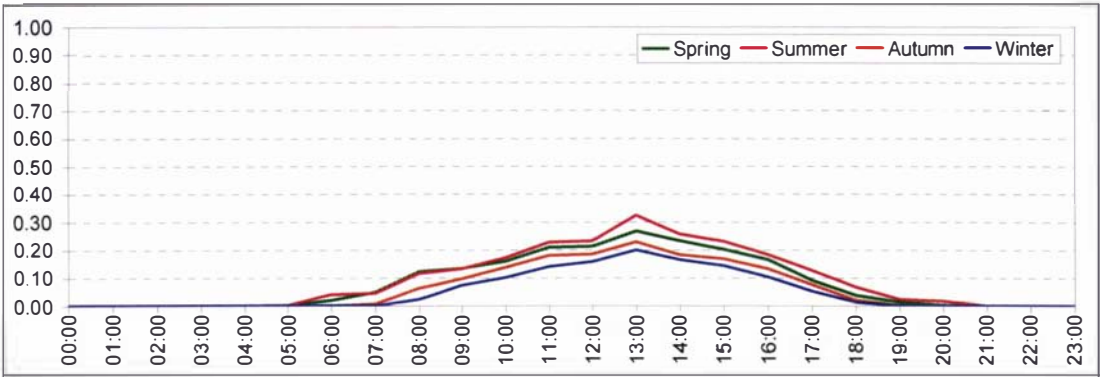


Figure 9.22 The fractional proportion of the seasonal electricity load met by the solar PV (S) option in the short-term study.

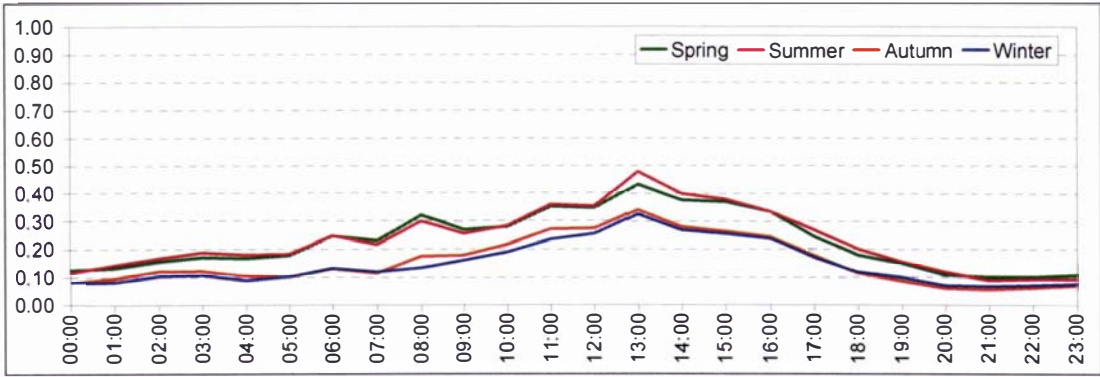


Figure 9.23 The fractional proportion of the seasonal electricity load met by the solar PV – wind (SW) option in the short-term study.

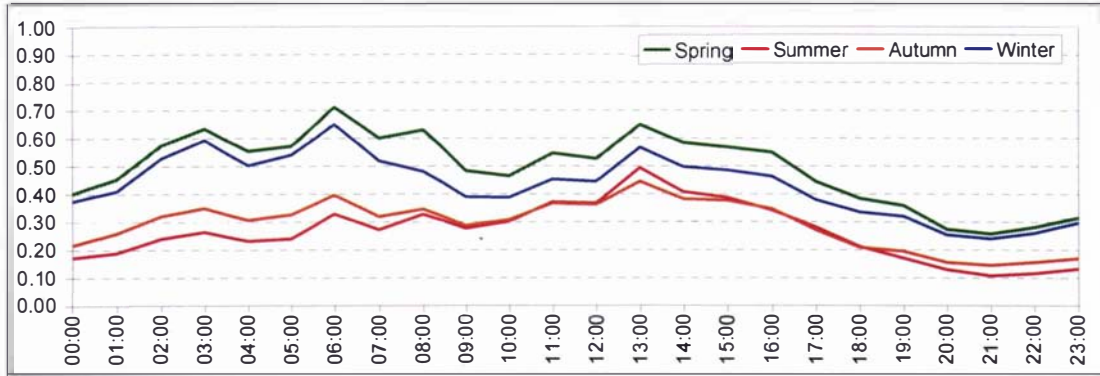


Figure 9.24 The fractional proportion of the seasonal electricity load met by the solar PV – hydro (SH) option in the short-term study.

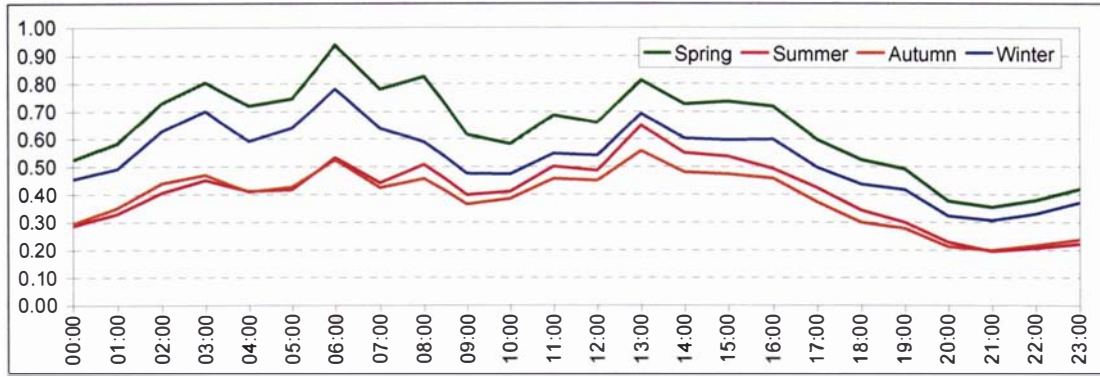


Figure 9.25 The fractional proportion of the seasonal electricity load met by the solar PV – wind – hydro (SWH) option in the short-term study.

The analysis based on the short-term duration data clearly indicated the impacts of using data levels derived from the full-term duration data, and that derived from analysis for the short-term duration (Table 9.14). There was a relatively small percentage change in the electricity load levels and mean wind-speed, and relatively larger changes to the mean solar energy and the Weibull 'k' value. However, the most important changes were to those values most likely to have an impact on the results, the slightly increased electricity load levels, solar and wind resources. These differences are quantified by percentage differences between the short-term and full-term duration cost of energy, net present cost, carbon emissions, and delivered energy (Table 9.15); peak-load reductions (Table 9.16); and the miscellaneous values (Table 9.5).

Table 9.14 A comparison of HOMER model inputs between the full-term and the short-term duration models.

	Electricity load (kWh/d)	Solar radiation (kWh/m ² /d)	Mean wind-speed (m/s)	Weibull 'k'	Auto-correlation factor	Diurnal pattern strength
Full-term data	197	2.99	6.27	1.61	0.91	0.13
Short-term data	207	3.58	6.80	2.07	0.91	0.13
% difference	5	16	8	22	0	0

The (slightly) decreased cost of energy (Table 9.15) was due to the slightly higher level of electricity use relative to the total cost of producing it. The small increases in the net present costs and the carbon emissions of the grid-connected renewable energy systems resulted from the increased level of the loads cancelling the effect of an increased level of resources. The higher level of the energy resources was also indicated by the increased level of energy production of all the systems. The increases in the levels of peak-load reduction for the solar systems (Table 9.16) result from the increased level of the solar resource cancelling the effect of an increased load level.

Table 9.15 The percentage differences between the full-term and short-term duration results for levelised cost of energy, net present value, carbon emissions, and hourly delivered energy.

Alternative	Levelised cost of energy (% difference)		Net present cost (% difference)		Carbon emissions (% difference)		Hourly energy (% difference)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
G	-1	0	4	45	5	45	-	-
W	-5	0	0	27	0	27	14	6
H	-1	29	3	45	7	45	0	0
WH	-5	-6	0	26	0	27	8	3
S	-2	25	2	45	4	45	35	29
SW	-3	25	1	46	3	43	22	20
SH	-3	24	2	45	6	45	6	12
SWH	-4	25	1	43	4	43	8	10

Table 9.16 The percentage differences between the short-term and long-term duration results for the mean and standard deviation of the percentage of peak-load met by each option.

Alternative	Morning Mean (%)	Morning SD (%)	Midday mean (%)	Midday SD (%)	Evening Mean (%)	Evening SD (%)
	0600 – 1000 hours		1100 – 1500 hours		1700 – 2200 hours	
G	-	-	-	-	-	-
W	16	-2	15	5	-3	-5
H	-30	12	-24	22	-27	11
WH	2	-1	7	4	-2	-5
S	250	125	31	17	-50	-50
SW	62	13	22	25	-14	-14
SH	2	-5	7	6	-7	-21
SWH	6	-4	7	14	-8	-11

Table 9.17 The percentage differences between the short-term and long-term duration results for the miscellaneous values that were not otherwise outputs from HOMER modelling.

Alternative	Total system capacity (%)	Grid capacity displacement (%)	Initial capital (%)	Annual O&M (%)	Net grid purchases (%)	RE fraction (%)
G	-	-	-	4	5	-
W	0	0	0	-1	-1	9
H	0	0	0	5	7	-5
WH	0	0	0	-1	-3	3
S	0	0	0	2	3	27
SW	0	0	0	1	2	16
SH	0	0	0	3	5	1
SWH	0	0	0	1	-5	3

9.3 Discussion

The distributed generation options for the community of Totara Valley were simulated and optimised and the ranked result indicated that the grid-only option (the status quo) was the best system as it had the lowest NPC (Table 9.4). Accordingly, the COE and the initial capital cost were also the lowest. Key drawbacks of this were; the carbon emissions were the highest, the annual operation and maintenance costs were not the lowest, and the peak-loads remained high with the potential to increase in the future to a point of possible supply constraint.

Thus, this result indicates the status quo of grid network connection was the best system as ranked according to the lowest NPC (Table 9.4) but by all other measures set the benchmark of 'what to better'.

Of the renewable energy based DG options, W had a slightly higher COE, and there were additional benefits such as a 36% reduction of the carbon emissions. Morning, midday, and evening peak-loads were reduced by 45%, 41%, and 39% respectively, operation and

maintenance costs reduced by 18%, and the net grid purchases for the whole community were reduced by 38% to \$5,801. Analysis of the other options revealed similar examples of benefits with few major negative economic impacts.

The high capacity of the *WH* option had the greatest impact on carbon emissions (Table 9.5) but the variation was also the highest due to the large 10 kW WTG and the variability of the wind resource. In relative terms, this option had a high level of standard deviation due to the combined variation of the load and the wind.

The hourly kWh generated could be termed the consistency of supply. The *S*, *W*, and *SW* options had the higher levels of standard deviation variation. Wind and solar variability may account for these large variations in consistency of the level of supply.

Although only singular technology capacities were modelled in this study (i.e. only 4.5 kW of solar PV etc), this format (Figure 9.1) could be used to model multiple capacities of technologies for use in the decision-analysis stage of SPiRAL. The singular technology capacity format was a natural outcome from the HOMER optimisation process where the lowest net present cost is the optimising factor. This approach of using only singular technology capacities was for simplicity of the decision-analysis stage.

The percentage differences between the full-term and short-term duration in the peak load reduction (Table 9.16) indicated some very high percentage increases for the options involving solar photovoltaic technology. The large increases in the morning and midday load reductions and the reduced level of load matching in the evening resulted from the use of the NASA data and a slightly changed electricity load. These percentages seem relatively large, however the actual changes are still relatively small compared to the other technologies and combinations.

9.4 Summary

The results from this study were analysed in preparation for use in the decision-analysis process (Chapter 10). The economic, environmental, and technical sensitivity analysis results provided the inputs for an uncertainty model in Logical Decision for Windows. Further miscellaneous environmental and technical values were used to set measured levels of the decision alternatives.

A full sensitivity analysis of the effects of resource levels and cost data indicated several ranking changes. Of all the sensitivity values used wind speed appeared to be the most sensitive.

The differences between the full-term and short-term duration modelled results were comparatively small and indicated that the short-term duration modelling parameters had little effect in the context of ranking changes in the HOMER results.

This section on renewable energy generation modelling highlights a complex situation where the economic optimisation parameter of the net present cost alone cannot indicate which system is most suitable or sustainable and where a rational decision-analysis process would be

of advantage in the design process. This is especially so when environmental, social, and technical preferences are also considered when a large range of options are available.

As such, this analysis identified several interesting combinations each with energy supply merit. The results from this chapter will ensure the decision modelling will have a diverse selection of options to rank in order of the decision-analysis preferences used.

10 Multiple Criteria Decision Analysis

The process analysed in this section is the last component of the SPiRAL decision-analysis framework (Figure 1.1, Figure 8.2, and Figure 9.1). The eight alternative renewable energy options (Table 9.4) used in this analysis resulted from the HOMER simulation and economic optimisation of renewable energy technologies for the whole community of Totara Valley. These alternative options provide this decision analysis stage of the SPiRAL model with the challenge of assessing which of them will be better suited to meeting stakeholder preferences.

Lloyd *et al.* (2000) reported a considerable number of parameters and anecdotal user preferences that were of particular interest for this section on decision-analysis processes (Section 2.2). Of these, clearly consultation with the stakeholders from the outset of the project was necessary to ensure an adequate level of interest within the community, thereby leading to an increased chance of system success. Consultation can allay unrealistic expectations that can sometimes hinder perceptions of renewable energy systems, and can greatly influence the technical design philosophy. Economic or lifestyle reasons for adopting renewable energy based systems have tended to be more common than environmental reasons (*ibid.*). Even though the environmental issues surrounding renewable energy systems might seem relatively benign, they still needed consideration.

Renewable energy system failure can result from lack of consideration of any risk and uncertainty, especially as it relates to varying resources and loads, so this must become a part of renewable energy system design. All the aforementioned economic, environmental, social, and technical parameters should therefore become part of the decision-analysis and design process within a consultative environment with the stakeholders.

The aim, therefore, was to utilise the Logical Decisions for Windows® (LDW) software in a formal decision-analysis process to assess which of these renewable energy systems (Table 9.4) best meet the needs of the stakeholders. This procedure utilised three techniques of decision analysis in a multi-method approach similar to that adopted by Hobbs and Horn (1997). It involved two multiple criteria decision analysis (MCDA) theories, the multi-attribute utility theory (MAUT) and the analytic hierarchy process theory (AHP), both of which were suitable for the discrete choice situation as provided by this study. All three methods convert the ordinal, cardinal, and probabilistic decision alternative values into a common unit called 'utility', and then rank the respective decision alternatives in order of best overall utility to meet the needs of the stakeholders.

This process is described outlining the MCDA process used in this study (Section 10.1). This leads to the construction of the MCDA model for SPiRAL (Section 10.2). This section documents the problem identification (section 10.2.1), model building (section 10.2.2), the MCDA methods used (section 10.2.3), preference and weight elicitation methods (section

10.2.4), the decision model structure (section 10.2.5), decision criteria definitions (section 10.2.6), the decision measures and measure levels (section 10.2.7), the model of uncertainty (section 10.2.8), and the weights and preferences (section 10.2.9).

The results (Section 10.3) are given in two sections, the full-term duration (section 10.3.1) and the short-term duration (section 10.3.2). Each section includes the results by stakeholder group and MCDA method, ranked results illustrating the effects of uncertainty and the absolute weighting, and the results of a sensitivity analysis of the utility of the individual options by stakeholder group and MCDA method.

The discussion (Section 10.4) includes sections on the problem structure (section 10.4.1), the multi-method MCDA approach adopted for this study (section 10.4.2), and the overall results analysis including the effects of the uncertainty and weighting (section 10.4.3). The discussion is followed by a summary (Section 10.5).

10.1 The Decision Analysis Process Utilised

Multiple criteria decision analysis is the application of decision theory to real decision problems. Decision theory is the “formal axiomatic theory of rationality” (Bond, 1995). Saaty (1994) indicated that the decision-analysis process should be simple, adaptable to use by individuals or groups, intuitively natural, encouraging of compromise and consensus, and “not require inordinate specialisation to master and communicate.”

The key phases of the MCDA process include clearly identifying the problem, problem structuring, model building, analysing results, and developing an action plan (Figure 10.1). Aspects of the process have been adopted for the practice and presentation of the MCDA as used in this study. Clear identification of the problem (Step 1) involves clarifying objectives leading to an understanding of how to measure their attainment. Once the problem was clear and unambiguous, the problem composition and structuring could be undertaken (Step 2). This entailed the identification of all stakeholders, decision alternatives, key issues, constraints, and goals. Careful structuring of the problem should lead to smaller and more manageable portions, in a “divide and rule” strategy (Clemen, 1996).

A characteristic of many MCDA approaches is the development of formal models of stakeholder (or decision maker) preferences, value trade-offs, goals etc., so that the alternatives under consideration can be compared relative to one another in a systematic and transparent manner (Clemen, 1996). Thus, model building (Step 3) involves specification of all the alternatives, definition of the criteria and values, clearly defined uncertainties, and stakeholder preferences. Within the modelling process, utility functions will be used to convert ordinal, cardinal, and probabilistic preferences into common units, and uncertainty will be modelled through probabilistic functions. This will enable mathematical interpretation of the decision variables thereby leading to the preferred alternative.

Decision analysis is typically an iterative process (Clemen, 1996) so the results from mathematical modelling can be used to either denote a clear alternative, or be used to challenge intuitive thinking, thus leading to a reappraisal of the model or variables used (Step

4). Stakeholder preferences used in the modelling process can highlight community sector differences or similarities otherwise not realised. This may lead to rigorous debate and discussion to establish goals and values or alternatives not otherwise already considered. Sensitivity analysis at this stage (Step 4) can be used to analyse “what if” scenarios. If any aspect of a decision is sensitive to small changes in preferences in the model, then careful consideration can be extended to that aspect. It may then be time to ask, “Is further analysis necessary?” If so, this becomes the time to redefine critical aspects of the model and then the process restarts at whatever stage is required (Belton & Stewart, 2002; Clemen, 1996).

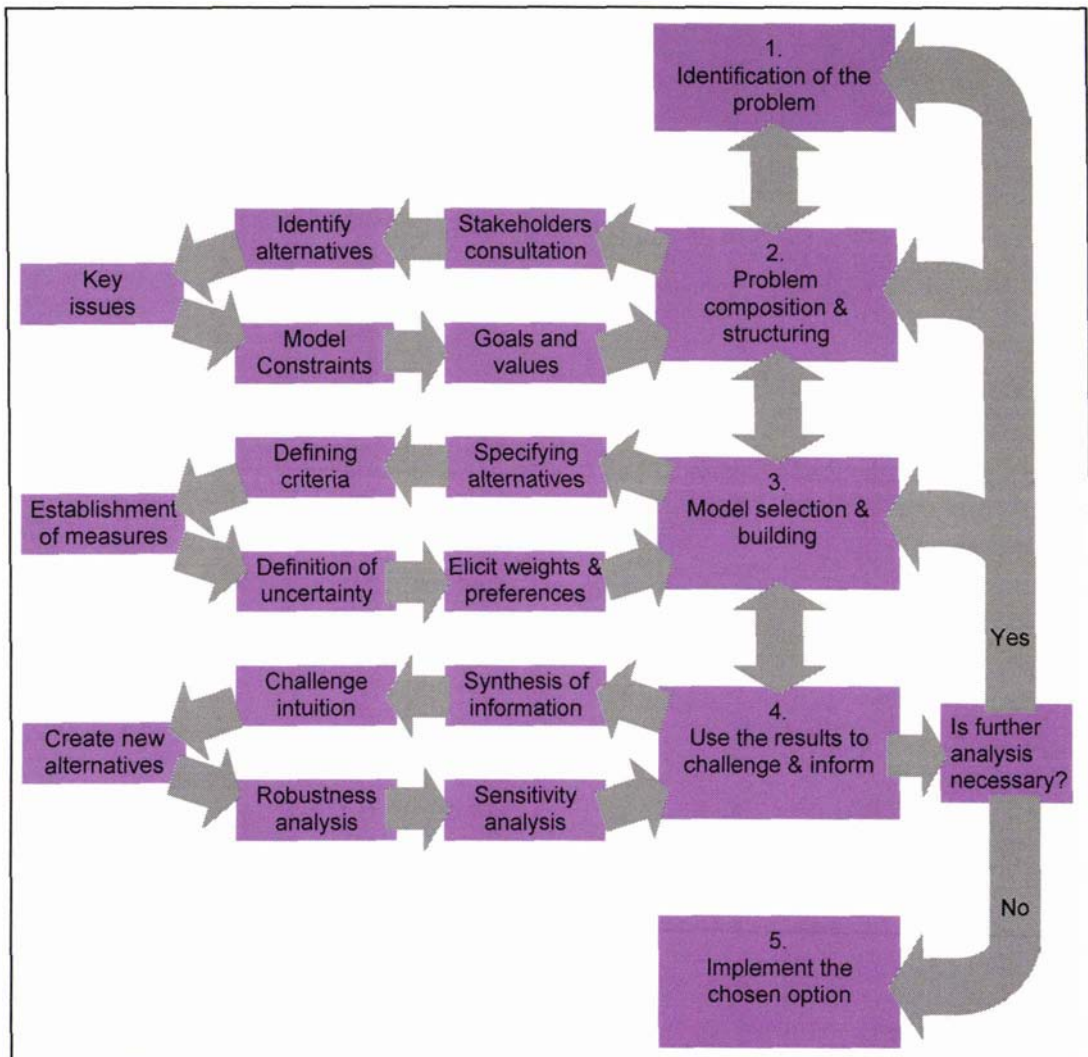


Figure 10.1 The process used in this study to develop a multiple criteria decision analysis decision model.

Figure 10.1 was adapted from Belton & Stewart (2002), and Clemen (1996).

It is vital to note that MCDA does not ‘solve’ the decision problem but rather highlights and ranks the most suitable options relative to the stakeholder preferences (Belton & Stewart, 2002). Edwards & Barron (1994) stipulated for most decision analysts “the most important goal of decision analysis is insight, not numerical treatment.” Therefore, if no further analysis is required the final step (Step 5) of the MCDA process involves the development of an action plan for implementation of the chosen solution, driven by the insight gained during the analysis.

10.2 The Multiple Criteria Decision Analysis Model in SPIRAL

This decision analysis considered the problem of which energy supply option is the most sustainable by utilising the assumed input from two stakeholder groups. The interests of the energy supply company were known as the *distribution network* preference set and the interests of the local farming community as the *individual farm* preference set.

A multi-method MCDA process was used in this study for robustness of results (Hobbs & Horn, 1997). The two stakeholder groups were used to develop a set of assumed preferences for use in the decision analysis process (Figure 10.2). Two methods of applying the multi-attribute utility theory were used, simple multi-attribute rating technique using swings (SMARTS), and simple multi-attribute rating technique exploiting ranks (SMARTER). More details of each of these methods are given later in section 10.2.3.

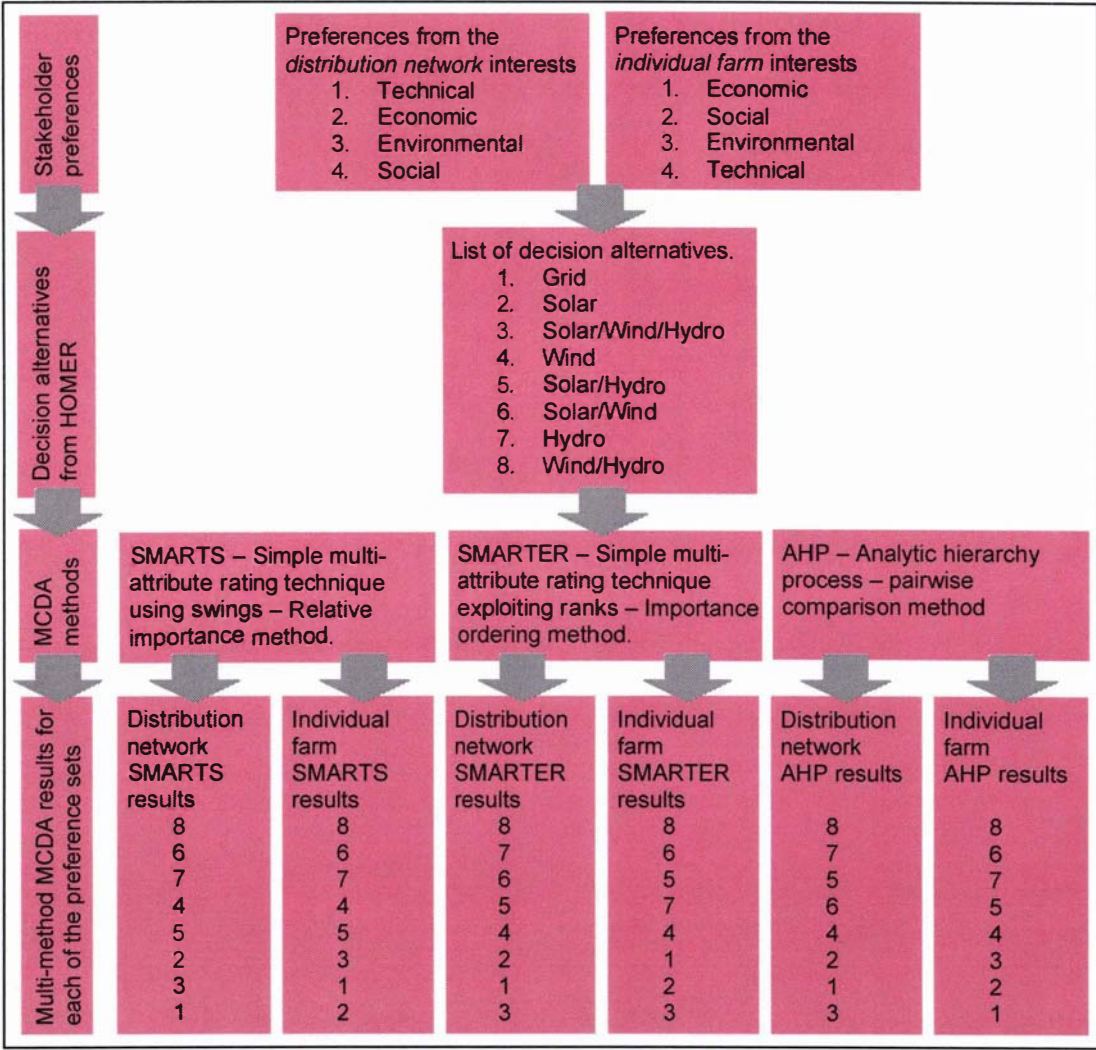


Figure 10.2 A schematic diagram of the multi-method MCDA approach used in this study.

Although direct stakeholder involvement would have been desirable for this analysis, it was deemed fraught with difficulties of the monetary cost and time involved of gathering the varying groups of stakeholders together into one location and the appropriate amount of time was not available for instruction of the three methods used. This instruction was deemed critical

to the successful elicitation of preference values (Keeney *et al.*, 1990) where the lack of immediate feedback from the facilitator to participant can contribute to misunderstandings, from which can lead to the elicitation of misrepresentative weights. To have undertaken a series of meetings to gather the required information was considered a time-consuming and expensive option (Keeney *et al.*, 1990; Tung, 1998; Keeney & McDaniels, 1999; Bana e Costa, 2001) and so was deemed inappropriate at this stage of the development of the overall model. However, the stated preferences of the stakeholders in this study had been garnered over time by way of, indirect elicitation, intuition, and anecdotal references. In effect, this is a demonstration of what the decision analysis framework can do with all the ensuing results hypothetical. On application with other communities, stakeholder participation would be appropriate at all levels as discussed in this study.

10.2.1 Problem Identification

Sustainability issues within the renewable energy sector decision-analysis include the cumulative localised and collective national effects of renewable energy projects, which may appear sustainable on an individual basis, but when such projects occur on a wider scale within a defined area, catchment, or network, the environmental, economic, social, and technical sustainability of the projects could be jeopardised.

A sustainable energy system must be able to supply energy services, whilst minimising the impacts on climate and biodiversity via increased pollution levels; it would create employment; be affordable, cost-effective, and relatively least-cost (in a broad sense) to society, both local and global; and at the very least not increase any existent social inequity (Outhred *et al.*, 2002). The achievement of perfect sustainability is not a practical goal (*ibid.*), neither is a formal consensus between all stakeholders, but rather, trade-offs must be made that allow communities to improve all aspects of sustainability through time.

The sustainability of the renewable energy sector should thus involve many more attributes other than merely economic in the decision-making stage of project implementation. To achieve this, the stakeholder preferences must be made explicit in the decision-analysis process. Stakeholders in this context include all people who are directly involved in the project, and their involvement is seen as a precursor to successful sustainable development.

The problem being analysed in this study is the need to make a choice between the seven renewable energy based grid-connected options identified (Table 9.4) to assess which of them best meets the sustainability criteria as set by assumed stakeholder preferences orientated towards the achievement of an economically, environmentally, socially, and technically sustainable energy supply system.

10.2.2 Multiple Criteria Decision Analysis Model Building

A decision comprises having to choose between alternatives to achieve a primary goal or objective. Logical Decisions for Windows (LDW) depicts the decision problem by way of a hierarchy arrangement that enables the user to segment the problem into smaller component secondary and sub-goals, each comprised of measures relating to the decision alternatives. The decision problem hierarchy is used to set out the series of intrinsic calculations used to

calculate the utility of the options. A simple depiction and example of this is given in Figure 10.3.

Within Logical Decisions for Windows, each potentially problem-solving *alternative* (such as *wind/hydro* or *solar/wind*) can be clearly defined by cardinal, ordinal, or probabilistic values called *measures* (e.g. 'Local economic good' or 'measure A' in Figure 10.3). These measures are clearly defined by *measure levels* (e.g. 'Local investment' or 'measure level 1, 2, 3...' in Figure 10.3). Cardinal *measure levels* can be defined further by *measure categories* (e.g. 'capital expenditure' & 'operation and maintenance costs' or 'measure category 1 and 2' in Figure 10.3). Measure categories allow for an aggregation of values, where a whole or a calculated fraction of the original values can be summed to a final measure level (e.g. '20% of capital expenditure' and '80% of operation and maintenance costs' equals the estimated level of 'local investment', Figure 10.3).

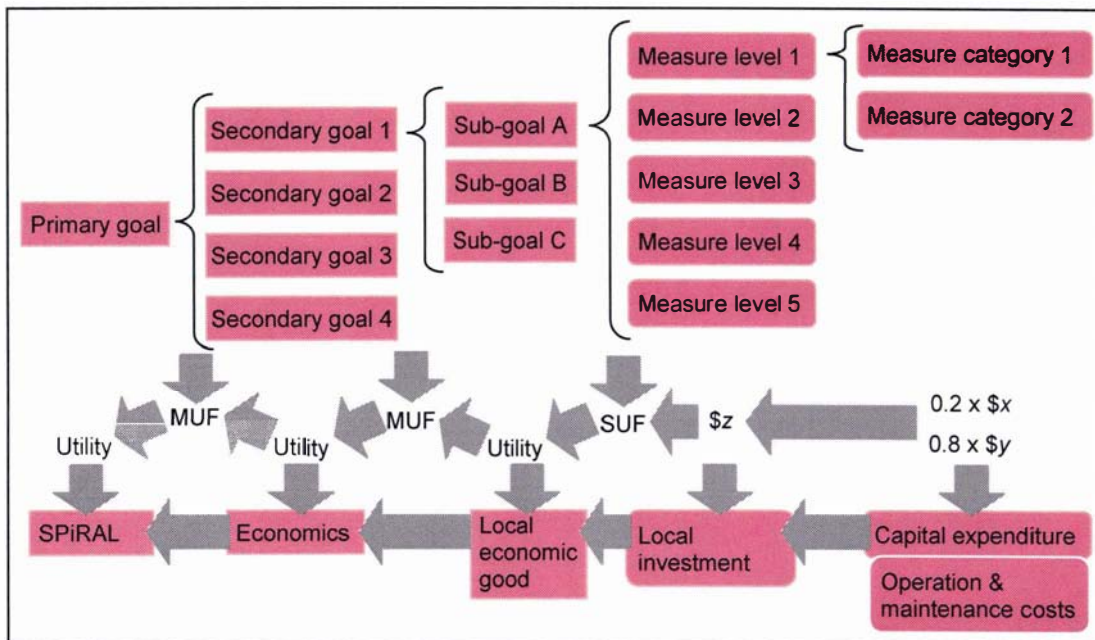


Figure 10.3 An overview of the Logical Decisions for Windows analytical procedure using an example from this study.

The measures of many decision problems will consist of a mix of cardinal, ordinal, or probabilistic *measure levels* and because of this, these mixed values will need to be converted to a common unit called 'utility', for further analysis by a single-measure utility function (SUF) (Figure 10.3). It is through the graphical form of the SUF that initial stakeholder preferences can be expressed (Figure 10.4). The nature of these preferences can be defined by either negative or positive straight-line SUF (Equation 10.1 and A – Figure 10.4) or a negative or positive exponential SUF (Equation 10.2 and B – Figure 10.4) to give a *utility* for that *measure level*.

Whether negative or positive straight-line or exponential functions are used is dependant on both the situation being measured and the preferential requirements of the stakeholders and/or decision makers. LDW uses a Monte Carlo simulation process to calculate the overall utility if a probabilistic measure level is present. Probabilistic measure levels are

from those measures where an uncertainty is expressed in the form of a mean and a standard deviation of the value.

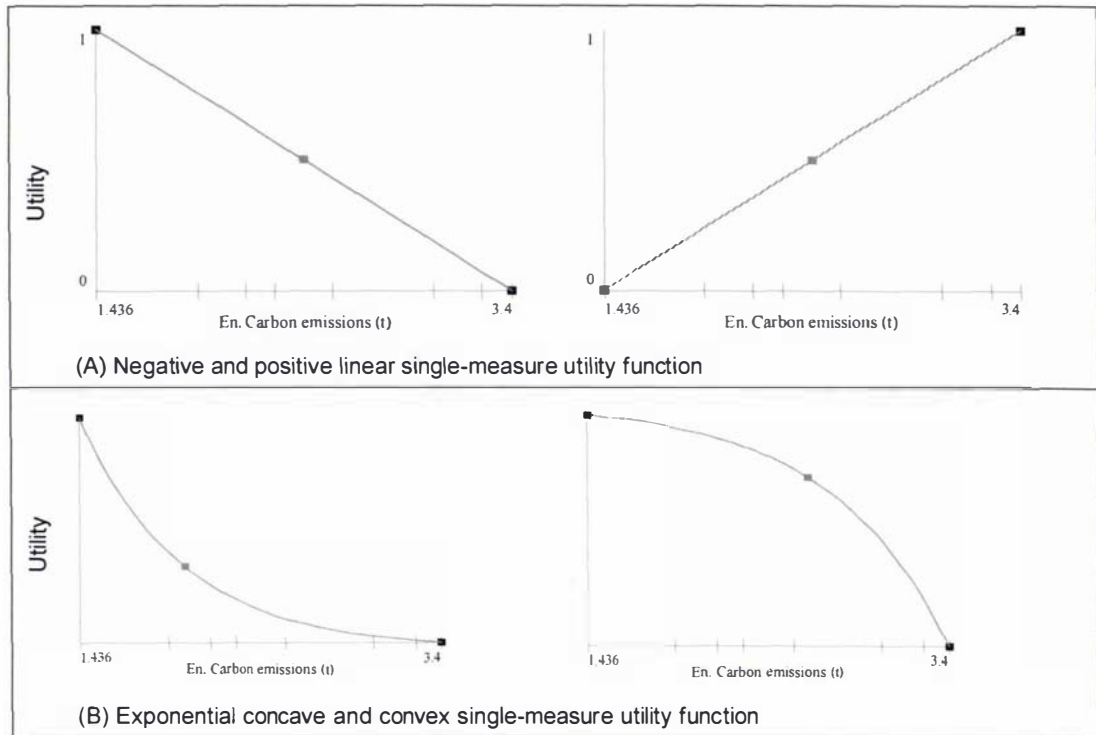


Figure 10.4 Four examples of the linear and non-linear Single-Measure Utility Functions (SUF).

Equation 10.1 The straight-line single-measure utility function (SUF).

$$U(X) = ax + b$$

Where :

$U(X)$ = the utility of the measure X

a and b = the LDW automatically computed scaling constants

x = the measure level of measure X

Source: Anon, (2001).

Equation 10.2 The exponential single-measure utility function (SUF).

$$U(X) = a(e^{-cx}) + b$$

Where :

$U(X)$ = the utility of the measure X

a , b , and c = the LDW automatically calculated scaling constants

e = the exponent 2.178...

x = the measure level of measure X

Source: Anon, (2001).

The *primary goal*, *secondary goals*, and *sub-goals* are given a user-defined importance by way of a stakeholder and/or decision maker defined *weight* setting. The type of weighting method (pairwise comparison, importance ratios, and importance ordering) and settings used is dependant on which one of two MCDA methods are employed by the user. Multi-attribute utility theory (MAUT) and the analytic hierarchy process (AHP) were both used in this study. The weighting techniques that were used in this LDW analysis were:

- pairwise comparisons method (trade-offs – AHP),
- simple multi-attribute rating technique using swings or SMARTS – (importance ratios method – MAUT), and
- simple multi-attribute rating technique exploiting ranks or SMARTER (importance ordering method – MAUT).

Secondary goals or sub-goals that have *measure levels* or the utility of other (sub) goals as members utilise the measure level or utility within a multi-measure utility function (MUF) (Figure 10.3). This calculates effective utility for each of the various member *measure levels* or *goals*. MUF can take the form of either additive (Equation 10.3) or multiplicative functions (Equation 10.4). Secondary goals have sub-goals as members and as such, each sub-goal will usually have multiple measures comprising an assortment of measure levels. These measure levels will have been converted to utility through single-measure utility functions (SUF). Secondary goals likewise will need to have utility calculated for each sub-goal and this is done using multi-measure utility functions (MUF).

Equation 10.3 The additive multi-measure utility function.

$$U_g(X) = b_1U_1(X_1) + b_2U_2(X_2) + \dots \dots b_nU_n(X_n)$$

Where :

$U_g(X)$ = the utility of alternative X for goal g

$U_i(X_i)$ = the utility of X for the i th member of goal g

b_i = the LDW automatic calculated scaling constant for the i th member of goal g

Source: Anon, (2001).

Equation 10.4 The multiplicative multi-measure utility function.

$$U_g(X) = \frac{((1 + Bb_1U_1(X_1)) \times (1 + Bb_2U_2(X_2)) \times \dots \dots \times (1 + Bb_nU_n(X_n)) - 1}{B}$$

Where :

$U_g(X)$ = the utility of alternative X for goal g

b_i = the automatically calculated scaling constant for member i of goal g

b_i defines the the interaction between goals

$b_i > 0$ = a destructive interaction

$b_i < 0$ = a constructive interaction

B = the magnitude of the interaction

$U_i(X_i)$ = the utility of alternative X for member i

Source: Anon, (2001).

The LDW computed *scaling constant*, denoted ' b ', calculated from the assignment of user-defined weights, was used in both additive and multiplicative functions. User adjustment of the default scaling constants can be used within a multiplicative MUF (Equation 10.4) to further define interactions between *measures*, and such interactions can be destructive or constructive as defined by user adjustment to the default value of ' b ' for a particular *measure*. If the value of ' b ' is left to the default value, there are no interactions. If the value of ' b ' is set to be less than the default value, a destructive interaction between goals will be set and a low utility in one goal

measure will result in a low overall goal utility. If 'b' is set to be greater than the default value, a constructive interaction will be set and a high utility in one goal measure will result in a high goal utility.

In the multiplicative function, the value of 'B' (Equation 10.4) defines the *magnitude* of the interaction. If B is greater than zero, the interaction will be destructive, and a low utility for one member will result in a low utility for the goal, B of less than zero will give a constructive interaction where a high utility for one member will give a high utility for the goal.

The conversion of measure levels into utility with the SUF and the ensuing aggregation of these utility values by way of the weighted MUF calculations will result in an overall weighted average utility value for each decision alternative. These aggregated totals can then be used to assess the best overall option according to the measure levels used and the user defined weighting applied to the various goals of the decision-analysis hierarchy.

10.2.3 The Analysis Theories Used by Logical Decisions for Windows

Two key methods of decision analysis were used in the decision analysis in this study, the analytic hierarchy process (AHP) and the multi-attribute utility theory (MAUT) in a multi-method approach (Figure 10.2) (Hobbs & Horn, 1997).

Analytic Hierarchy Process

The AHP method was developed by Saaty in 1980 (Belton & Stewart, 2002) and has many similarities to MAUT, though controversy exists as to whether AHP is indeed a value function method (*ibid.*). The operational theory behind the AHP is that of a systematic pairwise comparison that requires the consideration of all possible pairs of alternatives with respect to each decision criterion in turn to determine which of the pair is preferred and the strength of that preference (Figure 10.5). AHP treats the responses of the pairwise preferences as ratio judgements and this is the main difference from the value-based theory, MAUT (*ibid.*). The development of semantic scales (e.g. moderate importance or high importance etc, Figure 10.5) has been preferred by some decision-makers rather than using numerical scales of importance or preference.

As an example of this, the relative importance of the measures "Grid capacity Displacement" and "Carbon Emissions" were queried (Figure 10.5). The dialog box indicates the question being asked, in this example, "Which is more important, carbon emissions or Grid capacity displacement?" The strength of importance is noted in the dialog box here as "moderately more important." After a pairwise comparison between all measures, the overall weight is calculated and shown in the matrix diagonal. In this example, the overall weight of carbon emissions was calculated as being 0.356 and the Grid capacity displacement, 0.157. The elicitation of weights and preferences in the AHP method as used in the Logical Decisions for Windows software (Figure 10.5) was clear and easily understood. The semantic scale has been enhanced with intermediaries giving stakeholders and decision makers choices where there would be hesitation between the descriptions (Saaty, 1994; Anon, 2001, Belton & Stewart, 2002).

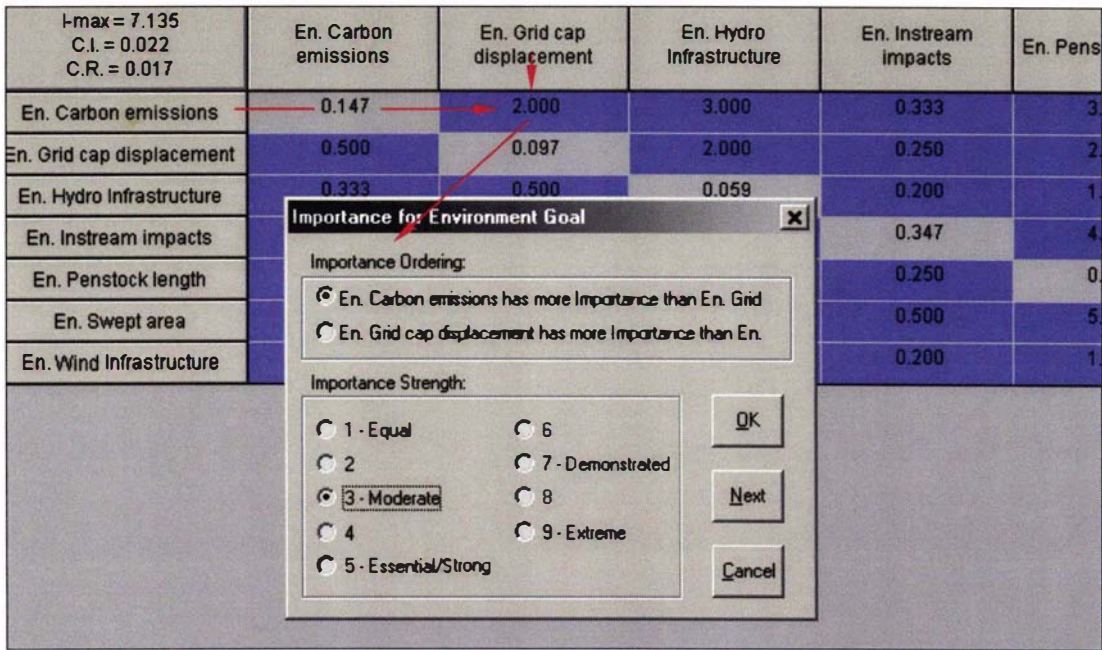


Figure 10.5 The AHP method of weight elicitation as used in the Logical Decisions for Windows software.

The data in the top left hand cell of Figure 10.5 are the matrix statistics. The eigenvalue is shown by $\lambda_{\max} = 7.135$ and the consistency index (CI) is the measure of absolute matrix consistency as calculated from the principal eigenvalue (Equation 10.5) (Saaty, 2003).

Equation 10.5 The consistency index equation used in Logical Decisions for Windows.

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

Where :

CI = the consistency index

$\lambda_{\max}$ = the principle eigenvalue of the matrix

n = the matrix size

Source: Anon, (2001).

The Lambda-Max ($\lambda_{\max}$ or $\lambda_{\max}$) is the principal eigenvalue and is the product of the matrix and the vector of the (unadjusted) weights or utilities for the matrix (Anon, 2001). The consistency ratio (CR) is calculated from the CI by comparison with a number derived from a random reciprocal matrix and used to indicate the consistency of the weight ratios used. A CR of less than 0.1 is deemed acceptable as this indicated a relative consistency within the pairwise ratios selected (Saaty, 1994; Belton & Stewart, 2002).

Two key drawbacks of the AHP method were the potentially large number of preference judgements required in a large problem structure, and the "rank – reversal" problem which occurs when a new alternative is placed into a previously calculated alternatives list. The value scores automatically rescale but the relative magnitudes of the weighting remain unchanged due to their allocation directly to criterion and are therefore independent of the

alternatives. Forman & Gass (2001) doubted that this was a major drawback if it was understood and the problem structured accordingly.

Multi-Attribute Utility Theory

Multi-attribute utility theory (MAUT) clearly espouses the use of value measurement theory (sometimes called multi-attribute value functions) and usually employs an additive aggregation method which is most easily explained and more readily understood by stakeholders and decision makers (Anon, 2001; Belton & Stewart, 2002). Widespread use of the MAUT method has led to many different ways of obtaining and calculating the weights and preferences required including the two techniques used in this study, SMARTS and SMARTER.

The MAUT method 'simple multi-attribute rating technique' (SMART) was first developed by Edwards in 1971, was named as such in 1977, but discovered to have "a fatal intellectual flaw" in 1978 (Edwards, 1994). The 'simple multi-attribute rating technique *using swings*' (SMARTS) was developed soon after, correcting the faults by the use of *swing weights* representative of the relative importance of the measures (Figure 10.6). Edwards (1994) conceded that, although many citations in the research literature have acknowledged both Edwards and von Winterfeldt as the developers of SMARTS, it is not known who exactly first used the *swing weights* concept (Edwards & Barron, 1994). The concept of 'relative importance' works well as most decision makers are at ease with the concept and feel comfortable with the visual technique (Anon, 2001). This follows on from the explanation by Edwards & Barron, (1994) that the motivation for the ensuing deployment of the technique was that if simple tools existed for the elicitation of weight values then the tools would be easy to use, be used by many, and the weights elicited would be reflective of the preferences of stakeholders and decision makers' preferences.

The use of the SMARTS method is both a visual and numerical method (Figure 10.6). When weights are elicited from the stakeholders either the percentage swing weight can be used (if weights are being elicited remotely by survey or other methods), or the weights gained through direct elicitation while viewing the relevant LDW screen presentation by sliding the 'bar' to a proportion representing their relative importance against the most preferred alternative. The numerical equivalent of this preference appears below the bar.

The underlying principle of 'relative importance' is behind the SMARTS elicitation technique. In this example (Figure 10.6), it is indicated by the 'carbon emissions' measure being rated as the most important. The 'in-stream impacts' measure has 90% of this importance, and the 'Grid capacity displacement' measure at 80% as important and so on. The absolute weight of each measure was obtained by normalising the swing weights to sum to one (Anon, 2001; Edwards & Barron, 1994).

Please enter the swing weights for Environment
 Swing weights must be between 0 and 100. One swing should equal 100.
 Swings indicate importance of going from least to most preferred level

	Done	Cancel	
	Least Preferred Level	Most Preferred Level	Swing Weight (100 = most imp.)
En. Instream impacts Measure (Labels)	Dam & Weir	0	100
En. Swept area Measure (Labels)	1 x 10kW	0	90
En. Carbon emissions Measure (t)	3.4	1.436	80
En. Grid cap displacement Measure (kW)	0	12.33	70
En. Hydro Infrastructure Measure (m)	150	0	40
En. Penstock length Measure (m)	170	0	40
En. Wind Infrastructure Measure (m)	1300	0	40

Figure 10.6 The SMARTS method of weight elicitation as used in the Logical Decisions for Windows software.

SMARTER (SMART Exploiting Ranks) developed by Barron and Barrett (1996a) utilises the Rank Order Centroid (ROC) approach to weights setting (Edwards, 1994; Barron & Barrett, 1996a&b). The weight elicitation method used in SMARTER can be used to elicit weights by way of a survey sent to stakeholders and is a relatively easy method to understand and use in LDW. It requires a simple importance ordering of all the options under consideration. The option of most importance is ranked '1', the second most important, '2' and so on with rankings of equal importance allowed (Figure 10.7).

Please enter the importance ordering for Environment
 Importances must be between 0 and 7. Ties are allowed.
 Lower numbers indicate more importance. 0 = no importance.

	Done	Cancel	
	Least Preferred Level	Most Preferred Level	Importance Preferred Order Level (1 = most)
En. Hydro Infrastructure Measure (m)	150	0	5
En. Penstock length Measure (m)	170	0	5
En. Wind Infrastructure Measure (m)	1300	0	5
En. Grid cap displacement Measure (kW)	0	12.33	4
En. Carbon emissions Measure (t)	3.4	1.436	3
En. Swept area Measure (Labels)	1 x 10kW	0	2
En. Instream impacts Measure (Labels)	Dam & Weir	0	1
Minimum Weight			0

Figure 10.7 The SMARTER method of weight elicitation as used in the Logical Decisions for Windows software.

An example of the LDW use of this technique shows the ranking in importance of the options (Figure 10.7). A minimum weight can be manually imposed on the normalised weights. There are two situations where the SMARTER method might be more useful in weight elicitation than other methods. Where the decision maker(s) may be "unavailable, unable or unwilling" to provide values any more specific than rankings, or where there may be many decision makers and the ranking of options may be the only way a consensus can be reached (Barron & Barrett, 1996b).

10.2.4 Preferences and Weights Elicitation Methods

An important component of the development of a multiple criteria decision analysis model is the method employed in the elicitation and analysis of the attribute weights (Barron & Barrett, 1996b). The elicitation of values, weights, and preferences from either an individual or a group is a complex and time consuming task (Keeney *et al.*, 1990; Tung, 1998; Keeney & McDaniels, 1999; Bana e Costa, 2001) and has long been seen as an essential topic for research by many practitioners of decision analysis (Tung, 1998). Keeney *et al.* (1990) elaborated extensively on methods of elicitation from groups to include surveys, indirect and direct elicitation of values, focus groups, and public involvement. Groups can include direct stakeholders, experts, representative samples of population sectors and general public opinions.

Surveys can directly elicit information about goal priorities, views on alternatives, and the goal preferences that the surveyed population has between the decision criteria. The disadvantages of this method are based on the hypothetical nature of many of the questions, the intentional or accidental influence of the survey author, the difficulties that are inherent in survey design and administration, and results interpretation (*ibid.*). In addition, the lack of immediate feedback from facilitator to participant can contribute to misunderstandings that can then lead to misrepresentative weights being elicited.

Indirect elicitation involves the elicitation of values, weights, and preference levels from marketplaces, published or anecdotal social opinion and in the context of historical community and society, the uptake of technology, knowledge, or values relevant to the goal objectives (*ibid.*). An example of such indirect interpretation was given as being the commodity prices for products relevant to the key goal, or previous community actions that imply (implicitly or explicitly) trade offs between goal objectives (*ibid.*). A key disadvantage with this method was listed as being the inference of values from trade offs that do not have a monetary or economic value. Contingent valuation of non-monetary values would circumvent this problem although with MAUT, the use of clearly distinguishable trade offs amongst goals can also be used to elicit utility directly instead of contingent valuation methods (*ibid.*). This direct use of utility would negate one of the key disadvantages of using contingent valuation, described by Keeney *et al.*, (1990) as being the combining of the hypothetical with the factual leading to mistakes, the magnitude of which can be exacerbated by sensitivity to one factor or another.

Direct value elicitation methods involve either facilitator and/or decision-analyst interaction with individual or groups of stakeholders in the elicitation of values, weights, and

preferences towards the various goals and objectives. This approach should be used only to elicit weighting preferences from within the clearly defined set of goals and measure levels and should not be used to question the alternatives or measure levels associated with the alternatives (*ibid.*). This 'diversion' from the purpose of weights and preferences elicitation would make an already complex task a prolonged and expensive exercise in both money and time where many people were involved. This approach though would avoid the problem associated with contingent valuation by clearly separating the hypothetical values from the factual values of a goal or objective through the framework of a MAUT technique. Disadvantages of this method are the difficulties and expense involved in the gathering of people in one place, and the difficulty lay people have in understanding questions involving trade-offs, preferences and utility theory (*ibid.*).

Focus groups, also known as the 'Delphi group approach' can be used to learn of public, industry, and perhaps government preferences and trade-off values. An open format is used and the task involves testing out goal ideas and concepts on a group able to authoritatively speak on behalf of the wider affected community (*ibid.*). Winkler *et al.* (1995) indicated that expert participants should be chosen based on their expertise and the potential to contribute to the immediate task. The advantage of using this approach is that much information relevant to the values associated with the goals can be amassed. Disadvantages include the small and sometimes unrepresentative nature of the groups and that the information collected can sometimes be only anecdotal (Keeney *et al.*, 1990).

Public involvement is contact with the section or group of the community directly affected by, and concerned with the solution of a problem or situation where alternatives need assessment. Keeney *et al.* (1990) specified this group to include experts, policy makers and administrators, members of the community affected or otherwise, and interest groups. The distinct advantage this approach has over that of the focus group is that if a specific problem or issue is needing specific resolution, the values, and preferences are solicited from the participants directly rather than solutions implied by focus groups. A disadvantage is that the problem needs to be compiled such that an understanding of the issues is clear and unambiguous amongst all the relevant groups. In a situation where the problem is large or complex, the required simplification may impose a situation where difficulties or bias towards the under stated aspects of the problem impose a degree of bias in the solicited values and preferences (*ibid.*).

Keeney *et al.* (1990) resolved some of the difficulties involved in weight and values elicitation by combining the *direct value elicitation* method with the *focus group* technique that they termed the "*Public Value Forum*". A series of workshops formed the basis of this technique where selected members of the community and stakeholders were introduced to the framework of a multi-attribute utility analysis and were asked to consider a series of questions after a discussion of the objectives and goals of the problem being assessed. This method could also provide the forum for the formation of an objective or goal and measure list if not already compiled by the decision analyst. The agenda of such forums was problem introduction, objective or goal refinement, SUF elicitation, MUF trade-off and preference elicitation, trade off

and preference settings with expert judgements, and then reconciliation between the evaluation result and the intuitive choices of the participants.

The conclusions Keeney *et al.* (1990) drew from their experiences was that although the overall process of the forum was feasible, initial intuitive values differed from the formally elicited values once the problem was formally explained, and while the forum elicited all relevant values it was time consuming and expensive. This latter point of high money and time cost is also a finding of Bana e Costa (2001). Hämäläinen *et al.* (2000) indicated that much of the time used in the elicitation of weights and preferences was in the education of the participants to understand the processes involved in the use of their respective responses. Biases and unbalanced decision analyses could easily result from information obtained because of a lack of understanding of the processes involved in the decision analysis technique. Hobbs & Horn (1997) indicated that feedback from decision analysis facilitators were essential to aid in the understanding of the methods used and the techniques used to elicit the appropriate weights and preferences.

The weights as used after the elicitation of values, trade-offs and preferences can be documented a number of ways and Keeney *et al.* (1990) suggested simple rating methods (SMARTS and SMARTER) as being sufficient. Most situations can be assessed using a simple additive multi-attribute utility model using the weighted average of the SUF (Equation 10.3). Problems that are more complex can utilise a multiplicative model (Equation 10.4) but the use of such models would require an additional range of questions and further explanation of a complex process. Sensitivity analyses may be required where there is disagreement between participant responses about weight levels and preferences. This would clarify whether changes to the particular weight or preference levels result in a change in the overall ranking of the alternatives (*ibid.*).

Belton & Stewart (2002) suggested three methods of analysing and utilising values and preferences elicited from a participating group. These were; the sharing of values or preferences amongst a group that may lead to commonality by consensus; aggregating values and preferences to obtain commonality by compromise, and comparing values and preferences to gain commonality by negotiation and Tung (1998) mentioned similar methods using the geometric mean of the individual values and preferences.

Given these findings of high expense of money and time in the gathering of values and preferences from the group of stakeholders it was decided by the author, mainly due to time a constraint, that the values and preferences used in this study would be set by the author for use in LDW. These singular preferences would then be entered into an LDW preference set to represent either of the two representative groups of *distribution network* or *individual farm*.

Recommended Elicitation Method

Although the version of LDW used in this study was orientated toward an individual decision-maker, a specialised version of LDW exists that is specifically aimed at group decision-analysis. Logical Decisions for Windows for Groups operates the same way in every respect as the version used in this study except for the additional dialog boxes that aid in the elicitation of

weights and preferences from individuals within a named group. Elicitation of weights and preferences within a workshop setting can be done either by way of a special keyboard or by direct entry into the programme against an individual's name or identification tag. The collected values are aggregated by either geometric or arithmetic means into the weight or preference that represents the named group. When AHP is the MCDA method used the elicited weights and preferences are aggregated by geometric mean; when MAUT is used, the weights or preferences are aggregated by the arithmetic mean. The key value of this software version is that the results can be viewed with the individual inputs indicated and potential conflicts can thus be identified.

It is recommended by the author because of experience gained using the LDW software in this study that a similar concept adopted by Keeney *et al.* (1990), of the '*Public Value Forum*' in conjunction with a *Focus Group* be adapted for use in any future application of this method using the group version of LDW. In many cases, this combination would be the most cost effective method of preference and weights elicitation. The 'focus group' component would determine certain aspects of the problem structure as it relates to renewable energy system and distribution network constraints or requirements etc. These could then become useful as a template in similar settings even though there would be different stakeholder groups. Such 'generic' problem structures incorporating constraints could then be applied on a site-specific basis with a minimum need for further focus group input.

The financial cost of such meetings is unknown and therefore not included in any of the ensuing analyses. Estimates of the time involved have been made (Figure 4.1) and these will be updated according to revised estimates after the decision analyses in this section (Section 11.2).

10.2.5 Decision Model Structure

The primary goal of this study, "*sustainable power in rural areas and locations*" (SPiRAL) (Figure 10.8) was divided into four main secondary goal areas: economic, environmental, social, and technical, each characterising the underlying nature of sustainability (Keeney & McDaniels, 1999; Outhred *et al.*, 2002). The 'Economic' secondary goal was further divided into the sub-goals of 'Local Economy' and 'RE Industry Economy' to reflect the splitting of the economic costs and returns of an energy system into local system effects and industry effects, where the latter are likely to be remote from the former. The 'Environment' secondary goal was further divided into the more specific 'Hydro impacts' and 'Wind impacts'. The 'Social' secondary goal was divided into the sub-goals of 'Social benefits' and 'Social impacts'. The 'Technical' secondary goal was divided into the sub-goals of 'Encourage RE industry', 'Peak-load reduction', and 'System availability'.

10.2.6 Decision Criteria Definitions

The measures used in this study (Figure 10.8) are defined more fully below.

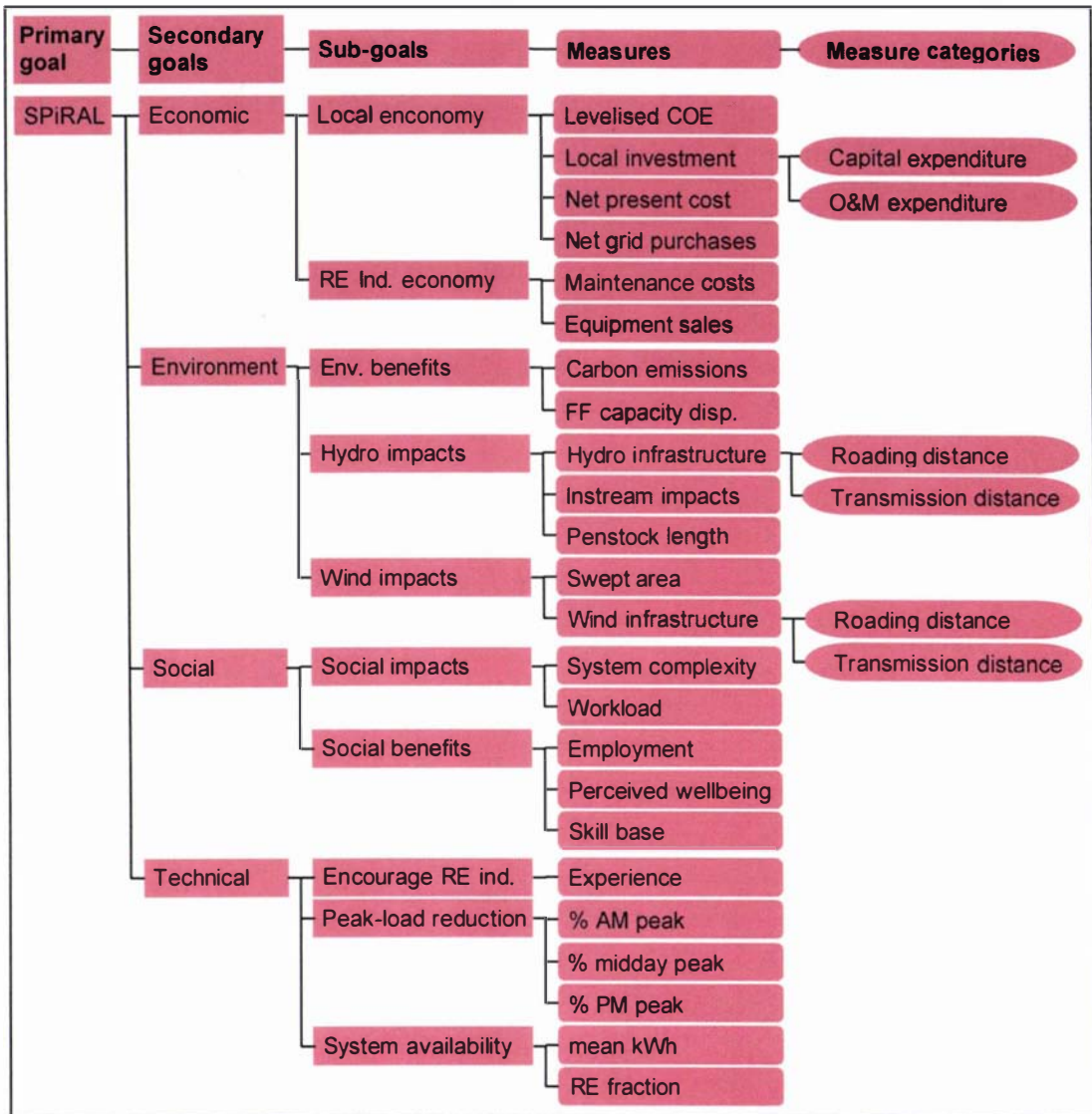


Figure 10.8 The decision hierarchy used in this study showing the primary goal, secondary goals, and subsequent sub-goals, measures, and measure categories.

Economic

- COE – The 'levelised cost of energy' (Equation 9.3) is the average cost of the energy produced over the year by the renewable energy generation system. The mean COE and standard deviation figures from the HOMER simulation and optimisation modelling were used to model the uncertainty of the COE in LDW.
- NPC – The 'net present cost' (Equation 9.1) is the net cost of the renewable energy generation system over the 25-year period of the system lifetime, using the real interest rate of 3.76% (Equation 9.4), expressed in 2004 dollars. The mean NPC and the standard deviation figures from the HOMER simulation and optimisation modelling were used to model the uncertainty of the NPC in LDW.

- Local investment – This measure level was split into two categories to include capital expenditure and operation and maintenance expenditure, both derived from the HOMER model results. This measure level was calculated assuming 20% of capital expenditure and 80% of the operation and maintenance expenditure was spent in the local economy.
- Net grid purchases – The net grid purchase of each alternative was the dollar value of the net amount of energy needing to be purchased to meet the load. This was the amount of energy not generated by the renewable energy generation system.
- Sales – This measure level was the value of the capital goods bought from industry for the renewable energy system only. It did not include any values other than the provision of equipment.
- Maintenance costs – This was the dollar value of the annual operation and maintenance costs including grid operation and maintenance and was derived from HOMER.

Environmental

- Carbon emissions – These from a renewable energy based generation system will be close to zero and so could be expected to mitigate emissions from grid-sourced electricity with a fossil fuel component. The measure level of tonnes of carbon emitted was based on the output from HOMER, which indicated the amount of carbon the community was responsible from the electricity used. The mean carbon emissions and the standard deviation figures from the HOMER simulation and optimisation modelling will be used to model the uncertainty of the amount of carbon emissions.
- Hydro infrastructure – This combined road length required for the hydro development and transmission line length in metres. Length of both road and transmission line was seen as a way of assessing the visible impacts of this development.
- In-stream impacts – This considered whether the hydro development was a dam, a diversion weir or, as was the case in this case study, a combination of a dam and two weirs in three locations. The use of labels allowed for selection of either “no hydro,” or “dam/weir” impact. Each option was graded with a weighted preference relevant to the impact it is likely to have on the stream.
- Penstock length – This was used as an estimate of the length of stream with a reduced flow because of water diversion through the hydro scheme. The assumption was that the longer the length, the greater the environmental impact.
- Wind infrastructure – This combined road length required for the wind development with transmission line length to point of use. Length of both road and transmission line was a way of assessing the visible impacts of the development.
- Swept area – This measure was based on the swept area of the wind turbines and the potential visual impact this may pose. Labels defined the capacity of the wind turbine used with the assumption that a 3 kW turbine will have a lesser visual impact than the larger 10 kW turbine. This assumption was used, as all wind turbines would be visible on a ridgeline.
- Grid capacity displacement – This was a measure of the capacity of fossil fuel generation displaced by use of a renewable energy system. The measure was based on the kW capacity of the system on the supply side of the inverter of the alternative being considered.

This assumed that every kW of renewable energy capacity displaced the need for expansion of more fossil fuel capacity as load demand increases on the network.

Social

- **Workload** – The level of workload any owner or manager of a renewable energy system would probably be related to the level of complexity of the system and it was this that would lead to an increased 'workload', something that would be considered a negative impact.
- **System complexity** – This measure, based on the reported desire for simple renewable energy system designs (Lloyd *et al.*, 2000), sought to put in place simple systems. This followed from studies that indicated routine operation and maintenance was often undertaken by the user of the system, or others from the immediate locality (Outhred *et al.*, 2002; MacGill *et al.*, 2002, MacGill & Watt, 2002; Watt & MacGill, 2002).
- **Employment** – The employment related to any renewable energy system installed was likely to be relative to the size of system but there was little in the way of statistics related to small renewable energy industries collectively or individually. The information available was related to large-scale renewable energy industry (Outhred *et al.*, 2002; MacGill *et al.*, 2002, MacGill & Watt, 2002; Watt & MacGill, 2002). MacGill & Watt (2002) suggested that operation and maintenance offered more stable employment than manufacturing though this was set to fall as reliability and quality of renewable energy technology improved. Therefore, operation and maintenance employment levels selected in this case study were related to the complexity of the systems and the assumption that combinations of technologies indicate a higher employment level.
- **Skill base** – Complex systems usually require more maintenance work to keep them in operation. A positive 'spin-off' of complex systems is that by combining technologies into hybrid renewable energy systems the 'skill base' of the person operating and maintaining the system will inevitably increase as the need to learn how to operate and maintain the system increases.
- **Perceived well-being** – An individual or community may feel well-being related to security of supply, autonomy, and environmental good and this would more likely result from combined technologies. The more technologies combined into the system the greater the perceived well-being.

Technical

- **Mean kWh** – The measure of the 'mean hourly level of energy delivered' by the system was calculated from data derived from HOMER simulations. The mean kWh and the standard deviation figures were used to model the uncertainty of the mean kWh.
- **Experience** – This measure was an indication of the experience gained by the renewable energy industry based on the installed capacity (kW) of the renewable energy system.
- **Morning peak** – The percentage of morning peak-load reduction (% am peak) was calculated from data derived from HOMER simulations. The mean reduction and the standard deviation figures were used to model the uncertainty of the reduction.

- Midday peak – The percentage of midday peak-load reduction (% midday peak) was calculated from data derived from HOMER simulations. The mean reduction and the standard deviation figures were used to model the uncertainty of the reduction.
- Evening peak – The percentage of evening peak-load reduction (% pm peak) was calculated from data derived from HOMER simulations. The mean reduction and the standard deviation figures were used to model the uncertainty of the reduction.
- RE fraction – The measure of the ‘renewable energy fraction’ was calculated by HOMER as the portion of the total energy used, originating from the renewable energy components of the installed system (Lilienthal *et al.*, 2003).

10.2.7 Decision Measures and Measure Levels

The full-term and short-term duration measures and their respective measure levels for the sub-goals are listed in Table 10.1 to Table 10.7. Where the preference was towards a high measure level, this is indicated as ‘High’ and ‘Low’ where the preference was for a low measure level. All measure levels that had uncertainty modelled as a normal distribution were listed as such. There was no difference between the full-term and short-term duration measures for the social measures so these were listed in Table 10.3 only.

Full-Term Duration Measure Levels

Table 10.1 The full-term duration economic measure levels obtained from HOMER modelling.

	Cost of energy (\$/kWh)	Net present cost (\$)	Local Investment (\$)	Net grid purchases (\$/y)	Sales (\$)	O&M costs (\$/y)
Preferences	Low	Low	High	Low	High	High
Uncertainty	Yes	Yes	No	No	No	No
G	0.153	184,658	0	9,487	0	11,048
W	0.190	236,346	22,224.80	5,801	66,400	9,023
H	0.202	242,953	22,766.00	6,817	72,170	10,182
WH	0.226	294,686	35,133.20	3,131	138,570	8,157
S	0.251	302,478	26,185.60	8,957	76,036	12,423
SW	0.287	344,679	31,391.60	8,018	102,446	12,306
SH	0.300	360,773	39,088.40	6,286	148,206	11,557
SWH	0.334	402,972	44,293.60	5,348	174,616	11,440

Table 10.2 The full-term duration environment measure levels obtained from HOMER modelling and based on the renewable energy system configuration details.

	Carbon emissions (t)	Hydro Infrastructure (m)	In-stream impacts (labels)	Penstock length (m)	Wind Infrastructure (m)	Swept area (labels)	Grid Capacity displacement (kW)
Preferences	Low	Low	n/a ²⁹	Low	Low	Low	High
Uncertainty	Yes	No	No	No	No	No	No
G	45,275	-	-	-	-	-	-
W	28,664	-	-	-	1,300	1 x 10kW	10.00
H	33,140	150	Dam/Weir	170	-	-	2.06
WH	16,528	150	Dam/Weir	170	1,300	1 x 10kW	12.06
S	43,052	-	-	-	-	-	4.50
SW	38,815	-	-	-	1,300	1 x 3kW	7.50
SH	30,917	150	Dam/Weir	170	-	-	6.56
SWH	26,679	150	Dam/Weir	170	1,300	1 x 3kW	9.56

Table 10.3 The full-term duration social measure levels based on the renewable energy system configuration details.

	Workload	System complexity	Employment	Skillbase	Perceived wellbeing
SUF settings	n/a ³⁰				
Uncertainty	No				
G	Grid				
W	10 kW Wind				
H	2.06 kW Hydro				
WH	10 kW Wind & 2.06 kW Hydro				
S	4.5 kW Solar				
SW	4.5 kW Solar & 3 kW Wind				
SH	4.5 kW Solar & 2.06 kW Hydro				
SWH	4.5 kW Solar & 3 kW Wind & 2.06 kW Hydro				

²⁹ See Table 10.8 for details of the direct entry values used in this analysis.³⁰ See Table 10.9 for details of the direct entry values used in this analysis.

Table 10.4 The full-term duration technical measure levels obtained from HOMER modelling.

	Mean kWh (kWh)	Experience (kW)	Morning peak (%)	Midday peak (%)	Evening peak (%)	RE fraction (%)
Preferences	High	High	High	High	High	High
Uncertainty	Yes	No	Yes	Yes	Yes	No
G	0	0	0	0	0	0
W	3.19	10.00	45	41	39	37.4
H	2.31	2.06	50	34	30	28.1
WH	5.50	12.06	85	68	62	61.2
S	0.46	4.50	2	16	4	6.2
SW	1.27	7.50	13	27	14	16.9
SH	2.77	6.06	41	43	27	34.1
SWH	3.58	9.56	53	54	37	44.4

Short-Term Duration Measure Levels

The measure levels used in the short-term duration analysis resulted from the modelling of both the electricity loads, and energy resources in HOMER (Table 10.5 to Table 10.7).

Table 10.5 The short-term duration economic measure levels obtained from HOMER modelling.

	Levelised cost of energy (\$/kWh)	Net present cost (\$)	Local Investment (\$)	Net grid purchases (\$/y)	Sales (\$)	O&M costs (\$/y)
Preferences	Low	Low	High	Low	High	High
Uncertainty	Yes	Yes	No	No	No	No
G	0.152	192,852	0	9,973	0	11,535
W	0.180	236,359	21,886	5,749	76,036	8,971
H	0.199	251,143	22,488	7,303	72,170	10,669
WH	0.215	294,966	34,821	3,048	148,206	8,110
S	0.245	308,485	25,684	9,258	102,446	12,725
SW	0.277	349,052	30,927	8,175	174,616	12,463
SH	0.291	366,776	38,643	6,588	66,400	11,859
SWH	0.322	406,776	43,856	5,055	138,570	11,597

Table 10.6 The short-term duration environment measure levels obtained from HOMER modelling and based on the renewable energy system configuration details.

	Carbon emissions (t)	Hydro Infrastructure (m)	Instream impacts (labels)	Penstock length (m)	Wind Infrastructure (m)	Swept area (labels)	Grid Capacity displacement (kW)
Preferences	Low	Low	N/A ³¹	Low	Low	Low	High
Uncertainty	Yes	No	No	No	No	No	No
G	47,599	-	-	-	-	-	-
W	28,668	-	-	-	1,300	1 x 10kW	10.00
H	35,463	150	Dam/Weir	170	-	-	2.06
WH	16,531	150	Dam/Weir	170	1,300	1 x 10kW	12.06
S	44,756	-	-	-	-	-	4.50
SW	39,895	-	-	-	1,300	1 x 3kW	7.50
SH	32,619	150	Dam/Weir	170	-	-	6.56
SWH	27,758	150	Dam/Weir	170	1,300	1 x 3kW	9.56

Table 10.7 The short-term duration technical measure levels obtained from HOMER modelling.

	Mean hourly kWh (kWh/h)	Experience (kW)	Morning peak (%)	Midday peak (%)	Evening peak (%)	RE fraction (%)
Preferences	High	High	High	High	High	High
Uncertainty	Yes	No	Yes	Yes	Yes	No
G	0	0	0	0	0	0
W	3.65	10.00	52	47	38	40.8
H	2.31	2.06	35	26	22	26.8
WH	5.96	12.06	87	73	61	63.0
S	0.62	4.50	7	21	2	7.9
SW	1.55	7.50	21	33	12	19.6
SH	2.93	6.56	42	46	25	34.5
SWH	3.86	9.56	56	58	34	45.7

10.2.8 Model of Uncertainty

The effect of the uncertainty assigned to the COE, NPC, carbon emissions, mean kWh, and the peak load reduction percentages was modelled using the Monte Carlo simulation technique in LDW. This method employed by LDW is a method for estimating the uncertainty of a utility value that is a complex function of one or more probability distributions. In order to calculate the overall utility including the seven measures with probability distributions, 250 trials

³¹ See Table 10.8 for details of the direct entry values used in this analysis.

were conducted and the results for each trial saved. These results were then used to form an estimate of the certainty equivalent of the overall utility.

10.2.9 Weights and Preferences

Single-measure Utility Function Preference Settings

Single-measure utility functions (SUF) were used to indicate stakeholder preferences of one measure level over others for a particular measure. Although the SUF settings used could be set to individual stakeholder preferences of either straight line or exponential functions, for simplicity in this case study all preferences were set to the LDW default straight-line functions either negative or positive (Figure 10.4) reflecting the nature of the measure and stakeholder preferences towards them.

For the measures that have numerical values the SUF were simple linear equations which were formulated to equate the least preferred measure level with a utility of zero, and the most preferred measure level with a utility of 1. The values between are assigned utility on the linear scale. For measures with direct entry values (includes in-stream impacts in Table 10.2 and Table 10.3), the SUF were again linear, but were to utilise the values in Table 10.8 and Table 10.9.

Table 10.8 The environmental measures as assessed by direct entry.

Measures	Label	Utility
Instream impacts (labels)	0	1
	Dam & Weir	0
Penstock length (m)	0	1
	170	0
Swept area (labels)	0	1.0
	1 x 3kW	0.5
	1 x 10kW	0

Table 10.9 The social measures as assessed by direct entry.

Measures	Label	Utility
Employment (labels)	Solar & wind & hydro	1.000
	Wind & hydro	0.800
	Solar & wind	0.625
Perceived well being (labels)	Solar & hydro	0.500
	Wind	0.375
	Hydro	0.250
Skill base (labels)	Solar	0.125
	Grid	0
System complexity (labels)	Grid	1.000
	Solar	0.800
	Hydro	0.625
	Wind	0.500
	Solar & hydro	0.375
Workload (labels)	Solar & wind	0.250
	Wind & hydro	0.125
	Solar & wind & Hydro	0

Multi-measure Utility Function Weights

Three MCDA techniques, AHP, SMARTS and SMARTER, each using separate multi-measure utility functions (MUF), were used to calculate the weights for this study. The AHP method (Figure 10.5) automatically calculated the weight after each pairwise comparison was completed (Table 10.10 and Table 10.11). The SMARTS method utilised both a visual and numerical method of 'swinging weights' (Figure 10.6). The SMARTER method was the simpler method of the three to use because of the ranking method (Figure 10.7). The assumed preferences of the two stakeholder groups, *distribution network* and *individual farm*, are shown in Table 10.10, and the subsequent LDW calculation process converted these to default 'scaling constants' (absolute weights) (Table 10.11). These scaling constants were used to calculate the utility of the measures and sub-goals with respect to each renewable energy system.

The assumed values, allocated by the author, are subjective and reflect the author's interpretations of anecdotal and implied preferences of the two preference sets assessed in this study. Such subjectivity of preferences has long been an issue with such decision analysis methods but as each preference was noted, it became explicit in the analysis. It should be noted, decision makers can directly or inadvertently abuse such application of subjective values in order to obtain results reflecting their requirements rather than an objective result reflecting the true requirements of all involved.

The preference set of *distribution network* assumed the secondary goal 'technical' issues to be of foremost importance, followed by 'economic', 'environment', and then 'social'. The *individual farm* preference set assumed 'economic' to be paramount, followed by 'social', 'environment', and then 'technical'.

In the 'economic' measures, the net present cost had more importance to the *distribution network* preference set whereas the levelised cost of energy was assumed more important to *individual farm*. In the environment measures the carbon emissions level had more importance to distribution perspectives whereas, the in-stream impacts were assumed more important to the *individual farm* preference set. In the social measures, the skill base (or experience) was of more importance to distribution perspectives whereas employment prospects were assumed more important to individual farm. In the technical measures, the evening peak reduction (% PM peak) was of more importance to distribution perspectives whereas the 'mean kWh' was assumed more important to *individual farm*.

Table 10.10 The relative weights as entered for use for each MCDA method and preference set.

Preference set	Distribution network			Individual farm		
Measures	AHP	SMARTS	SMARTER	AHP	SMARTS	SMARTER
Economic secondary goal						
Levelised cost of energy	0.244	90	2	0.364	100	1
Local investment	0.067	50	5	0.173	75	3
Maintenance costs	0.116	70	3	0.063	33	5
Net present cost	0.384	100	1	0.100	65	4
Net grid purchase	0.067	50	5	0.237	85	2
Sales	0.123	70	3	0.063	33	5
Environment secondary goal						
Carbon emissions	0.356	100	1	0.147	80	3
Grid Capacity displacement	0.157	80	3	0.097	70	4
Hydro infrastructure	0.066	33	4	0.059	40	5
Instream impacts	0.222	90	2	0.347	100	1
Penstock length	0.065	33	4	0.057	40	5
Swept area	0.068	33	4	0.230	90	2
Wind infrastructure	0.065	33	4	0.063	40	5
Social secondary goal						
Employment	0.096	40	4	0.344	100	1
Perceived well being	0.059	20	5	0.087	50	5
Skill base	0.416	100	1	0.259	90	2
System complexity	0.271	90	2	0.155	80	3
Workload	0.158	65	3	0.155	80	3
Technical secondary goal						
% AM peak reduction	0.252	95	2	0.119	80	3
% midday peak reduction	0.150	85	3	0.119	80	3
% PM peak reduction	0.397	100	1	0.119	80	3
Experience	0.039	20	6	0.217	90	2
Mean kWh	0.099	70	4	0.363	100	1
Renewable energy fraction	0.063	50	5	0.064	50	6
SPiRAL primary goal						
Economic	0.262	90	2	0.483	100	1
Environment	0.118	65	3	0.157	50	3
Social	0.055	40	4	0.272	75	2
Technical	0.565	100	1	0.088	25	4
SPiRAL = Sustainable power in rural areas and locations						

Table 10.11 The absolute weights as calculated by Logical Decisions for Windows to be used for each MCDA method and preference set.

Preference set	Distribution network			Individual farm		
Measures	AHP	SMARTS	SMARTER	AHP	SMARTS	SMARTER
Economic secondary goal						
Levelised cost of energy	0.244	0.209	0.229	0.364	0.256	0.450
Local investment	0.067	0.116	0.042	0.173	0.192	0.150
Maintenance costs	0.116	0.163	0.104	0.063	0.084	0.033
Net present cost	0.384	0.233	0.479	0.100	0.166	0.083
Net grid purchase	0.067	0.116	0.042	0.237	0.217	0.250
Sales	0.123	0.163	0.104	0.063	0.084	0.033
Environment secondary goal						
Carbon emissions	0.356	0.249	0.494	0.147	0.174	0.145
Grid Capacity displacement	0.157	0.199	0.119	0.097	0.152	0.079
Hydro infrastructure	0.066	0.082	0.036	0.059	0.087	0.029
In stream impacts	0.222	0.224	0.244	0.347	0.217	0.445
Penstock length	0.065	0.082	0.036	0.057	0.087	0.029
Swept area	0.068	0.082	0.036	0.230	0.196	0.245
Wind infrastructure	0.065	0.082	0.036	0.063	0.087	0.029
Social secondary goal						
Employment	0.096	0.127	0.090	0.344	0.250	0.488
Perceived well being	0.059	0.064	0.040	0.087	0.125	0.050
Skill base	0.416	0.318	0.457	0.259	0.225	0.238
System complexity	0.271	0.286	0.257	0.155	0.200	0.113
Workload	0.158	0.206	0.157	0.155	0.200	0.113
Technical secondary goal						
% AM peak reduction	0.252	0.226	0.242	0.119	0.167	0.092
% midday peak reduction	0.150	0.202	0.158	0.119	0.167	0.092
% PM peak reduction	0.397	0.238	0.408	0.119	0.167	0.092
Experience	0.039	0.048	0.028	0.217	0.188	0.217
Mean kWh	0.099	0.167	0.103	0.363	0.208	0.467
Renewable energy fraction	0.063	0.119	0.061	0.064	0.104	0.042
SPiRAL primary goal						
Economic	0.262	0.305	0.271	0.483	0.400	0.521
Environment	0.118	0.220	0.146	0.157	0.200	0.146
Social	0.055	0.136	0.065	0.272	0.300	0.271
Technical	0.565	0.339	0.521	0.088	0.100	0.063
SPiRAL = Sustainable power in rural areas and locations						

10.3 Results

The results of the full-term and short-term duration decision analysis are presented in sections 10.3.1 and 10.3.2. These are presented as a comparative analysis of the results of the three MCDA methods based on the two representative stakeholder groups, and the uncertainty of the utility expressed as the standard deviation with maxima and minima plots around the mean, including the effect of the absolute weighting. A detailed sensitivity analysis of each of the four sustainability secondary goals for each MCDA method and each stakeholder group was detailed where the effects of changing weights and on overall rankings was indicated.

10.3.1 Full-Term Duration Results

The full-term duration results of the individual MCDA methods (AHP, SMARTS, and SMARTER) in each of the preference sets (*distribution network* and *individual farm*) indicates the best option from all MCDA methods in both preference sets was the combined system of the 10 kW AC wind turbine and the 2.06 kW AC hydro (WH) option (Figure 10.9).

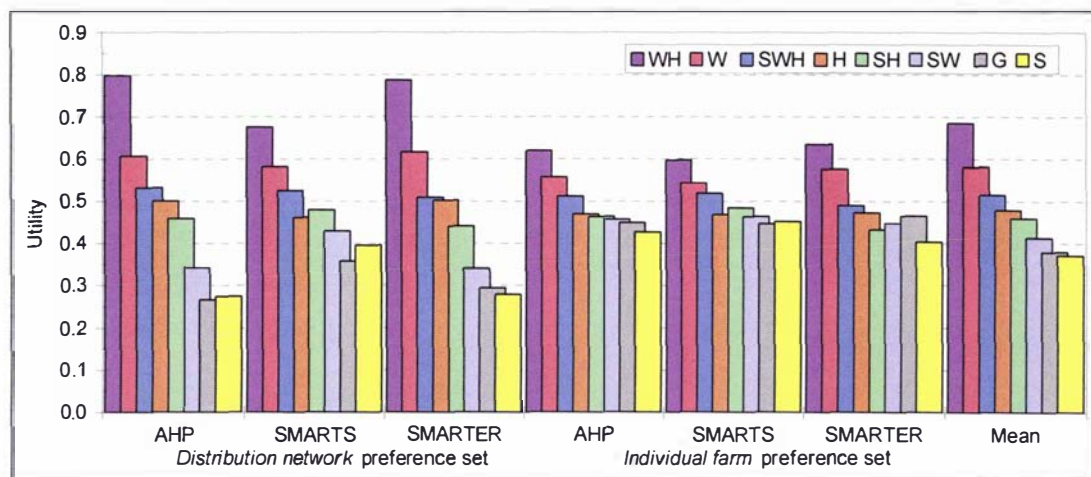


Figure 10.9 A comparison of the utility between MCDA methods and preference sets for the full-term duration analysis and the mean results.

The mean results of all the methods clearly indicated the WH option had the highest mean utility of all the alternative systems and wind (W) and Solar PV (S), were the next clearly highest ranked renewable energy systems. The mean results, when used as a benchmark for a comparison between methods and preference sets, can be used to assess any outliers or results not consistent with the overall mean results of the decision analysis.

The ranked results of the uncertainty analysis for each MCDA method and preference set (Figure 10.10 and Figure 10.11) include the mean utility of each alternative, the maximum, and minimum of the utility, and the standard deviation about the mean utility. These results clearly indicate the consequential uncertainty stemming from the combination of measures with uncertain measure levels expressed as a normal distribution, derived from the HOMER simulations (Table 10.1, Table 10.2, and Table 10.4).

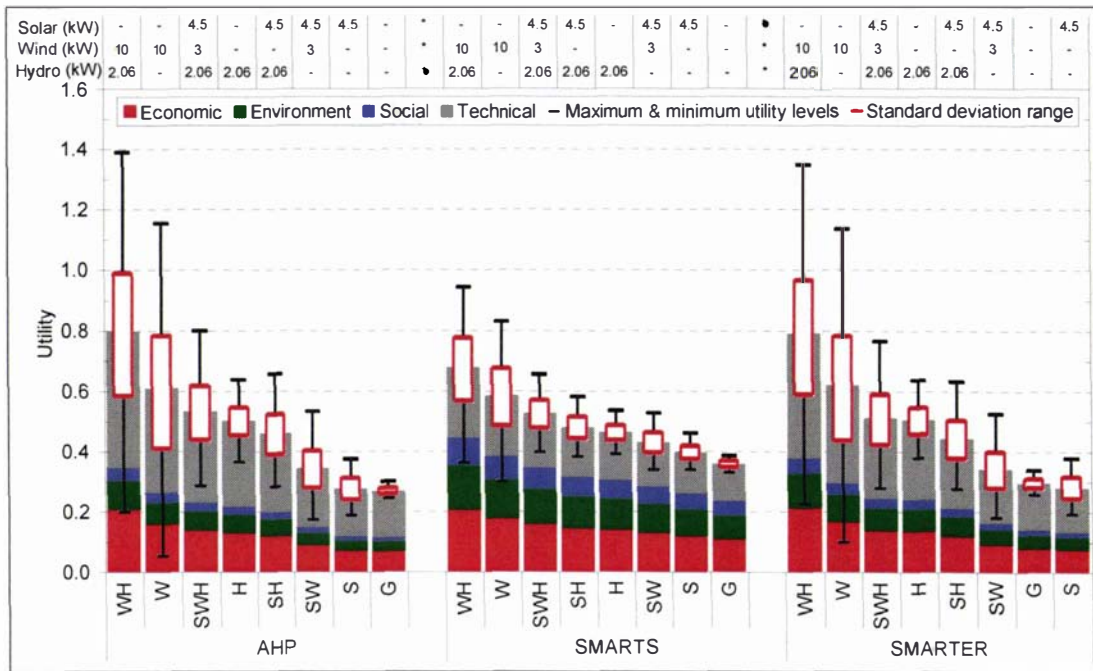


Figure 10.10 The full-term duration mean utility (expressed in absolute weights), standard deviation range, and maximum-minimum utility for the *distribution network* preferences for the three MCDA methods.

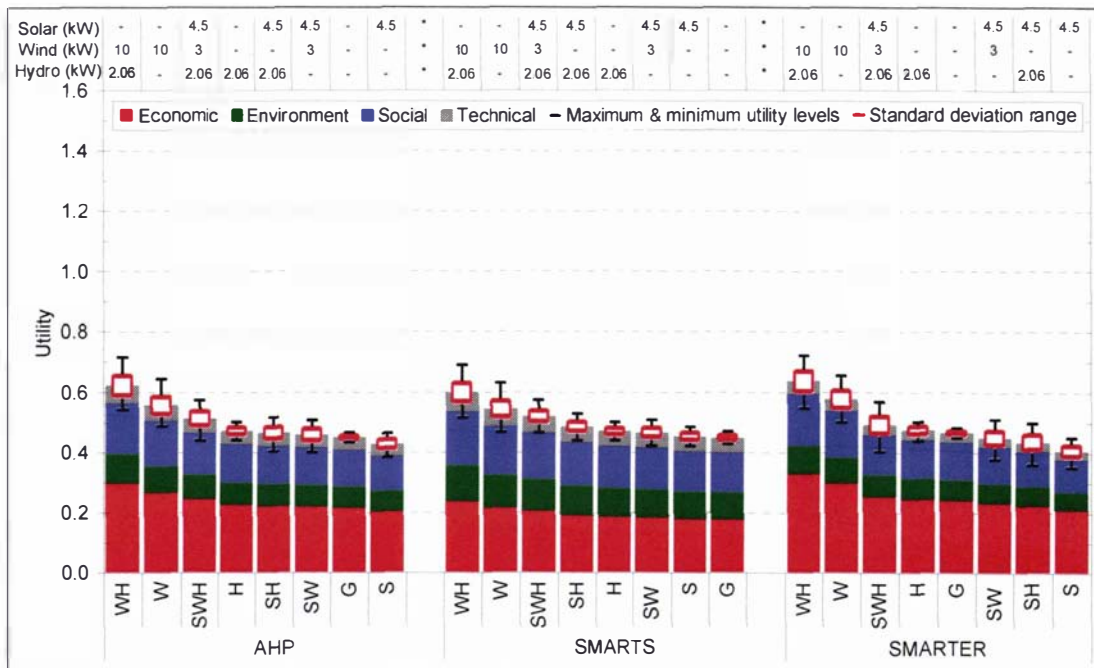


Figure 10.11 The full-term duration mean utility (expressed in absolute weights), standard deviation range, and maximum-minimum utility for the *individual farm* preferences for the three MCDA methods.

The maxima and minima values of utility illustrate the full range of possible utility values, whereas the range of standard deviation indicates those values likely 68% of the time. This analysis allowed a visual interpretation of the effects of the uncertainty stemming from the variability of the electricity loads, and wind and solar resource levels on the utility of the renewable energy options. From the *distribution network* preference set (Figure 10.10), not only

are the levels of utility relatively higher, but the relative levels of variation are larger than those of the *individual farm* preference set (Figure 10.11).

The absolute weights (Figure 10.10 and Table 10.11) of each of the four sustainability secondary goals were included to give an indication of the relative effect of these on the levels of utility of each of the MCDA methods. For the *distribution network*, preferences showed the majority of the weighting given to Technical, followed by Economic, Environment, and then Social. The levels of utility relative to each of the *individual farm* preferences showed that the majority of the weighting given to Economic, followed by, Social, Environment, and then Technical secondary goals.

These effective levels of weighting affect the spread of the normal curve of the uncertainty for each option, as the weight increased on an option, so too does the relative level of uncertainty increase. This can be illustrated by comparing the uncertainty of an option between preference sets. If the option has a higher level of uncertainty due to electricity load or resource uncertainties (Table 10.1, Table 10.2, and Table 10.4), the resultant utility uncertainty will increase or decrease relative to the weighting placed on the effective sub-goal and dependent secondary goal. Consequently, options with a higher relative utility may also have a higher degree of uncertainty about the utility, and may be less preferred by the decision-maker than a lower overall utility with a lower level of uncertainty.

A sensitivity analysis conducted on each of the decision methods (Figure 15.1 to Figure 15.6) indicated the weighting changes required in each of the main sub-goals before the ranking of any of the renewable energy options changed (Table 10.12 and Table 10.13). Such changes revealed that the rankings of *WH* and several of the minor placed options were sensitive to reasonable weighting changes in the environmental secondary-goal in the *individual farm* preference set. The changes required to the individual secondary goal weightings sufficient to effect changes to the overall ranking of *WH* have been calculated for each of the MCDA methods over both preference sets.

The existing secondary goal weights are given alongside the changed weights, with the secondary goal weight that was changed indicated by a shaded cell. In all cases, the remaining secondary goal weights were changed proportionally to accommodate this new weighting. Where there was no change possible that would alter the option's ranking these were noted as no change (n/c). Where there were two possible changes in ranking options, both an increase and a decrease in weights, both weights and both new options have been given.

The magnitude and polarity of the change required is indicated and the new 'best' option identified. These figures indicate the required weight change in absolute terms and not the percentage of change required.

Table 10.12 The *distribution network* preference set weighting changes that would effect ranking changes in the full-term duration analysis.

MCDA method	Secondary goal	Existing weights (%)	Changed weightings required to effect a ranking change(%)				Percentage change required	'New' best option
			Economic	Environment	Social	Technical		
AHP	Economic	26.2	80.4	3.1	1.5	15.0	54.2	W
	Environment	11.8	12.6	57.7	2.6	27.1	45.9	W
	Social	5.5	4.8	2.2	82.6	10.3	77.1	SWH
	Technical	56.5	50.3	22.6	10.6	16.5	-40.0	W
SMARTS	Economic	30.5	n/c	n/c	n/c	n/c	n/c	n/c
	Environment	22.0	22.3	43.1	9.9	24.7	21.1	W
	Social	13.6	6.4	4.6	81.8	7.1	68.2	SWH
	Technical	33.9	39.7	28.7	17.6	14.0	-19.9	W
SMARTER	Economic	27.1	70.1	6.0	2.6	21.4	43.0	W
	Environment	14.6	9.2	71.1	2.1	17.6	56.5	W
	Social	6.5	5.2	2.8	82.0	9.9	75.5	SWH
	Technical	52.1	46.3	25.9	11.1	16.7	-35.4	W

Table 10.13 The *individual farm* preference set weighting changes that would effect ranking changes in the full-term duration analysis.

MCDA method	Secondary goal	Existing weights (%)	Changed weightings required to effect a ranking change(%)				Percentage change required	'New' best option
			Economic	Environment	Social	Technical		
AHP	Economic	48.3	5.2	28.8	49.9	16.2	-43.1	SWH
	Environment	15.7	41.0	28.4	23.1	7.5	12.7	W
	Social	27.2	23.1	7.5	65.2	4.2	38.0	SWH
	Technical	8.8	n/c	n/c	n/c	n/c	n/c	n/c
SMARTS	Economic	40.0	n/c	n/c	n/c	n/c	n/c	n/c
	Environment	20.0	32.9	34.2	24.7	8.2	14.2	W
	Social	30.0	18.9	9.5	66.9	4.7	36.9	SWH
	Technical	10.0	n/c	n/c	n/c	n/c	n/c	n/c
SMARTER	Economic	52.1	13.0	26.5	49.2	11.3	-39.1	SWH
	Environment	14.6	45.5	25.3	23.7	5.5	10.7	W
	Social	27.1	68.7/24.4	19.2/6.8	3.8/65.9	8.2/2.9	n/c	W/SWH
	Technical	6.3	n/c	n/c	n/c	n/c	n/c	n/c

The sensitivity plots of the *distribution network* secondary goals (Figure 15.1 to Figure 15.3) revealed that the option, *WH*, was in a mostly dominant position in all the secondary goals over the three MCDA methods. In most cases, it would take major weighting increases in any of the economics, social or environment secondary goals or a large reduction in the weighting of the technical secondary goal to effect a change in its overall ranking (Table 10.12). However, the results for the SMARTS method indicated that the reasonable changes of 21.1 and -19.9 percentage points in the environment and technical sub-goals respectively could incur changes in ranking.

There are only potential benefits listed as measures for the technical secondary goal (Figure 10.8) and therefore any reduction in the weighting would lead to increased weighting in other secondary goals where there are negative impacts listed in the measures of decision alternatives.

For the *individual farm* preference set, the sensitivity analyses displayed the wind turbine and hydro combined systems (*WH*) in a relatively strong position although this strength varied amongst the secondary goals over the three MCDA methods (Figure 15.4 to Figure 15.6). However, '*WH*' appeared to be vulnerable to ranking changes through relatively small increases in the environment secondary goal of between 10.7 to 14.2 percentage points (Table 10.13). A change in this secondary goal of the magnitude indicated would also see the ranking of several of the other decision alternatives change.

It is important to note that all the original preferences were subjective assumptions expressed by the author, and any resultant changes incorporate this subjectivity explicitly. The inherent dangers of subjectivity of the weights as quantified by stakeholder preferences can be seen in some of the smaller changes required before ranking changes were effected (Table 10.12 and Table 10.13). Subjective measures can be abused by the decision maker in order to elicit results favourable to their requirements.

10.3.2 Short-Term Duration Results

The only model input changes between the full-term duration analysis and the short-term duration analysis were in the measure levels from the short-term duration HOMER modelling (Table 9.15 to Table 9.17). Consequently, there were only minor changes to the overall levels of utility (Figure 10.12). These changes were noted by comparing the full-term utilities (Figure 10.9) and the short-term utilities (Figure 10.12) and compiling the resultant percentage change of the utility (Figure 10.13). With the notable exceptions of the hydro (*H*) option in the *distribution networks* preference set, the differences in this comparison were all less than $\pm 5\%$.

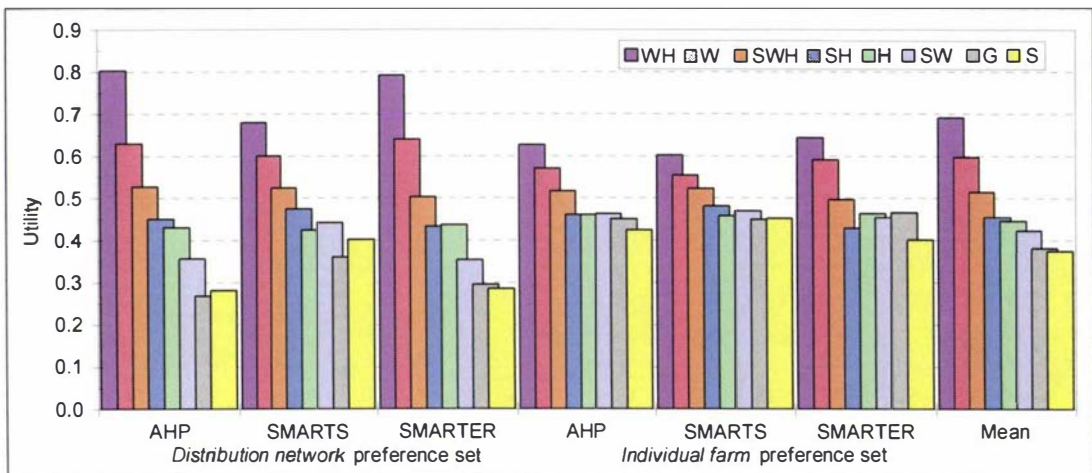


Figure 10.12 A comparison of the utility between MCDA methods and preference sets for the short-term duration analysis and the mean results.

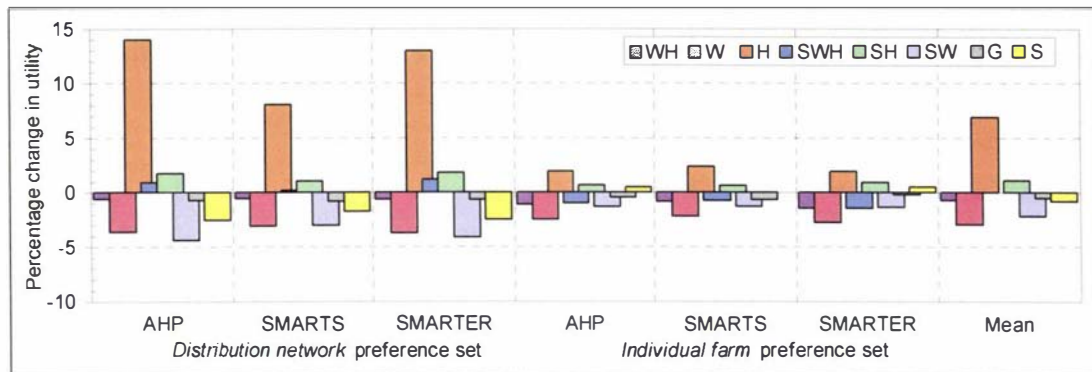


Figure 10.13 An analysis of the percentage change of the utility from the full-term to the short-term duration results.

The level of uncertainty was increased in many of the *distribution network* preference set alternatives (Figure 10.14), with the maximum utility levels increasing, minimum levels decreasing, and the range of the standard deviation extending to match. Whereas, the differences were relatively small and imperceptible in the *individual farm* preference set (Figure 10.15). The stacked-bar utility levels representative of the weightings have changed only slightly due to the small changes in the measure levels.

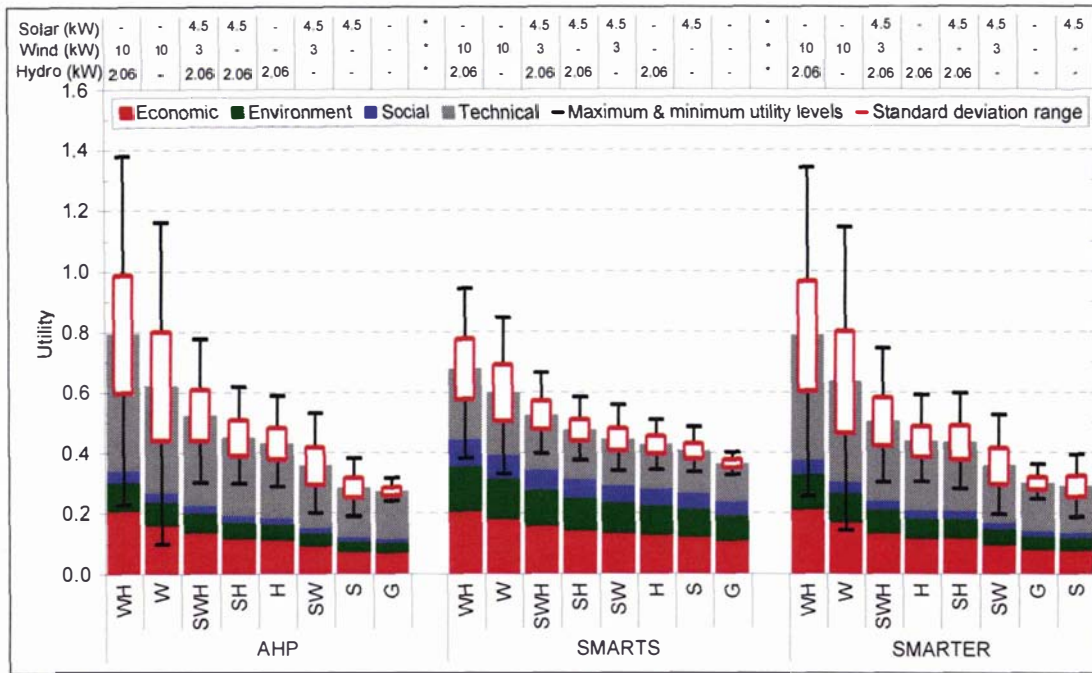


Figure 10.14 The short-term duration mean utility (expressed in absolute weights), standard deviation range, and maximum-minimum utility for the *distribution network* preferences for the three MCDA methods.

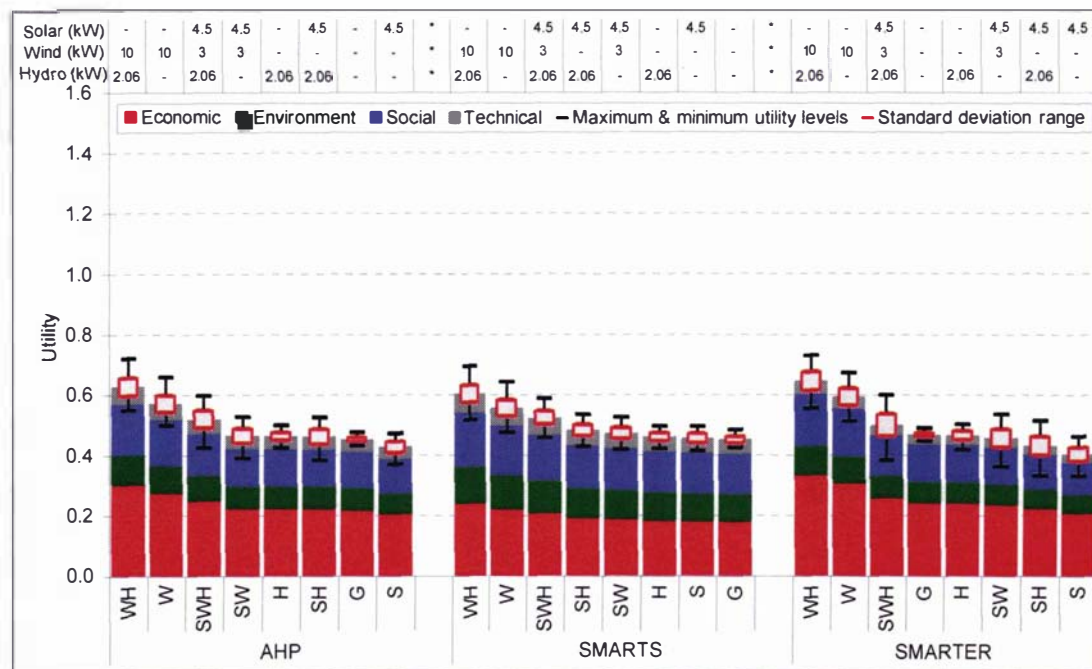


Figure 10.15 The short-term duration mean utility (expressed in absolute weights), standard deviation range, and maximum-minimum utility for the *individual farm* preferences for the three MCDA methods.

The results of the short-term duration sensitivity analysis (Figure 15.7 to Figure 15.12) revealed very few changes to sensitivity. This was due to the preference weightings of the short-term duration analysis being the same as the full-term weightings, and having only small measure level differences. Therefore, the weight changes required to effect option ranking changes were similar in the short-term duration (Table 10.14 and Table 10.15) to those of the full-term duration (Table 10.12 and Table 10.13).

Table 10.14 The *distribution network* preference set weighting changes that would effect ranking changes in the short-term duration analysis.

MCDA method	Secondary goal	Existing weights (%)	Changed weightings required to effect a ranking change(%)				Percentage change required	'New' best option
			Economic	Environment	Social	Technical		
AHP	Economic	26.2	77.8	3.5	1.7	17.0	51.6	W
	Environment	11.8	13.6	54.1	2.9	29.4	42.3	W
	Social	5.5	4.7	2.1	83	10.2	77.5	SWH
	Technical	56.5	49.0	22.0	10.3	18.7	-37.8	W
SMARTS	Economic	30.5	n/c	n/c	n/c	n/c	n/c	n/c
	Environment	22.0	23.4	40.3	10.4	26.0	18.3	W
	Social	13.6	6.3	4.5	82.2	7.0	68.6	SWH
	Technical	33.9	38.8	28.0	17.3	15.9	-18.0	W
SMARTER	Economic	27.1	67.5	6.5	2.8	23.2	40.4	W
	Environment	14.6	10.9	65.7	2.5	20.9	51.1	W
	Social	6.5	5.0	2.7	82.6	9.7	76.1	SWH
	Technical	52.1	45.7	24.6	10.6	19.1	-33.0	W

Table 10.15 The *individual farm* preference set weighting changes that would effect ranking changes in the short-term duration analysis.

MCDA method	Secondary goal	Existing weights (%)	Changed weightings required to effect a ranking change(%)				Percentage change required	'New' best option
			Economic	Environment	Social	Technical		
AHP	Economic	48.3	4.9	28.9	50.0	16.2	-43.4	SWH
	Environment	15.7	41.8	27.0	23.6	7.6	11.3	W
	Social	27.2	23.0	7.5	65.3	4.2	38.1	SWH
	Technical	8.8	n/c	n/c	n/c	n/c	n/c	n/c
SMARTS	Economic	40.0	n/c	n/c	n/c	n/c	n/c	n/c
	Environment	20.0	32.5	33.8	25.3	8.4	13.8	W
	Social	30.0	18.8	9.4	67.1	4.7	37.1	SWH
	Technical	10.0	n/c	n/c	n/c	n/c	n/c	n/c
SMARTER	Economic	52.1	12.8	26.5	49.3	11.4	-39.3	SWH
	Environment	14.6	46.4	23.9	24.1	5.6	9.3	W
	Social	27.1	66.0/24.2	18.5/6.8	7.6/66.1	7.9/2.9	-19.5/39.0	W/SWH
	Technical	6.3	n/c	n/c	n/c	n/c	n/c	n/c

10.4 Discussion

The Logical Decisions for Windows software was suitable for the discrete choice that this study presented, a renewable energy design selection involving the use of modelled results from a case study site. An analysis of the results from this process indicated that this software, and indeed the overall method could successfully introduce the sustainability parameters of technical, social, environmental, economic into a formal decision-analysis process such that a sustainable renewable energy system was the outcome.

This discussion covers the problem structure (section 10.4.1), the multi-method approach used (section 10.4.2), and the overall results including the full-term and short-term duration analysis results and a comparison between them (section 10.4.3).

10.4.1 Problem Structure

French *et al.* (2001) indicated that the main problems perceived in the use of MCDA methods are the inherent subjectivity of the problem structure and weightings used, an apparent difficulty trading off very diverse attributes, and the consistency of these from one decision to another. The subjectivity of the problem structure was unavoidable in this case study but French *et al.* (2001) maintained that in decision-analysis, any and all such subjectivity was inevitable and the MCDA processes made this explicit no matter how the problem structure was assigned. They also indicated that no elicitation method would make the task of trading off between diverse attributes easy.

Due to time and money constraints and compounded by the complexity of administering a relatively new and untried system of decision analysis, consultation with the stakeholders through the recommended '*Public Value Forum*' was not undertaken as should be done in practice. Such extensive consultation as this study would require, would necessitate time to explain the multi-methods used in the decision analysis approach in order for an understanding of all the methods to be gained by the participants.

Such an understanding was seen as a prerequisite to elicitation of a meaningful problem structure, measures, single-measure utility function preferences, and multi-measure utility function weights. This understanding would be especially important in a multi-method approach to decision analysis but was seen as a major practical limitation of the methodology requiring time and willingness from each stakeholder.

All the settings used in this decision analysis were therefore set by the author and chosen to demonstrate how this decision analysis framework might work. The process of problem structuring, measure selection, measure level assessment, preference setting, and weight assignment was carried out using both intuition, and *indirect elicitation* methods (section 10.2.4).

Only two key stakeholder groups were clearly identified in this study. The views of landowners, farmers, and other community members were represented by the *individual farm* preference settings, and the views of the local electricity distribution company interests were represented by the *distribution network* preference settings. Thorough application of the

methodology would entail a complete site-specific stakeholder list and possibly include system design engineers, researchers, regional and local council planners, environmental groups, social planners, resource management groups, the local *Iwi*³² and, or *Hapu*³³, and any other affected groups as identified by any impact assessment undertaken.

If more than two stakeholder groups were involved, this then would become a very complex and time-consuming operation but this framework would still be the easiest way to deal with such complexity. The amount of data to be gathered at the preference setting stage would not be beyond the software's capability but would need careful management by the decision analyst.

In many cases, a *Focus Group* and *Public Value Forum* (Keeney *et al.*, 1990) (section 10.2.4) would be the most cost effective method of preference and weights elicitation. The 'focus group' component would determine certain aspects of the problem structure as it relates to renewable energy system and distribution network constraints or requirements etc. These could then become useful as a template in the application of the SPiRAL framework to similar settings even though there would be different stakeholder groups. Such 'generic' problem structures incorporating constraints could then be applied on a site-specific basis with a minimum need for further focus group input.

The problem structure (Figure 10.8) could have been developed further through input from a *Public Value Forum* consultation process and included aspects of other known impact issues. The primary goal of *Sustainable Power in Rural Areas and Locations* (SPiRAL) and the secondary goals indicating the four main sustainability aspects (economic, environment, social, and technical) could have others added in this process.

Economic input data were sourced solely from the results of the HOMER distributed generation system simulation inputs and outputs. Other economic data sources could have included sections on taxation, asset depreciation write-offs, subsidies etc. Measures could have been further divided into categories much like the 'local Investment' categories. Assuming the source of the technology was known, sales could have included local and non-local sales and purchases. Overseas purchases of equipment versus locally made and purchased technology could have been another factor within a new sub-goal of 'National Economic Good'. A further sub-goal of 'network economic good' could have included a measure of net avoided cost of transmission losses, reduced peak demand rates, load management of peak-load values, avoided cost of lines upgrade, and improved network utilisation etc.

The 'Environment' secondary goal could have included more detail than in this analysis. For example, had the planned hydro system been larger, or more options been available, a further detailed analysis of the impacts could have included in-stream habitat impacts. Changes to the fluvial system, groundwater impacts, siltation rates, and other impacts on the hydrological functioning of Totara Stream may also have been included. Resource

³² Regional tribe

³³ Local sub-tribe

consent procedural concerns could have been addressed with a ranking of the alternatives with respect to the ease of obtaining consent for each of the alternative systems. Exactly how much detail and what measures to include could be a function of the details addressed by any environmental impact assessment done with respect to each development. This could equally be applied with respect to any impact assessment necessary for wind, biomass, or any other development causing an impact.

The 'Social' secondary goal could have been developed along parallel terms to that already highlighted for the 'Environment' secondary goal discussion above. A social impact assessment would highlight many of the required measures and the extent of problem structuring depending on the extent of the assessed impacts. For example, had a large-scale application of any system been planned in many communities, national social impacts and benefits could have been specified to include national employment statistics, export potential of the expertise gained, inter-generational impacts or benefits, and rural community stability.

The 'Technical' secondary goal included only peak-load matching as a network-orientated measure but could also have included aspects specific to the local network operator on a site-specific basis. The different network line spurs involved in the analysis may have specific constraints that may need to be considered. Additional costs of any new transmission equipment could be considered in the 'Economics' secondary goal but the other aspects of transmission infrastructure such as line capacity, line configuration (overhead or underground), potential routing of lines etc could be considered as separate sub-goals.

10.4.2 Multi-Method Multiple Criteria Decision Analysis

Despite the danger of generating too much data (Hobbs & Horn, 1997), a multi-method decision analysis approach was utilised in this study because of the opportunity to compare findings between MCDA methods to aid reconciliation of any differences between preference weightings (*ibid.*). Not all methods of MCDA were well understood by the public (Belton & Stewart, 2002; Clemen, 1996). So, by using a multi-method approach, three separate sets of results were produced from the three methods, thereby increasing the chances of achieving both an understanding and trust in the results by the stakeholders given the potential similarity of the results (Hobbs & Horn, 1997).

In this study, the results between MCDA methods were indeed similar, though there were a few minor differences between the rankings of the options (Figure 10.9 and Table 10.16). In the sensitivity analysis, it was found that only the wind (*W*), and solar PV-wind-hydro (*SWH*) options were susceptible to ranking changes with reasonable weight changes. All other changes involving any option with minor ranking differences would require weighting changes too large to be considered reasonable (Table 10.12 and Table 10.13).

Should there have been any major differences in the results between the MCDA methods this would have become clear by comparison between methods and with the mean utility of all three methods (Figure 10.9). From this comparison of the overall differences in utility between results would come the identification of obvious utility 'outliers' thereby indicating something inconsistent or incorrect in the execution of one or more of the MCDA

methodologies. As there were no obvious outliers in this study over the three MCDA methods (Figure 10.9), it can be assumed that the apportioning of weights between the three systems was relatively consistent. There were however some discrepancies between the *distribution network* and the *individual farm* preference sets in the secondary goal analyses representing potential conflicts in the weighting between the measures.

The AHP and SMARTER methodologies produced some very similar results that differed slightly with the SMARTS result. The similarity of results between the AHP and SMARTER methods could be related to their weight elicitation methods of pairwise comparison (AHP) where trade-offs are made between preferred options, and the importance ordering method (SMARTER) where the options are ranked according to preference, one over the other (another form of trade-off analysis).

The use of a multi-method approach to decision analysis contributes robustness to the results and it is recommended that this approach be practiced in future analyses. If a multi-method MCDA approach was not deemed appropriate or applicable then only one of the methods need be utilised. Based on ease of application and understanding, it is recommended that either the analytic hierarchy process (AHP) or the SMARTER method (simple multi-attribute rating technique exploiting ranks) be used.

The AHP method was easy to use, as it requires definition of trade-offs between measures by systematic pairwise comparison using easy to understand semantic scales. The main drawback of this method is the large number of comparisons required should there be a large problem structure with many measures needing to be compared. The AHP method produced results that closely followed the mean results of the multi-method approach (Table 10.16) over both preference sets. This approach would not be easily utilised by application of a survey and would therefore best suit a one-on-one approach between the decision facilitator and the stakeholder in order to elicit the weights.

The SMARTER method simply required importance ranking and was easy to understand. This ease of understanding and application would be of use in stakeholder surveys where numerical ranking of preferences would be easy to apply. If the problem structure was large, a list of measures needed to be ranked only rather than the long exercise of pairwise comparison as with AHP. The SMARTER method produced results that closely followed the mean results of the multi-method approach (Table 10.16) over both preference sets.

10.4.3 Overall Results

Full-Term Duration Analysis

The combination of the resource and load uncertainty derived from HOMER modelling, the preference sets, and the weighting percentages resulted in a range of option rankings for the full-term duration analysis. These rankings were based on finding the option to best meet the primary goal, that of the 'best' sustainable outcome. They differed slightly between preference sets, but differed much from the original HOMER results, which were based solely on the economic outcome of the lowest net present cost (Table 10.16).

The wind-hydro option, *WH* (10 kW AC wind turbine, 2.06 kW combined hydro) was the clearly the highest ranked option, and consistently ranked as the number one option throughout all preference sets (Figure 10.9). The wind (*W*) and solar PV-wind-hydro (*SWH*) options ranked second and third respectively over all methods and preference sets. There was some interchange between the hydro (*H*) and solar PV (*S*) for the fourth and fifth rankings. The grid-only option (*G*) was ranked highly in HOMER due to it having the lowest NPC, while it was ranked lower in the decision analysis due to greater consideration of the environmental, social, and technical parameters.

Table 10.16 Summary comparison between HOMER and the full-term duration Logical Decisions for Windows ranked results.

Rank	HOMER results	Mean LDW results	Distribution network			Individual farm		
			AHP	SMARTS	SMARTER	AHP	SMARTS	SMARTER
1	G	WH	WH	WH	WH	WH	WH	WH
2	W	W	W	W	W	W	W	W
3	H	SWH	SWH	SWH	SWH	SWH	SWH	SWH
4	WH	H	H	SH	H	H	SH	H
5	S	SH	SH	H	SH	SH	H	G
6	SW	SW	SW	SW	SW	SW	SW	SW
7	SH	G	S	S	G	G	S	SH
8	SWH	S	G	G	S	S	G	S

G is grid alone (the status quo),
H is the combined hydro system of 2.33 kW (AC),
W is the 10 kW (AC) wind turbine,
WH is the 10 kW (AC) wind turbine and the combined hydro systems,
S is the equivalent of 500 W of solar PV on each house,
SW, is the solar PV combined with a 3 kW (DC) wind turbine,
SH, is the solar PV systems and the combined hydro systems, and
SWH is the solar PV systems, a 3 kW (DC) wind turbine, and the combined hydro systems.

The results included an analysis of the mean, standard deviation, and the maxima – minima of utility (Figure 10.10 and Figure 10.11). The results presented in such a manner allowed an easy visual interpretation of the effects of the uncertain electricity load and renewable energy resource levels on the utility of the renewable energy options. As such, the decision-maker could clearly see systems with a higher relative utility but also a higher degree of uncertainty about the utility, or options with a lower overall utility and a lower level of uncertainty.

An example of this was the top five ranked options in the *distribution network* preference set of each of the MCDA methods. The *WH* and *W* option each displayed a higher level of uncertainty about the mean utility, with the *SWH*, *SH*, and *H* options each displaying lower levels of uncertainty. Clearly, the *WH* option has the highest mean utility, but it also shared the largest spread of uncertain utility, the minimum value of which was well below the

mean utility of the other options. However, the minimum standard deviation of the utility was in most cases a slightly higher value than the mean of the other options.

The decision-maker would need to decide whether to accept the (remote) possibility that at rare times, the *WH* option may not be the 'best' option. Whereas, the standard deviation of the other four top ranked options all overlapped in value and hence there was more likely to be years when one or the other option may have been best. This was based on the larger weighting given to the technical and economic secondary-goals (which relates to technical and economic performance) rather than on the social and environmental secondary-goals.

This emphasised the high level of variation in the peak-load reduction capability of the larger 10 kW AC wind turbine used in these decision alternatives. This high level of variation stemmed from the combined effects of the wind resource and electricity load variation on the normal distributions simulated under the Monte Carlo trials in LDW. The maxima and minima levels of the grid decision alternative (G) can solely be attributed to the load uncertainty as expressed in the HOMER modelling. This level of maxima and minima was present in all other decision alternatives regardless of the technologies involved.

The break-down of the mean utility of an option by secondary-goal weighting, and hence by preference set (Figure 10.10 and Figure 10.11), provided an understanding of the effects of the relative strengths of the preference sets on the mean utility of an option. When the elicitation of weights takes place they would inherently be abstract from the overall results, and the decision-maker may wish to review these weights if the relative effects can be seen to obviously distort the results beyond what is thought acceptable. Thus, the visual approach to presenting results in such a manner lends insight to the decision not otherwise observed or understood.

Even though the overall highest ranked option was the wind-hydro system (*WH*), the strength of this ranking needed to be reviewed with respect to the sensitivity of the results to changes in weighting. If there were no reasonable changes in weighting that would effect a change in ranking, then indeed the *WH* option was the 'best' option. Such a sensitivity analysis was undertaken (Figure 15.1 to Figure 15.6), and the results of any possible changes were noted in Table 10.12 and Table 10.13.

For all three MCDA methods (AHP, SMARTS, and SMARTER) in *individual farm* preference set, the most realistic weight change was an increase of 12.7, 14.2, and 10.7 percentage points respectively in the environment secondary-goal. This would lead to the *W* option (wind turbine only) being ranked number one.

All other secondary goal weighting changes varied in proportion to the weight changes as listed. Therefore, given that the environment secondary-goal weight change may be the most realistic, the *W* option should be considered the most likely alternative option if the *WH* option was not chosen.

Short-Term Duration Analysis

The mean results of the short-term duration analysis differed only in the ranking of the solar PV-hydro (SH) and hydro (H) alternative from those of the full-term duration analysis (Table 10.17). There were ranking changes to some of the 'minor' alternatives, with none of the top three alternatives (WH, W and SWH) changed.

Table 10.17 Summary comparison between HOMER and the short-term duration Logical Decisions for Windows results.

Rank	HOMER results	Mean LDW results	Distribution network			Individual farm		
			AHP	SMARTS	SMARTER	AHP	SMARTS	SMARTER
1	G	WH	WH	WH	WH	WH	WH	WH
2	W	W	W	W	W	W	W	W
3	H	SWH	SWH	SWH	SWH	SWH	SWH	SWH
4	WH	SH*	SH*	SH	H	SW*	SH	G*
5	S	H*	H*	SW*	SH	H*	SW*	H*
6	SW	SW	SW	H*	SW	SH*	H*	SW
7	SH	G	S	S	G	G	S	SH
8	SWH	S	G	G	S	S	G	S

* Indicates changes in ranking from the full-term duration analysis.
 G is grid alone (the status quo),
 H is the combined hydro system of 2.33 kW (AC),
 W is the 10 kW (AC) wind turbine,
 WH is the 10 kW (AC) wind turbine and the combined hydro systems,
 S is the equivalent of 500 W of solar PV on each house,
 SW, is the solar PV combined with a 3 kW (DC) wind turbine,
 SH, is the solar PV systems and the combined hydro systems, and
 SWH is the solar PV systems, a 3 kW (DC) wind turbine, and the combined hydro systems.

Full-Term and Short-Term Duration Results Comparison

There were no significant differences in mean utility, standard deviation, and maxima and minima between durations (Figure 10.13). However, there were some ranking changes between some of the lower ranked options.

There were only a few percentage points difference between the changes required in the full-term and short-term duration analysis. Changes to the environment secondary-goal were still the only ones reasonably able to effect changes to the rankings of the options.

Due to the similarity between the sensitivity results of the full-term and short-term duration, the short-term duration analyses also indicated a susceptibility to changed alternatives with the environment secondary goal in the *individual farms* preference set (Table 10.14 and Table 10.15) of the short-term duration analysis.

10.5 Summary

A multi-method MCDA approach was undertaken using the Logical Decisions for Windows software. An analysis of the results revealed several points of discussion, among them, the problem structure, the 'worth' of using a multi-method of multiple criteria decision analysis, and the overall results with the impact of the levels of weighting and uncertainty applied, the sensitivity analysis results, and changes required before rankings were effected.

Due to cost and time constraints, both the problem structure and all the preferences for sub-goal measures were as set by the author. However, in practice a '*Focus Group – Public Value Forum*' approach (Keeney *et al.*, 1990) was recommended, while using the group version of LDW.

In many cases, this combination would be the most cost effective method of preference and weights elicitation. The 'focus group' component would determine certain aspects of the problem structure as it relates to renewable energy system and distribution network constraints or requirements etc. These could then become useful as a template in similar settings even though there would be different stakeholder groups. Such 'generic' problem structures incorporating constraints could then be applied on a site-specific basis with a minimum need for further focus group input.

The display of uncertainty in the Logical Decisions for Windows (LDW) model results (Figure 10.10 and Figure 10.11) indicated a successful integration of the HOMER simulation results and the LDW use of Monte Carlo simulation of probability functions. The process of extracting and using sensitivity values from HOMER for an uncertainty analysis in LDW clearly defined the uncertainty inherent in some of the renewable energy options.

The full-term duration sensitivity analysis (Figure 15.1 to Figure 15.6) revealed only a few reasonable changes could be made to effect changes to the overall ranking of the results. These changes were in the *individual farm* preference set, involved all three MCDA methods, and only affected the 'environment' secondary-goal. Such changes were between 11 and 14 percentage points from existing weights of 14 to 20 percent.

The ranking changes all indicated the *W* option (10 kW AC wind turbine) would become the first ranked option but only in the *individual farm* preference set. There were no reasonable changes that could be made to the *distribution network* preference set. The smallest change affecting a ranking was one of minus 20 percentage points.

The multi-method MCDA approach utilised both the analytic hierarchy process and two different approaches to the multi-attribute utility theory. Through this approach, the results were assessed for robustness of results from individual methods (Table 10.16). Should there be any differences in the results between the MCDA methods this became clear by comparison between methods and with the mean utility of all three methods (Figure 10.9). From this comparison would come the identification of obvious utility 'outliers' indicating something remiss or incorrect in one or more of the MCDA analyses.

There were no major differences between the full-term and short-term duration analyses due to the similarity in the inputs derived from the HOMER modelling. Overall, the rankings were the same. There were only small differences between the full-term and short-term duration sensitivity analyses.

Largely, the Logical Decisions for Windows software delivered results that were both detailed and easy to understand, and led to a greater insight into the effects of electricity load and resource uncertainty and stakeholder preference sets. When MCDA was used in a multi-method process, the results were shown to be robust, thus leading to an opportunity to increase confidence in the results produced.

Part four: the outcomes

The study outputs

Conclusion

11 The Study Outputs

The problem as initially identified was that there was no transparent, auditable decision-analysis method available to electricity consumers or other stakeholders for a systematic and rigorous assessment of their electricity supply options deliverable in a relatively short time frame. While such an analysis should be in technical and economic terms and must consider the sustainability of the options with respect to social and environmental impacts and benefits, it should be able to be completed over a short timeframe and therefore uncertainty must be made explicit in the results.

The aim of this research was to develop just such a decision analysis framework. The integrated decision analysis framework used in this study collectively delivered a set of results that were ranked in clear terms with respect to a wide range of economic parameters, the level of social benefits and impacts, the range of environmental impacts and benefits, and the technical merits of each system. This extensive evaluation of uncertainty instilled insight into the decision-analysis process. Therefore, the SPiRAL framework delivered results that increased awareness and understanding of the potential solutions to the problems of supplying a sustainable power supply to small communities.

This Chapter discusses the decision analysis framework that resulted from this study (Section 11.1), and the application of it over a short-term duration (Section 11.2). Prospective users were identified (Section 11.3), and the potential vulnerabilities of this study were acknowledged (Section 11.4). Recommendations for further research complete this Chapter (Section 11.5).

11.1 The SPiRAL Decision Analysis Framework

An extensive review process revealed a list of software considered for inclusion in the SPiRAL decision analysis framework (Figure 11.1). The process initially started with the gathering of electricity load and renewable energy resource data from the case study site, Totara Valley.

This provided preliminary data for the modelling of the wind resource in both WAsP and HOMER, and the electricity load in HOMER. Using the modelled electricity loads and renewable energy resources as inputs into HOMER, a range of renewable energy systems were simulated and optimised into hybrid energy systems. From these, an optimised list was produced and ranked according to the systems with the lowest net present cost.

Each system produced a set of economic and technical results and a select range of these results were extracted for use in a multi-method multiple criteria decision analysis process based on a range of assumed stakeholder preferences. The multi-method process produced a set of results that was used to assess consistency and robustness of the decision analysis process.

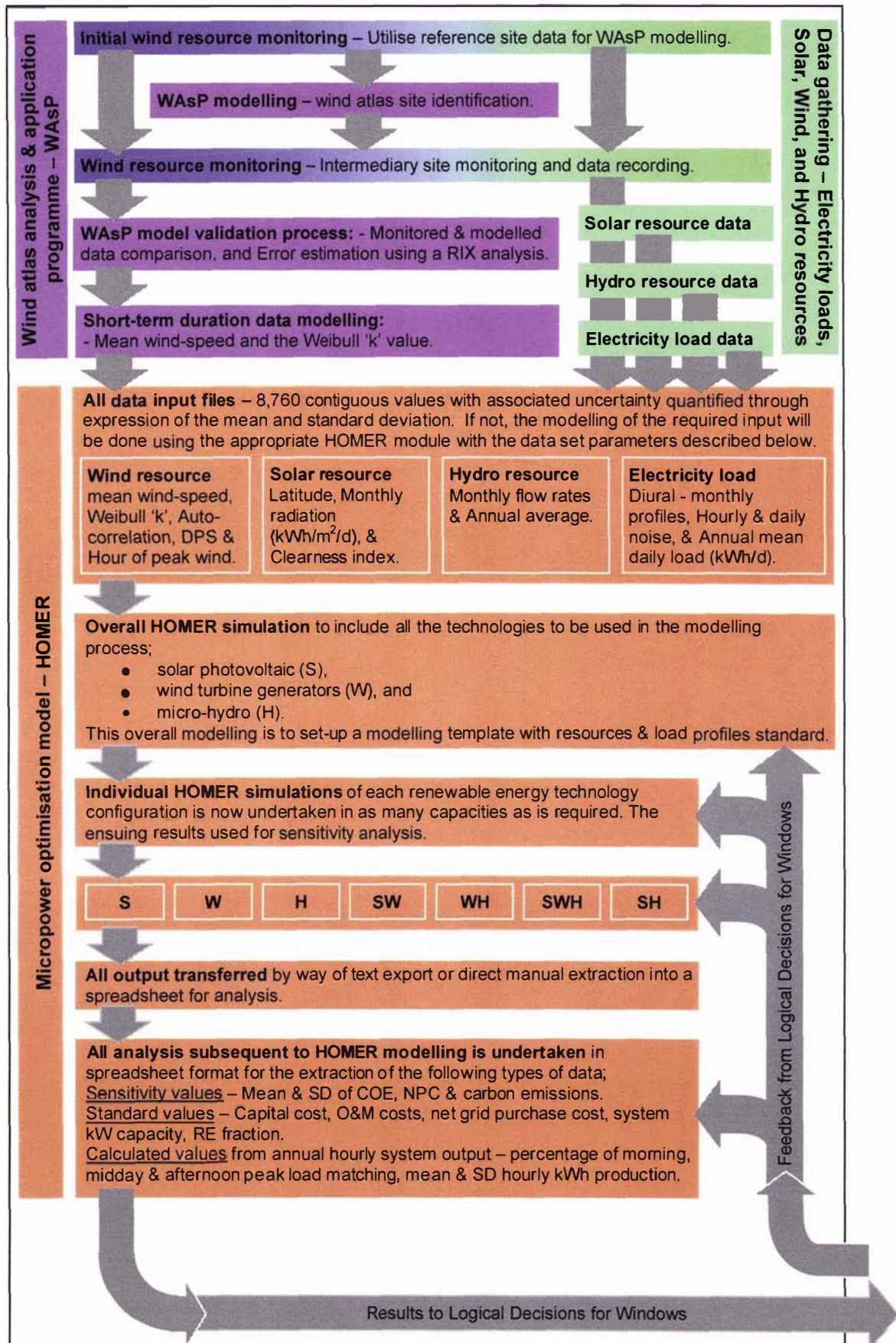


Figure 11.1 A complete view of the SPiRAL decision analysis framework developed by this study indicating the software interactions, and feedback loops.

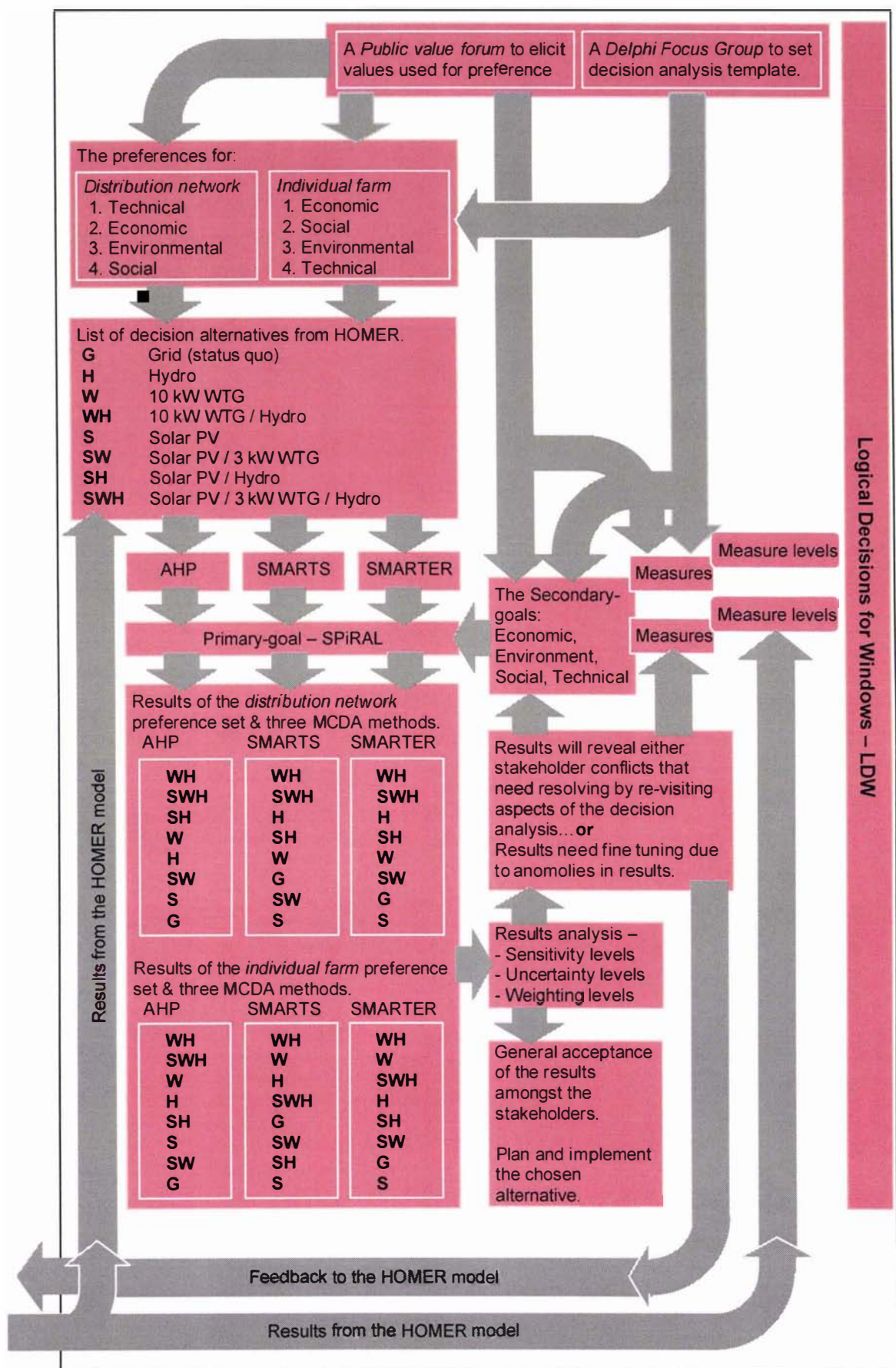


Figure 11.1 (Continued). A complete view of the SPiRAL decision analysis framework developed by this study indicating the software interactions, and feedback loops.

The SPiRAL decision analysis process reported in this study (Figure 11.1) was developed from that initially proposed (Figure 1.1). The data required, and the interactions between the software within the decision analysis framework were developed fully and the limitations were noted. The process started with the gathering of electricity load and the renewable energy resources data.

The aim of the monitoring and recording of the electricity use and the renewable energy resources was three-fold. These were: the accurate documentation of the electricity loads, solar, wind and hydro profiles; provision of data to use in the decision analysis framework modelling; and the provision of data from which to assess the duration of monitoring necessary before the pertinent modelling data for HOMER either stabilised to acceptable levels, or became apparent.

The electricity load monitoring produced an extensive data set useful to both the full-term duration SPiRAL model, and an analysis of duration before specific HOMER electricity load modelling parameters either stabilised or became apparent. Time-series data from the individual load data sets were used to produce the two distinct load profiles of domestic and farm electricity loads, and water heating load profiles. These were prepared for use in HOMER through extrapolation based on existing data to fill gaps in the original time-series. Sensitivity values were used to model load uncertainty.

The renewable energy resources of wind, solar and hydro were monitored over the same duration as the electricity load profiles. The wind resource monitoring was the most extensive component of the renewable energy resource assessments undertaken in the study. This was due to the variable nature of the resource, the need to quantify this variation, and the need to identify the best locations in the complex terrain surrounding the community. The reference sites and transitory sites were monitored simultaneously providing a data set able to be used in the WAsP wind resource modelling process. This modelling and the calculation of the minimum duration before the wind-speed settled to the acceptable confidence interval negated the need for lengthy and expensive monitoring in one or more locations. Sensitivity values were used to model the wind-speed uncertainty.

The hydro resource was monitored over a summer period of low stream flow and again in a stable winter period thereby providing an approximation of a maxima and minima flow level for hydro modelling in HOMER. No hydro sensitivity values were used for the flow rate in HOMER.

The solar resource was monitored at the Wind Site 1 monitoring station at a higher altitude than where the likely siting of photovoltaics would be. The values recorded therefore did not necessarily reflect an accurate resource level at the valley floor and a level of uncertainty was used to approximate this decreased resource.

The choice of the wind resource model and the distributed generation system model used in the SPiRAL decision analysis was relatively uncomplicated due to there being a limited range of suitable software available. The wind atlas analysis and application programme (WAsP – Section 3.1) was chosen for the wind resource modelling, as it was the only

commercially available wind modelling software and due to the large number of users was considered by many to be the 'industry standard' of wind resource models.

WASP provided a valuable start to the modelling process by initially characterising the wind resource in the form of a regional wind atlas, which led to further sites being identified. The monitored wind was used to model a predicted wind climate, which included mean wind-speed and an indication of the Weibull distribution. It was clear that Wind Site 3 was the better of the five sites monitored. The modelled wind-speed and Weibull statistics of this site were used in the subsequent modelling of the wind resource in HOMER.

The wind, solar and hydro resource data, and electricity load data all provided input for the HOMER model, which produced a set of results that clearly indicated the economic and technical performance of the electricity supply options. Sensitivity variables used in conjunction with the electricity load, solar, and wind resource inputs produced a data set of values representative of the effect of this variation. This was clearly seen in system performance both economically and technically.

These results provided input data for the LDW decision analysis programme, as a list of eight possible alternatives and associated measure level values. In setting up the LDW model, assumptions were used to set the problem structure, all the preferences for secondary goals and sub-goal measures, and all the weightings. In setting these assumptions for each of the decision criteria, subjectivity was undoubtedly introduced into the process. However, whatever manner they were set, whether assumed, or by stakeholder input, such subjectivity was inescapable as subjectivity was inherent in the process. What differed in this process was that the subjectivity was derived from the author and not the stakeholders. If the process had used a 'Focus Group – Public Value Forum' method, these values would be set with the stakeholders, within a consultative public value forum approach using a template of established parameters set by the focus group.

It is important to note that the appropriate and consistent setting of these preferences and weightings was vital, as the application of inappropriate or inconsistent preferences or weights would distort the results. Such susceptibility of MCDA processes to the effects of subjectivity could be abused by unscrupulous application of preference settings to achieve the aims of the decision maker. The author endeavoured at every point to maintain such appropriateness and consistency of assumptions. This consistency was reflected in the relative and absolute weights of Table 10.10 and Table 10.11.

The sensitivity results indicated where small changes to the weights of the environment secondary-goal had an effect on the rankings of some alternatives. The sensitivity analysis revealed that only realistic changes to the *individual farm* preference set, over all three MCDA methods, effected such ranking changes. Such changes were between 11 and 14 percentage points from existing weights of 14 to 20 percent. These changes all indicated the *W* option (10 kW AC wind turbine) would become the first ranked option in the *individual farm* preference set.

The display of uncertainty in the LDW results indicated a successful integration of the HOMER simulation results and the LDW use of Monte Carlo simulation of probability distribution data. This produced certainty equivalents for the respective measure levels, and from these came the ranked options from each method, each displaying the mean, standard deviation, and the maxima - minima of the levels of utility for each option. Furthermore, the relative effects of the weighting levels applied to the utility of the options were also indicated, each showing the four main secondary goal weighting levels. This indicated the effective weighting levels where previously they were only numbers and thus, less clear for comparison.

The process of using sensitivity values in HOMER to produce data for analysis in LDW clearly defined the combined uncertainty inherent in some of the renewable energy technology options for the decision analysis.

To further enhance the results, a multi-method MCDA approach utilised the pairwise comparison method (AHP), and the SMARTS and SMARTER methods of the multi-attribute utility theory (MAUT). Through this approach, the multiple sets of results were assessed for robustness through comparison for consistency. Were there any differences in the results between the MCDA methods, this would become clear by the identification of obvious utility 'outliers', thus indicating something remiss or incorrect in one or more of the MCDA analyses.

The combined output from WAsP, HOMER and Logical Decisions for Windows software delivered results that were both easy to understand, and led to a greater insight into modelling the effects of complex terrain on the wind resource in a short timeframe, the economics of distributed generation, and stakeholder preferences, in a clear and transparent manner. When MCDA was used in a multi-method process, the results were shown to be robust across three methods, thus leading to an increased confidence in the results produced.

What did such a large set of results indicate? As in many engineering design problems, there are usually several possible results, and this was no different. However, given the clearly indicated resultant levels of uncertainty, and the presence of a pattern of rankings with the *WH* option topmost, it would be easy to tend towards that option. Such is the vast amount of information, the decision maker would have plenty of additional information and gained insight on which to justify an option of choice.

Key outputs derived from this study were:

- a method of monitoring of wind energy resources over a short timeframe,
- an approach to using WAsP to model the wind-speed of an area based on short-term duration wind-speed and direction data,
- the successful use of HOMER to model wind-speed data based on the results of short-term duration monitoring and WAsP modelling,
- the successful use of HOMER to model electricity loads based on the results of short-term duration monitoring,
- the successful integration of the results of the economic optimisation results from HOMER into the Logical Decisions for Windows decision analysis stage, and

- an overall approach to designing sustainable renewable energy based distributed generation systems in a short timeframe using optimisation and decision analysis.

11.2 The Final Project Short-Term Duration Analysis

An objective of this study was to formulate and test the efficacy of a decision-analysis process over a short-term duration. An initial critical path and project evaluation and review technique (PERT) analysis (Figure 4.1) estimated the possible duration that a short-term SPiRAL framework analysis project in a rural community might take. The optimistic, likely and pessimistic durations were 21, 40 and 43-weeks respectively.

A revised critical path and PERT analysis using the duration assessed from the short-term duration data analysis (sections 6.3.3, 7.2.7, and 8.3.4) revealed that if the optimistic task durations were adhered to, a project outcome could result after a 16-week period though 28-weeks was more likely, or 32-weeks if it does not proceed smoothly. The wind-monitoring study remained the critical path (Figure 11.2).

An analysis of the wind monitoring data indicated the mean wind-speed took approximately 12-weeks to become stable such that the difference between the maximum mean wind speed and the minimum mean wind speed over a rolling 1,000-hour period (approx 6-weeks) was less than 0.3 m/s (or equivalent to less than 5% of the mean wind speed).

The Weibull probability density distribution function for Site 1 appeared to settle at approximately 5000-hours duration ($\approx$ 30-weeks) (Figure 19.8). Despite these large periods, the range of variation throughout the duration was relatively small.

However, with WAsP modelling, an analysis of the effect the size of the data set indicated there were no differences in the resultant atlases for the Totara Valley area over several 1000-hour incremental durations. Hence, after 2,177-hours of monitoring ($\approx$ 12-weeks), WAsP was used to model the mean wind-speed and the Weibull 'k' value required by the HOMER model.

Overall, if the application of the SPiRAL decision analysis framework at Totara Valley were based on the short-term duration data noted, results would be optimistically available in approximately 20-weeks, whereas the likely timeframe would have been 30-weeks duration. If there were problems with data gathering or the analysis took longer than initially anticipated, the duration would be slightly longer at 31-weeks.

Based on experience gained from this study, the time required for a full-term duration analysis was also revised to consider a new timeframe. These were initially set at optimistically 60-weeks, likely 72-weeks, and pessimistically 79-weeks. The revised durations are optimistically 59-weeks, likely 68-weeks, and pessimistically 72-weeks.

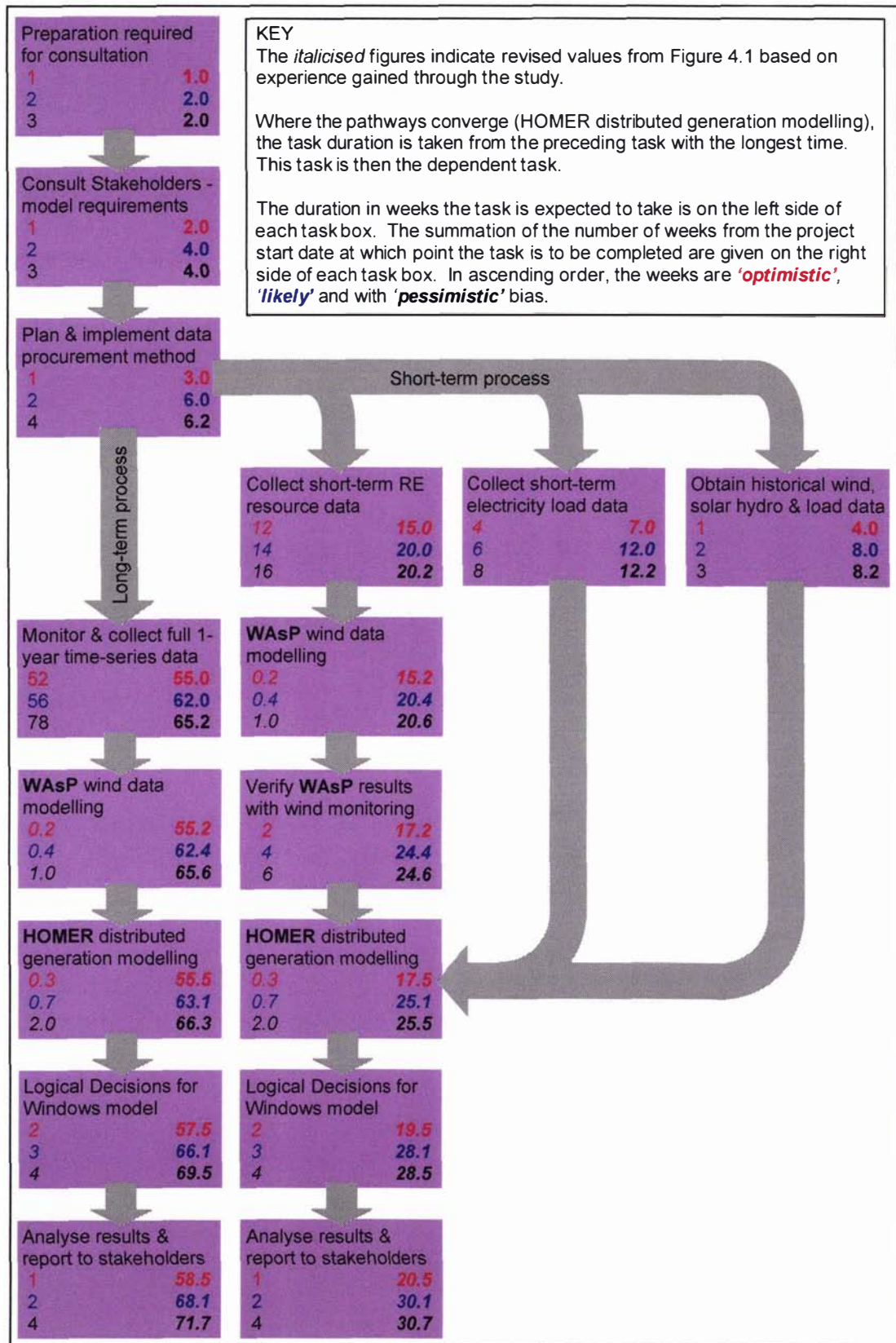


Figure 11.2 A revised critical path and project evaluation and review technique (PERT) analysis chart for the SPIRAL decision analysis framework for both the short-term and full-term duration.

11.3 Prospective Users of the Decision-Analysis Framework

Although this case study was a demonstration of one application of the SPiRAL framework, the potential opportunities for use of such a framework extend well beyond this. Renewable energy industry participants, policy analysts, research organisations, governmental aid agencies, and non-governmental aid organisations alike would all benefit from knowledge generated from application of the SPiRAL framework.

11.3.1 Renewable Energy Industry Participants

The SPiRAL framework, as illustrated (Figure 11.1) can be used by a wide range of people in the renewable energy industry for a wide range of applications to assess the ability of singular or combined renewable energy technologies to supply sustainable energy to a rural community or location.

Industry participants include industry associations, government agencies, energy companies, and crown research institutes.

Industry associations include:

- Solar Industries Association,
- Bioenergy Association of New Zealand,
- New Zealand Photovoltaic Association,
- New Zealand Geothermal Association,
- International Hydropower Association (NZ),
- New Zealand Wind Energy Association, and
- Renewable Energy New Zealand.

Government agencies include:

- Energy Efficiency and Conservation Authority
- Ministry of Agriculture and Forestry,
- Ministry of Economic Development,
- Ministry for the Environment,
- New Zealand Trade and Enterprise, and
- Foundation for Research, Science, and Technology.

Energy companies include:

- Generators,
- Retailers, and
- Line network companies.

Crown research institutes include:

- Industrial Research Limited,
- National Institute of Water and Atmosphere,
- Forest Research Institute,
- Maanaki Whenua – Landcare Research, and
- Institute of Geological and Nuclear Sciences.

11.3.2 Policy Analysis

Policy analysis is the systematic evaluation of the technical and political implications of alternative solutions proposed to solve problems. It can refer to both the process of assessing policies or programmes, and the product of that analysis. The SPIRAL framework of modelling could assess the effects of government policy on any number of design parameters, such as social and environmental requirements, subsidies, or other economic tools (technical or economic), and the barriers to sustainable energy uptake.

Government policy statements include:

- our renewable energy resources are to be progressively developed and their use maximised in order to achieve the renewable energy target of 30 PJ more by 2012,
- security of supply such that there is no uncertainty of supply and the supply is relatively free of disruption,
- the National Energy Efficiency and Conservation Strategy, which will lead to:
 - a reduction of CO₂ emissions,
 - a reduction of local environmental impacts,
 - improvement in economic returns,
 - an increased industry capacity, and
 - an improvement in local community health and welfare.
- the *Kyoto Protocol* requirements to reduce CO₂ emissions back to 1990 levels, and
- the carbon emissions tax related to thermal power generation.

11.3.3 International Aid Agencies

Governmental aid agencies such as USAID, AusAID, and NZAID are all involved in international aid work in developing countries. These organisations also provide funding for non-governmental aid agencies for specific projects. The United Nations also runs several development agencies directly, such as the UN Development Programme (UNDP), UN Development Fund for Women (UNIFEM), UN High Commissioner for Refugees (UNHCR), and UN Educational Scientific Cultural Organisation (UNESCO).

11.4 Potential Vulnerabilities of this Study

The choices made that could influence the results include model selection, data collection equipment, and modelling data inputs. Assumptions used had an influence on the results by driving the research direction and by affecting the modelling values. However, in most cases assumptions were justified by logic and reasoning, or by experience and intuition. There were no examples within this study where guesswork alone was used.

The selection of computer models used had the most important impact on the results. Any model will produce outputs that will be affected by the intrinsic modelling theory. The choice of models therefore resulted in a set of outcomes and conclusions likely to be different from selection of any other combination of models.

Operational research and management science are the two fields within which almost all multi-criteria decision analysis (MCDA) research is undertaken. As such, these sciences

produce skilled and eloquent practitioners of the MCDA approach to decision analysis. The author acquired such skills as the study progressed from a 'learning by doing' approach.

Good quality modelling requires good quality data to avoid compromising results. In the rural-community monitoring programme the data loggers and meters had their own respective flaws which at times led to incomplete data. Other 'flaws' in the data logging were the low resolution of data collected by the Seawards meters, and the lack of voltage monitoring to ensure that the level of energy consumption being logged was not being unduly affected by voltage variations. The accuracy of the data recorded however is unlikely to have affected the strong seasonal and daily trends identified.

The LDW model required a large number of assumptions to be made for stakeholder weightings and preferences. At the late stage of the overall study where actual elicitation of weightings and preferences would have been appropriate from stakeholders directly, time was too short to hold the required consultation meetings. The reported experiences of gathering people together in order for weights and preferences to be elicited (Keeney *et al.*, 1990; Tung, 1998; Keeney & McDaniels, 1999; and Bana e Costa, 2001) indicated that the task was complex and time consuming and as such an imposing exercise to conduct. Surveys were assessed by the author as being inadequate to the task because of the amount of feedback information needed by the respondents in order to elicit meaningful and relevant comments (Keeney *et al.*, 1990). Therefore, in this study, assumptions of stakeholder views were used in developing the LDW model. Further work would be needed to ascertain the measured preferences and views of the members of the community presented in this case study.

The weights and preferences used throughout the LDW model and assigned to the various secondary goals, and sub-goal measures, and measure levels were based on either informal anecdotal references from stakeholders, indirect elicitation of anecdotal preferences from stakeholders, published literature, or from HOMER modelling results. The environmental and social secondary goals utilised simple indicators of impacts and benefits. In some cases, these may have been too simple and the decision modelling may have benefited from more producing a more extensive list of indicators. The undertaking of full environmental and social impact assessments would have provided more of the indicators required for the full representation of the impacts and benefits but this was not possible due to time constraints.

11.5 Recommendations for Further Research

These recommendations result from newly defined topic areas or deficiencies in knowledge identified by the study. They cover a wide range of ideals, are not prioritised in any order of demand, nor are they mutually exclusive.

1. The progress of the household energy end-use project (HEEP) modelling should be followed and an assessment of the results should be made on its applicability to the load modelling of rural electricity loads with respect to the application of this model framework.

HEEP is an ongoing domestic electricity-use research programme in New Zealand, beginning in 2000 (Isaacs *et al.*, 2002; Stoecklein *et al.*, 2001a & b). When the HEEP data

becomes available in the level of detail proposed by the project researchers (Stoecklein *et al.*, 1998) the future monitoring of loads in such an extensive manner as undertaken in this study may not be necessary. The HEEP data could be used instead in a model based on such socio-demographic indicators as lifestyle, occupant ages and genders, wealth and income etc, with an emphasis on aspects of the rural lifestyle that differ from an urban lifestyle.

2. Assess the WindScape and Raptor_{NL} models for use in wide-area wind resource assessment.

The modelling of such a temporally and spatially variable renewable energy resource as wind is difficult to undertake without the use of a specific model such as WAsP. Although WAsP was purchased, an indication in the literature that another product, WindScape, was potentially technically better able to calculate and model wind flow in a complex terrain environment. At the time of the selection of the software for this study, it was not yet commercially available.

Further study of this software capability would reveal its potential to map the wind over a wide area using meso-scale wind data (Ayotte & Taylor, 1995; Steggel *et al.*, 2001), which may further reduce the time required to monitor the wind resource thus lowering the time required to assess overall energy system options.

3. Recommendations for improvement of HOMER for use in New Zealand situations.

Because of beta testing version 2.09 of HOMER in this study, research collaboration with the developers was formalised. The collaboration was ongoing, and as at April 2004, this extended to meeting the developers and testing version 2.10. From this, it was planned to develop HOMER further through continued discussion and testing in real world situations under the official NZ/US Climate Change scientific collaboration, administered by the New Zealand Ministry for Economic Development Climate Change Office.

Such changes would be:

WhisperGen external combustion co-generation – The introduction of the New Zealand designed WhisperGen into the HOMER model would be beneficial to the uptake of this technology into homes globally and not just in Europe (where sales are mainly centred). The modelling of this technology would be enhanced by the ability to separate the thermal load into two sections, dedicated space heating load, and water heating. It would also reverse the key assumption within HOMER that any co-generation heat is a by-product of electricity generation and not the other way around as it is with the WhisperGen device.

Solar water heating – This currently comprises only a very small proportion of applied renewable energy technology in New Zealand whereas the climate is ideal for further uptake. The introduction of thermal modelling in the form of solar water heating would be of great benefit when consideration is given to the 'whole' system of energy provision. This would require a fundamental paradigm shift for the HOMER modelling strategy from a distributed generation model to one of distributed energy.

Heat pumps – These are being installed in New Zealand in small numbers. If HOMER were able to model this technology then there would be a requirement for the ambient air or ground temperature to be a resource input for this option to be practical. This technology can be used for either space heating or water heating thus requiring further fundamental changes to the thermal load profile model in HOMER.

Multiple hydro options – currently only one hydro system can be modelled and simulated. In many sites, there may be several hydro options, such as high flow – low head and low flow – high head systems. There is currently no ability to assess which one would be the best to either implement alone, or with other technologies. The ability to model hydro storage of energy is currently unavailable. Any additional hydro modelling in HOMER should be developed to include a load following hydro storage component.

4. Develop a multiple criteria decision analysis (MCDA) module as an add-on model for HOMER such that outputs from the HOMER simulation and optimisation are used directly in a MCDA model.

Such a development must be undertaken in conjunction with the developers. Such an add-on should enable a MCDA process to dictate the optimality of any of the options according to the preferences used. This would require MCDA specific inputs into the add-on additional to the energy system inputs of HOMER. This would clearly be more complex than HOMER currently is, but as an add-on would be automatically available. It would be of interest to those with a desire to use it, as this would be of specific use when optimality cannot be represented in economic terms alone.

5. Analyse the Industrial Research Limited model 'Integrated Distributed Energy Systems' (IDES) for use in the SPiRAL framework in place of HOMER.

The IDES model was designed to model integrated energy supply systems and may be better suited to New Zealand conditions. It was not yet fully developed at the time of this study.

6. Investigate other MCDA software for capabilities appropriate to this research problem.

The range of software available in the MCDA discipline made the choice difficult and a screening process had to be undertaken. The science of MCDA appears to be a rapidly developing one and even though LDW appeared to be right choice at the time, there may be alternative products better suited to application for this study.

Logical Decisions for Windows now includes a group version suitable for compiling the weight values from individuals within a group and aggregating them into a weight representative of the group. This weights elicitation can be undertaken with the group members remote from each other or together in one place.

Other software such as Criterium DecisionPlus 3.0, assessed alongside Logical Decisions for Windows in the initial screening process, may be further investigated for use in the SPiRAL framework.

7. Incorporate a section into the overall modelling process to model network issues.

These issues would include such inputs as any grid-constraints, costs of any proposed line upgrade or maintenance, and network re-routing or other upgrade work required before distributed generation became viable. This stage could require the actual costs of any upgrade work required, into the decision-analysis process to be another detailed parameter in the MCDA process.

12 Conclusion

Since the reforms of the 1990s, there have been many regulatory and legislative changes, and policy initiatives clearly indicating a change of thinking and direction within the electricity generation and supply sectors. These have seen the electricity market change markedly in recent times, and indeed, change continues, with the costs for both electricity supply and reliability increasing, and large generation projects either being withdrawn or facing effective opposition from many sectors of society. Sustainability, security of the existing supply networks, renewable energy generation implementation, and a requirement of the continued growth in renewable energy generation capacity are fundamental to many of these changes. New Zealand's obligation to meet the requirements of the Kyoto Protocol will also require in part, an increasingly new look generation mix incorporating more renewable energy based generation.

If the growth in electricity demand continues and large hydro and thermal based generation becomes more difficult to implement due to environmental and societal concerns, then there will be problems with electricity supply shortages in New Zealand. One method of partially overcoming such problems would be to give attention to investment on sustainable small to medium capacity distributed generation projects and net-metered systems where both appropriate and necessary. New Zealand Government policy is steadily moving in this direction with the national energy efficiency and conservation strategy and the subsequent call for submissions regarding distributed generation (MED 2003).

Due to the changes pending the automatic repealing of the obligation to supply in the Electricity Act 1992, many individuals, and communities, especially rural, will be faced with electricity related challenges in the future. Hence, a growing number of rural enterprises and communities are looking towards sustainable and renewable energy sources of electricity, and there is a growing awareness of the social and environmental impacts associated with energy generation and use. Among them, the acceptance of the necessity of energy efficiency, the recognition of a need to become proactive on the energy supply security for their farms or communities, and the acceptance of renewable energy based distributed generation systems appearing in their locale (wind farms, biomass producing forests, and micro & small hydro systems). Because of this, the consideration of expressions of stakeholder preferences and concerns by investors and decision-makers are integral to the successful implementation of the most appropriate distributed generation technologies.

From the literature, one can conclude that certain sectors of the overseas electricity industry have already benefited from the application of formal decision-analysis methods. Innovative and practical application of decision-analysis methods to the problems and issues of renewable energy based distributed generation in the New Zealand rural sector would realise many benefits.

Such benefits would include:

- a greater understanding of the many complex and interacting sustainability issues affecting grid-connected renewable energy based distributed generation systems,
- stakeholder values expressed as formal preferences and concerns,
- an understanding and consideration of load and resource uncertainty and the inherent effect on choices, and
- the clear characterisation of the appropriate technology relative to sustainability and the stated stakeholder preferences.

The aim of this study was to develop and trial the efficacy of a decision-analysis framework while being restricted by a relatively short timeframe of monitoring programme, and an eclectic selection of software. This software would be used to identify within a short timeframe of both monitoring and modelling (six months to a year), a list of viable sustainable renewable energy resources and technologies suitable for use within a rural community to meet a measured or modelled demand. The expectations and preferences of the stakeholders would be considered through a fair and transparent decision-analysis that includes trade-offs.

To achieve this aim the research objectives were to monitor and record rural load profiles and renewable energy resource profiles, to identify and use suitable computer modelling software, and to model the decision-analysis process. The subsequent decision-analysis framework developed in this study (Figure 11.1) evolved from the initial (simple) concept outlined in by Figure 1.1. This framework resulted in a greater understanding of decision-analysis within the 'whole' system of renewable energy based distributed generation taking into account technical, social, environmental, and economic considerations including renewable energy resource and electricity load uncertainty, the effects of stakeholder preferences, and decision-analysis processes.

The software selection process was successful in identifying three models for use in the framework. The wind atlas analysis and application programme (WAsP), the micropower optimisation model (HOMER), and Logical Decisions for Windows (LDW) were chosen because of the capability to produce the required data for use in each subsequent stage of the decision-analysis framework. The developed framework (Figure 11.1) successfully integrated the results from each of these models and led to the formation of the decision-analysis framework, *Sustainable Power in Rural Areas and Locations* (SPiRAL).

WAsP produced a clear and relatively accurate assessment of the wind resource of the Totara Valley region. The model was validated using subsequent data, and the level of prediction error was quantified by comparison of the ruggedness index values and the differences between the predicted Weibull distribution values and the monitored Weibull distribution values. The modelled mean wind-speed and the Weibull 'k' formed the basis of the input into the next stage of the framework, wind modelling in HOMER.

HOMER formed the integral part of the renewable energy resources and energy systems modelling process. It provided detailed results for technically and economically feasible renewable energy systems for use in the subsequent stage of the SPiRAL framework.

Not only did it perform the modelling of the renewable energy based distributed generation systems for both short-term and full-term durations, but it also successfully facilitated the modelling of the renewable energy resources of wind, hydro, and solar, and the electricity loads in the short-term duration.

This was done using pertinent modelling parameters gleaned from the monitored data. These inputs were then used to model the short-term duration analysis with appropriate values utilised for a sensitivity analysis. From both the short-term and full-term duration analyses came full data sets of technical and economic performance that formed the input into the next stage of modelling. Some of these results were listed as mean values with an associated standard deviation that resulted from the sensitivity analyses. These were to form a normal distribution, thus defining the uncertainty of the results in the next stage of modelling. Other results were listed as single certain values.

The decision-analysis was modelled using Logical Decision for Windows in a multi-method approach incorporating the analytic hierarchy process, and two methods of multi-attribute utility theory. This stage utilised the technical and economic results of the HOMER modelling, while integrating environmental and social parameters, with the assumed preferences of the stakeholders creating the required weighting levels.

A sensitivity analysis of the effects of weighting level changes allowed the decision-maker to assess the relative effects of the weights used and the sensitivity of weighting changes to the overall results. From this process came a clear picture of any potential conflicts between weightings and hence by association, stakeholders.

The mean and standard deviation results from HOMER were used to model normal distribution curves for their respective values and these were then simulated using the Monte Carlo method to combine the uncertainty of many values into an overall level of uncertainty value of utility for each renewable energy option. This clear portrayal of the inherent uncertainty associated with the non-dispatchable sources of energy would indicate to the decision-maker the different levels of risk between the options, thus building a higher level of insight into the decision.

The method used in this study addressed the issues of the direct elicitation of preferences of many stakeholders into decisions in a pragmatic, transparent, and iterative manner. Through experience gained by this study, it is recommended that a similar concept to the '*Public Value Forum*' (Keeney *et al.*, 1990) be adapted for use in any future application of this method in conjunction with a '*focus group*'.

This would be the most cost effective method of preference and weights elicitation, as the '*focus group*' component would determine certain aspects of the problem structure as it relates to renewable energy system and distribution network constraints or requirements etc. These could then become useful as a template in similar settings even though there would be different stakeholders. Such 'generic' problem structures would then become applicable on a site-specific basis with a minimum need for further focus group input.

As a key aim of this study was to develop a rapid and relatively accurate decision-process, an initial critical path and PERT analysis was undertaken, and the optimum, likely, and pessimistic times of each task was estimated (Figure 4.1). These values indicated possible short-term project durations of 22 (optimistic) to 42 weeks (likely), with 49 weeks as a pessimistically biased estimate.

A revised critical path and PERT analysis used the short-term duration data (sections 6.3.3, 7.2.7, and 8.3.4) and revealed that the revised optimistic task durations would produce a project outcome after a 20-week period (Figure 11.2). The most likely outcome would be a project of 30-weeks duration from start to finish. The PERT analysis, which included a pessimistic bias, indicated the project duration of 31-weeks.

Although the testing of the efficacy of the decision analysis system may have been compromised by not directly eliciting preference values from the stakeholders, this did not altogether detract from the end result of an effective set of tools for decision making. The efficacy of the decision analysis method was tested and found to provide what was required.

The collective monitoring and modelling process used in this study (Figure 11.1) has delivered a set of results that transparently outlined electricity load requirements, the renewable energy resources, and the supply options. These results, presented in clear economic terms, extensively evaluated the environmental, social, and technical impacts and benefits related to the technology in a manner likely to instil insight into the decision-analysis process. The wind atlas analysis and application programme (WAsP), the micropower optimisation model (HOMER) and Logical Decisions for Windows (LDW) delivered results that extended awareness and understanding of the potential solutions to the problems of supplying a sustainable power supply to small communities.

Decision-making about electricity supply options in New Zealand has never been more complex than it is now and rational decision-analysis more necessary within a changing electricity industry. The decision-analysis framework presented in this study highlighted the crucial areas of monitoring to obtain pertinent data, and modelling to gain insightful, meaningful, and accurate results, all within a relatively short time-frame, using a framework that was transparent, iterative, and appropriate.

The type of decision-analysis conducted in this study should become an integral part of energy supply system decision-making processes. Sustainability in the electricity sector has been included in New Zealand Government policy as both acts of parliament and policy statements (e.g. Energy Efficiency and Conservation Act 2000, National Energy Efficiency and Conservation strategy) it now needs consideration in such decision-making processes.

Part five: the appendices

Renewable energy related legislation – A

Wind energy resource modelling – B

Multiple criteria decision analysis – C

The Limestone Downs case study site – D

Aerial photograph of Totara Valley – E

Electricity load profile data – F

Renewable energy resource data – G

References

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Appendix A

13 Renewable Energy Related Legislation

This section includes excerpts only from the relevant legislation. Reference to the full legislation should be made if further details are required.

13.1 Electricity Act 1992

Section 62 – Continuance of Supply

1. This section applies to---
 - (a) Every electricity distributor that, immediately before the 1st day of April 1993, was the holder of a licence issued under section 20 of the Electricity Act 1968 and in force immediately before that date:
 - (b) Every electricity distributor that is a successor to an electricity distributor to which paragraph (a) of this subsection applies.
2. Except as provided by this Act or any regulations made under section 169 of this Act or by written agreement with a particular consumer (whether entered into before or after the commencement of this section), where, at the commencement of this section, line function services are being provided to any place by any electricity distributor to which this section applies, that electricity distributor shall not cease to supply line function services to that place without the prior consent of the Minister or of every consumer who would be affected by the cessation of those services.
3. Nothing in subsection (2) of this section applies where an electricity distributor ceases to supply line function services to any place in any of the following circumstances:
 - (a) Where the electricity distributor is entitled to cease to supply line function services by reason of the failure of any consumer to pay any money due on account of---
 - (i) The supply of those line function services to that place; or
 - (ii) The supply of electricity to that place:
 - (b) Where cessation of supply is rendered necessary for reasons of safety or in order to carry out maintenance or upgrading work:
 - (c) Where cessation of supply results from circumstances beyond the control of the electricity distributor, including (without limitation) fire, earthquake, lightning, inevitable accident, act of God, or force majeure.
4. Where, for any of the reasons referred to in subsection (3) of this section, an electricity distributor ceases to supply line function services to any place, that cessation of services may continue only for so long as any 1 or more of those reasons continues to exist.
5. Except as provided by subsection (3) of this section, every electricity distributor to which this section applies commits an offence and is liable on summary conviction to a fine not exceeding \$10,000 and to a further fine not exceeding \$1,000 for every day or part of a day during which the offence continues who, in contravention of subsection (2) of this section, ceases to supply line function services to any place.
6. This section shall expire with the close of the 31st day of March 2013, and on the 1st day of April 2013 this section shall be deemed to have been repealed.

13.2 Electricity Industry Reform Amendment Act 2004

Section 3 – Purpose of this Part

The principal purpose of this Part is to provide new exemptions from the ownership separation rules (but not the corporate separation rules or the arms length rules) in respect of---

- (a) generation commissioned after 20 May 2003, if the generating capacity of the generation is no more than the greater of 50 MW and 20% of the maximum demand of the lines owned or operated by the person;
- (b) reserve energy contracted to the Electricity Commission as dry-year reserve.

Section 5 – Meaning of electricity supply business

- 1 Section 5(2)(e)(i) of the principal Act is amended by omitting the words "of the system", and substituting the words "of the lines".
- 2 Section 5 of the principal Act is amended by inserting, after subsection (3), the following subsection:

"(3A) Transpower New Zealand Limited, and any subsidiary of or successor to that company, may, without coming within subsection (1), contract with an electricity supply business for that electricity supply business to generate electricity for the purpose of deferring the need for investment by Transpower New Zealand Limited, or any subsidiary of or successor to that company, in the national grid."
- 3 Section 5(4) of the principal Act is amended by repealing the definition of maximum demand.

13.3 Energy Efficiency and Conservation Act 2000

Section 5 – Purpose

The purpose of this Act is to promote, in New Zealand, energy efficiency, energy conservation, and the use of renewable sources of energy.

Section 6 – Sustainability principles

In achieving the purpose of this Act, all persons exercising responsibilities, powers, or functions under it must take into account---

- (a) the health and safety of people and communities, and their social, economic, and cultural well-being; and
- (b) the need to maintain and enhance the quality of the environment; and
- (c) the reasonably foreseeable needs of future generations; and
- (d) the principles of the Treaty of Waitangi.

13.4 Resource Management Act 1991

Section 5 – Purpose

- 1 The purpose of this Act is to promote the sustainable management of natural and physical resources.
- 2 In this Act, "sustainable management" means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while—
 - (a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and
 - (b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and
 - (c) Avoiding, remedying, or mitigating any adverse effects of activities on the environment.

13.5 Resource Management (Energy & Climate Change) Amendment Act 2004

Section 3 – Purpose

The purpose of this Act is to amend the principal Act---

- (a) to make explicit provision for all persons exercising functions and powers under the principal Act to have particular regard to---
 - (i) the efficiency of the end use of energy; and
 - (ii) the effects of climate change; and
 - (iii) the benefits to be derived from the use and development of renewable energy; and
- (b) to require local authorities---
 - (i) to plan for the effects of climate change; but
 - (ii) not to consider the effects on climate change of discharges into air of greenhouse gases.

Section 4 – Interpretation

Section 2(1) of the principal Act is amended by inserting, in their appropriate alphabetical order, the following definitions:

"climate change" means a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.

"greenhouse gas" has the meaning given to it in section 4(1) of the Climate Change Response Act 2002.

"renewable energy" means energy produced from solar, wind, hydro, geothermal, biomass, tidal, wave, and ocean current sources".

Appendix B

14 Wind Energy Resource Modelling

This section contains should be read with Chapters 3 and 8. The origin of any accumulated error in the WAsP predictions are given in Section 14.1, which concludes with the origins of the Ruggedness Index (RIX) number. In Section 14.2 details of setting the distance from the Wind Site over which a RIX analysis was to be undertaken are given. The final distance of 3500 metres matched the default radii used by WAsP. Certain model parameters need setting in any WAsP model, and in this study the inversion scale length and the 'softness' parameters were used to 'force' the channelled flow of the wind over the complex terrain of Totara Valley. Section 14.3 details the results from the selection of the parameters to be used. An analysis was undertaken to test the efficacy of the RIX number to predict the error of the WAsP modelling and the results of sector analysis is given in Section 14.4.

14.1 WAsP Error Calculations

Bowen & Mortensen (1996) outlined the accumulated source of any WAsP error as being as follows:

Consider first the WAsP application procedure applied using generalised wind-speed data from the atlas file (U_A) to estimate the sector-wise wind-speeds at a particular (predicted) site (U_{Pe}). The accurate speed-up correction for orographic effects has an accompanying error (E_2). The error will normally have a positive sign in line with the tendency for WAsP to over predict rugged sites when using a flat reference site. Steep terrain promotes flow separation, particularly on the lee-side of a ridge lying at an obtuse angle to the wind flow.

Thus, for the Application procedure,

$$U_A + (\Delta U_2 + E_2) = U_{Pe}$$

where

U_{Pe} = estimated predicted mean wind speed at predicted site

U_A = generalise d wind speed data from atlas file

ΔU_2 = speed up correction associated with predicted site

E_2 = error associated with speed up correction

Conversely, when (previously) analysing the reference site measured data (U_{RM}) to create the corrected speed in the atlas file (U_A), a further accurate speed-up correction (ΔU_1) with its associated error (E_1) is involved. This analysis procedure involves the orographic model in the opposite sense such that,

$$U_{Rm} - (\Delta U_1 + E_1) = U_A$$

Where

U_A = generalised wind speed data from atlas file

U_{Rm} = measured data from reference site

ΔU_1 = speed up correction from reference site to atlas file

E_1 = error associated with this speed up correction

The overall prediction process utilises both Analysis and Application procedures in succession. Therefore combining both equations to eliminate U_A ,

$$(U_{Rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{Pe}$$

The estimated speed at the predicted site (U_{Pe}) is made up of the correct (measured) speed (U_{PM}) and the overall prediction error which has accumulated from the two stages of the prediction process. The measured speed at the predicted site is assumed to contain no errors and is,

$$U_{PM} = U_{Rm} - \Delta U_1 + \Delta U_2$$

The overall prediction error $U_{Pe} - U_{PM}$ is therefore determined by the difference in the individual WAsP procedure errors, $E_2 - E_1$. The magnitudes of the individual procedure errors depend on the degree that each site contravenes the orographic limits of the WAsP prediction model.

The relative sizes of the two procedure errors may be assumed to be roughly proportional; to the individual site ruggedness, thus determine the accuracy and bias of the overall prediction by the WAsP model.

The error assessment by Bowen & Mortensen (1996) led to the creation of the orographic ruggedness indicator known today as the Ruggedness Index or RIX number.

The ability to predict whether or not the flow will separate is fundamental to the estimation of the performance of the orographic model and other linear numerical models, which assume the presence of attached flows.

An orographic performance indicator to predict the overall error ($E_2 - E_1$) can now be defined as the difference in these percentage fractions of steep terrain between the predicted and reference sites.

14.2 Initial Wind Atlas from Wind Site 1

The initial data from Wind Site 1 was used to model the wind atlas for the Totara Valley region (Figure 14.1). From this wind atlas, potential wind sites were identified for further monitoring in the sequential multi-mast wind-monitoring programme adopted in this study.

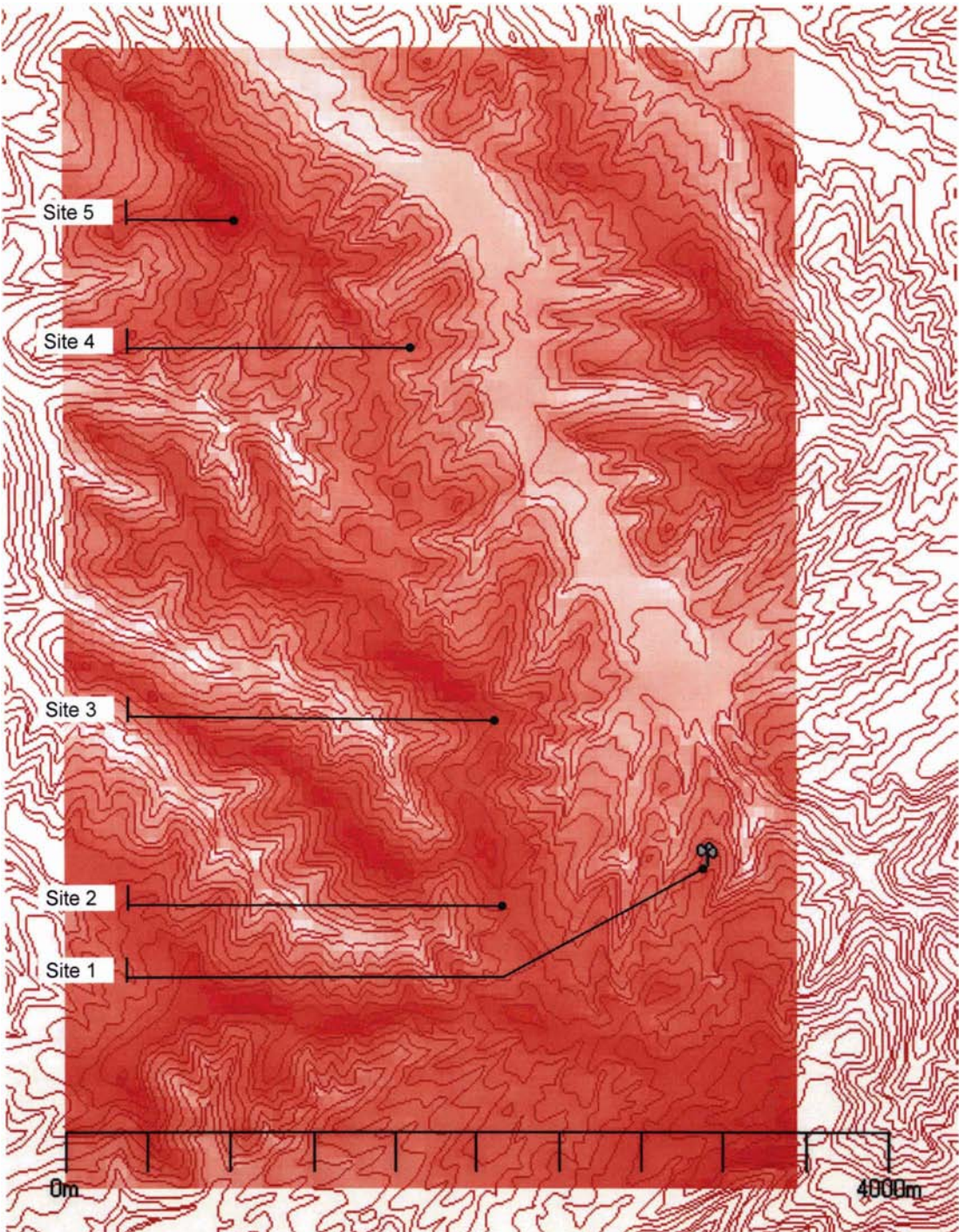


Figure 14.1 Initial wind atlas from Wind Site 1 used to identify potential wind sites for further monitoring.

14.3 WAsP Inversion level Setting

Wind Site 5 was used to predict the mean wind-speed at other sites under the varying inversion scale lengths with the 'strength' of this inversion set at 0.5, 0.25, and 0.1. An inversion scale length of 600 metres with a softness of 0.1 was used in the WAsP modelling. This is covered in detail in Chapter 8. The same scale lengths with softness parameters of 0.5 and 0.25 were also calculated and the resulting matches between observed wind climates and predicted wind climates are given in Figure 14.2 and Figure 14.3 where the solid line represents the observed mean wind-speed at the given site. The dashed lines are the modelled mean wind-speeds for the given inversion length scale and softness (forcing) parameter.

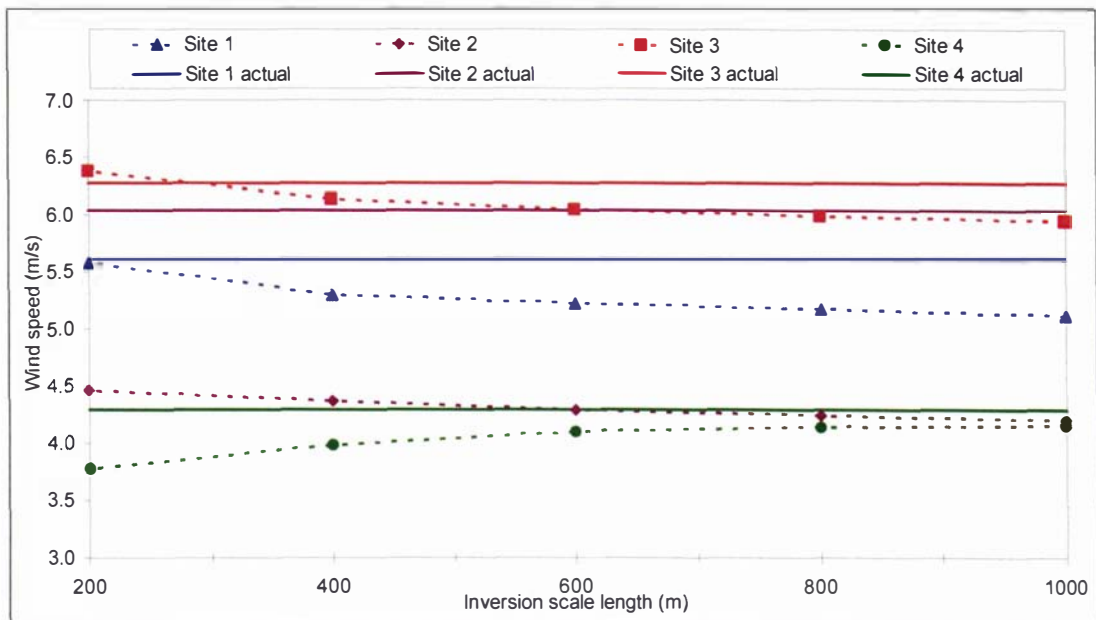


Figure 14.2 WAsP inversion testing against the Site 5 data for all other sites at 0.5 softness.

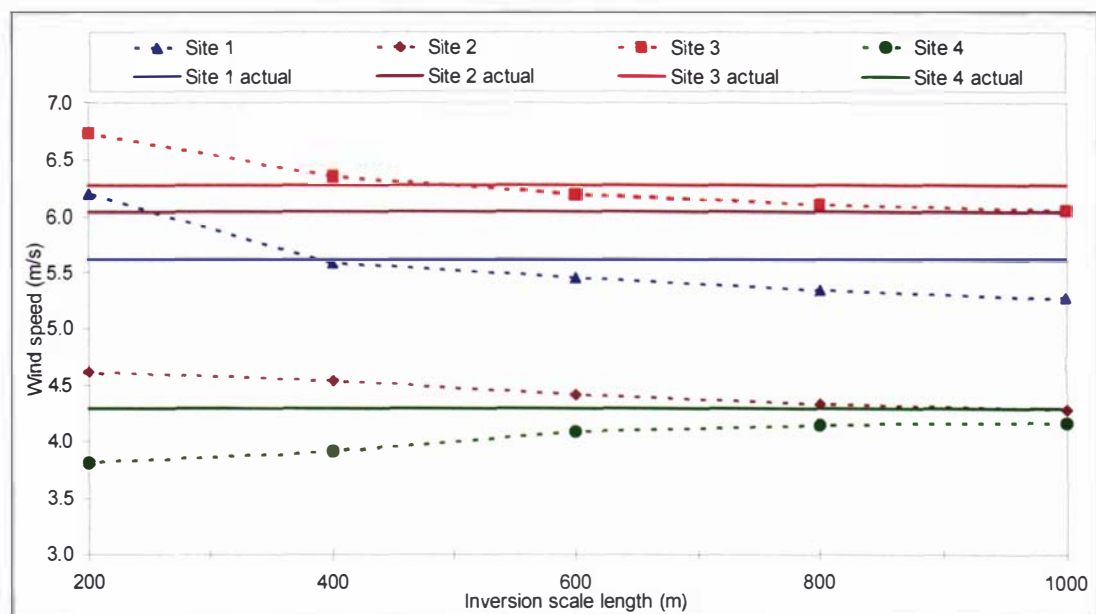


Figure 14.3 WAsP inversion testing against the Site 5 data for all other sites at a softness of 0.25.

14.4 Ruggedness Index Error Analysis

The plots of the RIX difference and the prediction error of the Weibull 'A' and 'k' statistics between Site 5 and Sites 1, 2, 3, and 4 in each of the compass sectors are given in Figure 14.4 and Figure 14.5. In each of the plots the overall RIX – prediction error is given as the solid red shapes. The overall RIX – prediction error is shown in more detail in Chapter 8.

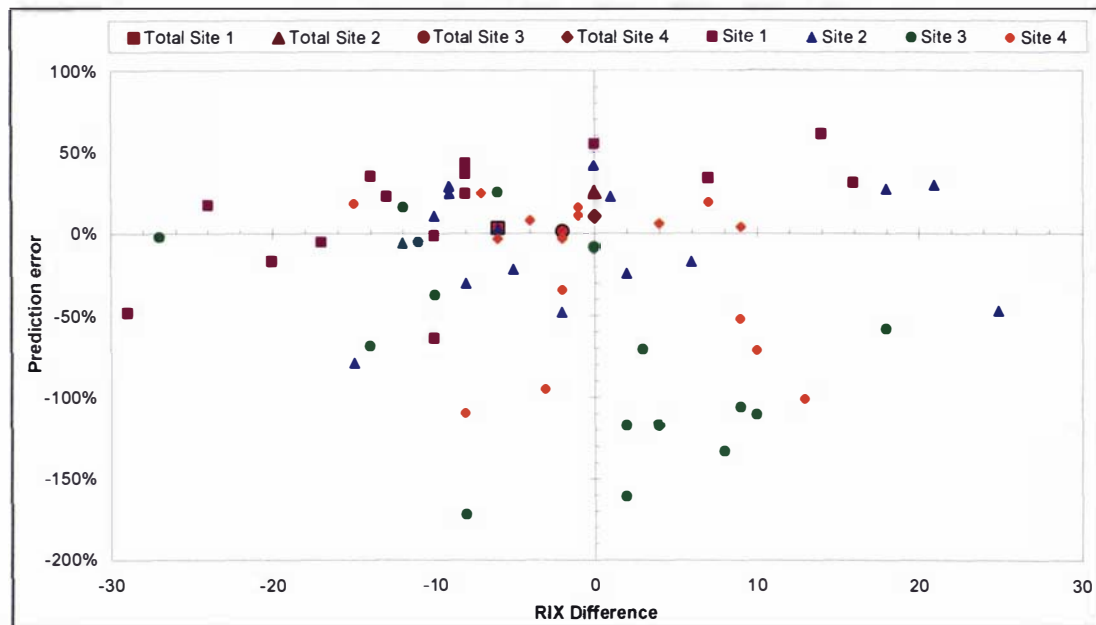


Figure 14.4 Individual sector RIX number and prediction error comparison for Weibull 'A'.

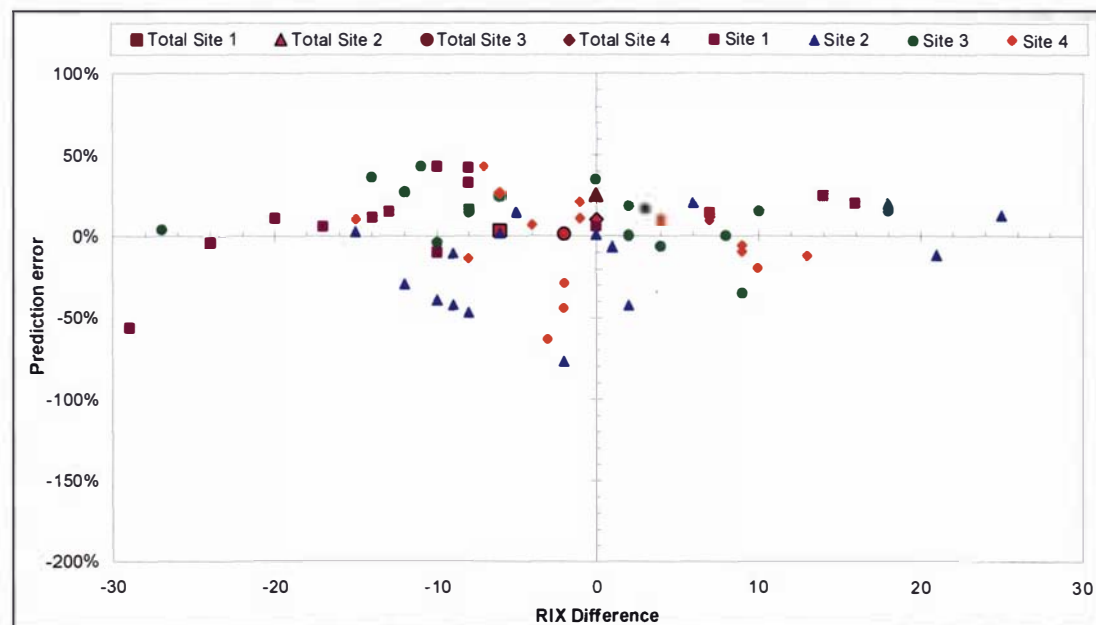


Figure 14.5 Individual sector RIX number and prediction error comparison for Weibull 'k'.

Appendix C

15 Multiple Criteria Decision Analysis

This section should be read in conjunction with Chapter 3 regarding the range of multiple criteria decision analysis software available, and Chapter 10.

15.1 Decision Analysis Software

Software reviews of decision analysis software have appeared in the literature in many publications but the software has evolved so rapidly over the last few years that only the latest publications were of any use. Benn (2002) had one of the latest surveys and some of the details can be found in Table 15.1.

Table 15.1 A survey of decision analysis software and their specific applications with comments.

Product and website	Specific applications for which software is most widely used	Comments
Analytica www.lumina.com/	Business models.	It offers intuitive influence diagrams, efficient Monte Carlo, and Intelligent Arrays for managing large models.
cdpGEO 1.0 No URL available	Resource allocation, portfolio management.	To be sold as a bundled package with Microsoft's Map Point.
Criterium DecisionPlus (CDP) 3.0 www.infoharvest.com/	Resource allocation, discrete choice, multiple stakeholders, portfolio management.	Currently developing cdpGEO 1.0 for geographically distributed decisionmaking. Also cdp 4.0 to include XML import/export.
Crystal Ball 2000 www.decisioneering.com/	Financial analysis, budgeting and cost estimation, sales forecasting and market penetration, portfolio management, etc.	An easy-to-use Monte Carlo simulation program that helps Excel spreadsheet users make better decisions by quantifying the risks and uncertainties associated with their models.
DATA 4.0 www.treeage.com/	Cost-effectiveness analysis of healthcare options, environmental remediation, and protection of facilities from terrorists.	Remote users can access the model, change values and perform analyses using a standard web browser.
Decision Explorer (Formerly Graphics COPE) www.banxia.com/	Strategy development, stakeholder analysis, project definition, competitor analysis, risk definition/management.	Software for analysing qualitative data. Build, navigate & analyse concept/cause maps. Structure thinking, thoughts/ideas in context, examine causes & consequences, manage complexity.
Adapted from: Benn, (2002); Belton & Stewart, (2002); and Clemens, (1996).		

Product and website	Specific applications for which software is most widely used	Comments
Decision Programming Language (DPL) www.syncopationsoftware.com/	Strategic business modeling under uncertainty.	Employs efficient algorithms for evaluation of large decision trees and complicated value models which gives the user unmatched power to solve very large decision analysis problems in reasonable time.
DecisionPro 4.0 www.mbaware.com/	Strategic planning, marketing, finance and accounting, operations, and legal and litigation analysis.	An integrated decision-support application supporting decision tree analysis Monte Carlo simulation, Linear program optimisation etc.
The DecisionTools Suite www.palisade.com/	Portfolio investment analysis, drilling decisions in oil and gas, retirement planning, market sensitivity analysis.	Seamless integration with MS Excel & transparent nature makes it easy for anyone to turn an Excel model into a high-powered risk analysis spreadsheet.
EQUITY www.catalyze.co.uk/ www.enterprise-lse.co.uk/	Resource allocation, discrete choice, portfolio selection.	Widely used in USA & UK, based on research from the London School of Economics, designed to support both individual users and the Decision Conferencing process.
Expert Choice 2000 2nd Edition www.expertchoice.com/	Resource allocation, IT project portfolio management, project management, vendor selection, marketing, human resource.	With the new Resource Allocation Module users can tackle the most complex allocation challenges and achieve the optimal distribution of their resources. Group decision support system.
Frontier Analyst www.banxia.com	Performance measurement and benchmarking for improved resource allocation and process improvement. Data Envelope Analysis.	Efficiency analysis using performance comparisons between similar business units. Designed to provide graphical and numerical output for professional presentation of results to managers and decision makers.
HIVIEW www.catalyze.co.uk/ www.enterprise-lse.co.uk/	Discrete choice and resource allocation.	Widely used in USA and UK, based on research from the London School of Economics, designed to support both individual users and the Decision Conferencing process.
HiPriority No URL available	Resource allocation, Discrete choice, R&D budgeting, post merger rationalisation.	The first Pareto Optimization software to model interactions between alternatives. Explicit sets of 'must do' and 'won't do' Buffers allows users to focus attention on 'might do' options."
Impact Explorer www.banxia.com/	Risk analysis, option prioritisation.	For use with groups. Allows various forms of voting, ranking and matrix assessment, uses a separate radio-based keypad response system. Group Decision Support System.
Adapted from: Benn, (2002); Belton & Stewart, (2002); and Clemens, (1996).		

Product and website	Specific applications for which software is most widely used	Comments
Joint Gains www.jointgains.hut.fi/	Multiple stakeholder negotiations.	Multiattribute negotiation support Web software for multiple participants based on the Method of Improving Directions. Continuous decision variables with linear constraints. Negotiators' most preferred directions elicited by value comparisons. Web-based negotiation support.
Logical Decisions for Windows www.logicaldecisions.com/	Discrete choice, multiple stakeholders, engineering design, environmental impacts, financial evaluation, force/generation mix.	Helps evaluate decisions requiring many evaluation criteria and critical preference and value judgments using MAUT or AHP. LDWs features and displays make it a powerful software.
Netica www.norsys.com/	Bayesian network builder for data mining capabilities.	Has true Bayes net capability, with junction tree algorithms. Can learn under missing data or hidden variables using EM or gradient descent algorithms.
PRIME Decisions www.sal.hut.fi/	Evaluation of discrete choice alternatives under incomplete information.	Supports the analysis of interval-valued preference statements in value trees.
Risk Detective www.riskdetective.com/	All potential applications of MCDA.	Provides powerful decision analysis tools for Microsoft Excel spreadsheets. This software combines with spreadsheet models to create tabular and graphical results.
TreePlan www.treeplan.com/	Sequential decision problems under uncertainty.	A decision tree add-in for Microsoft Excel.
WINPRE www.sal.hut.fi/	Evaluation of discrete choice alternatives under incomplete information.	Workbench for interactive preference programming; runs value tree and AHP models with incomplete interval type preference statements. SMART can also be used by point estimates.
Web-HIPRE www.hipre.hut.fi/	Evaluation of discrete choice alternatives, multiple stakeholders.	General Purpose MCDA software on the Web. Can also be installed locally. Supports SMART/Swing, SMARTER, AHP, direct weighting and value functions. Possibility to combine individual models into a group model.
Adapted from: Benn, (2002); Belton & Stewart, (2002); and Clemens, (1996).		

15.2 Sensitivity Analysis Results

This section provides supplementary material for sections 10.3.1 and 10.3.2.

In the sensitivity analyses (Figure 15.1 to Figure 15.12) the black vertical line bisecting the decision alternatives represents the weighting given to that particular parameter in that preference set and where it bisects the line of an alternative, is the utility of that alternative.

The secondary goals of Economic, Environment, Social, and Technical had percentage weightings of 26.2%, 11.7%, 5.5%, and 56.5% respectively in the *distribution network* preference set using the AHP MCDA method (Figure 15.1); 30.5%, 22%, 13.6%, and 33.9% respectively in the *distribution network* preference set using the SMARTS MCDA method (Figure 15.2); and 27.1%, 14.6%, 6.3%, and 52.1% respectively in the *distribution network* preference set using the SMARTER MCDA method (Figure 15.3).

The secondary goals of Economic, Environment, Social, and Technical had percentage weightings of 48.3%, 15.7%, 27.2%, and 8.8% respectively in the *individual farm* preference set using the AHP MCDA method (Figure 15.4); 40%, 20%, 30%, and 10% respectively in the *individual farm* preference set using the SMARTS MCDA method (Figure 15.5); and 52.1%, 14.6%, 27.1%, and 6.3% respectively in the *individual farm* preference set using the SMARTER MCDA method (Figure 15.6).

15.2.1 Full-Term Duration

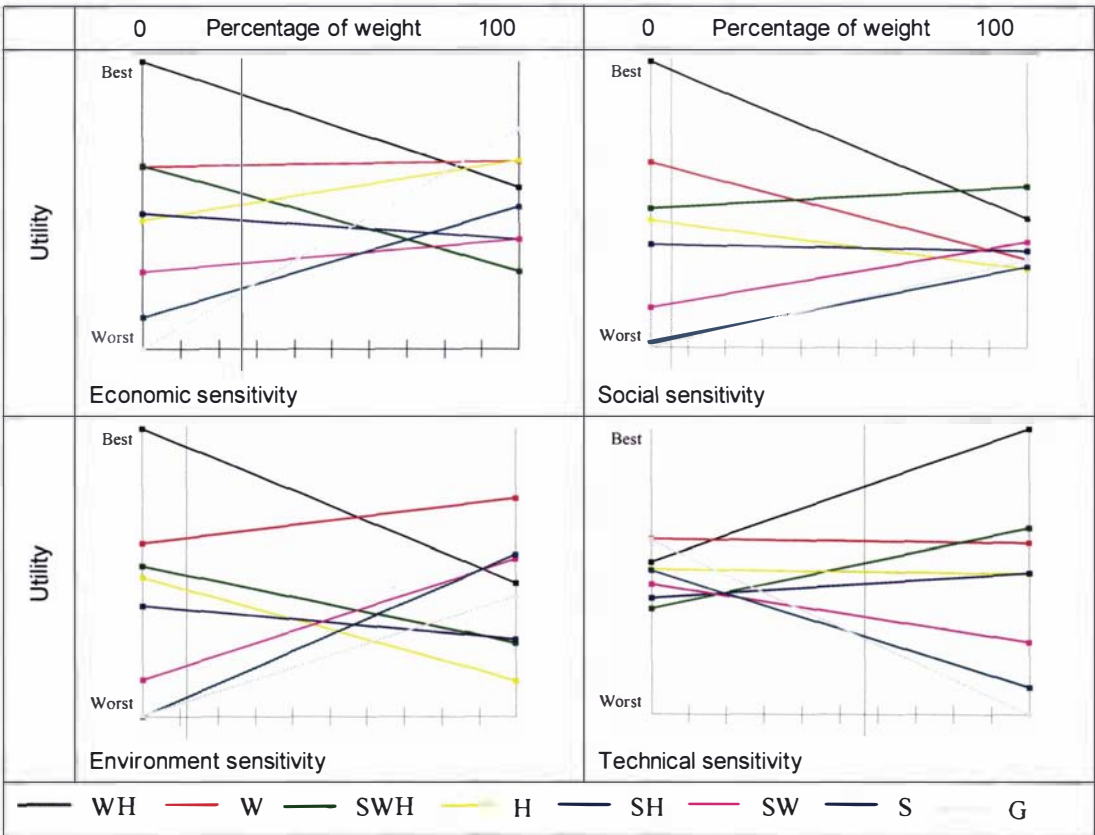


Figure 15.1 Full-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the AHP method.

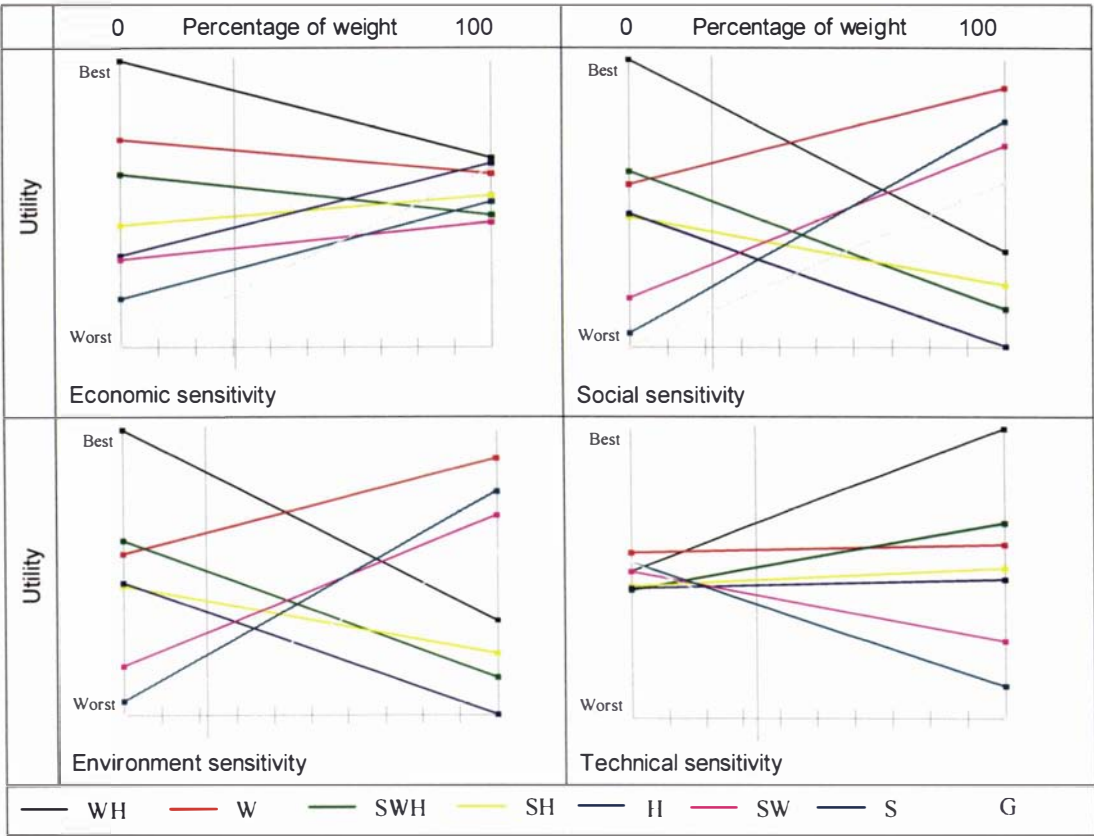


Figure 15.2 Full-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the SMARTS method.

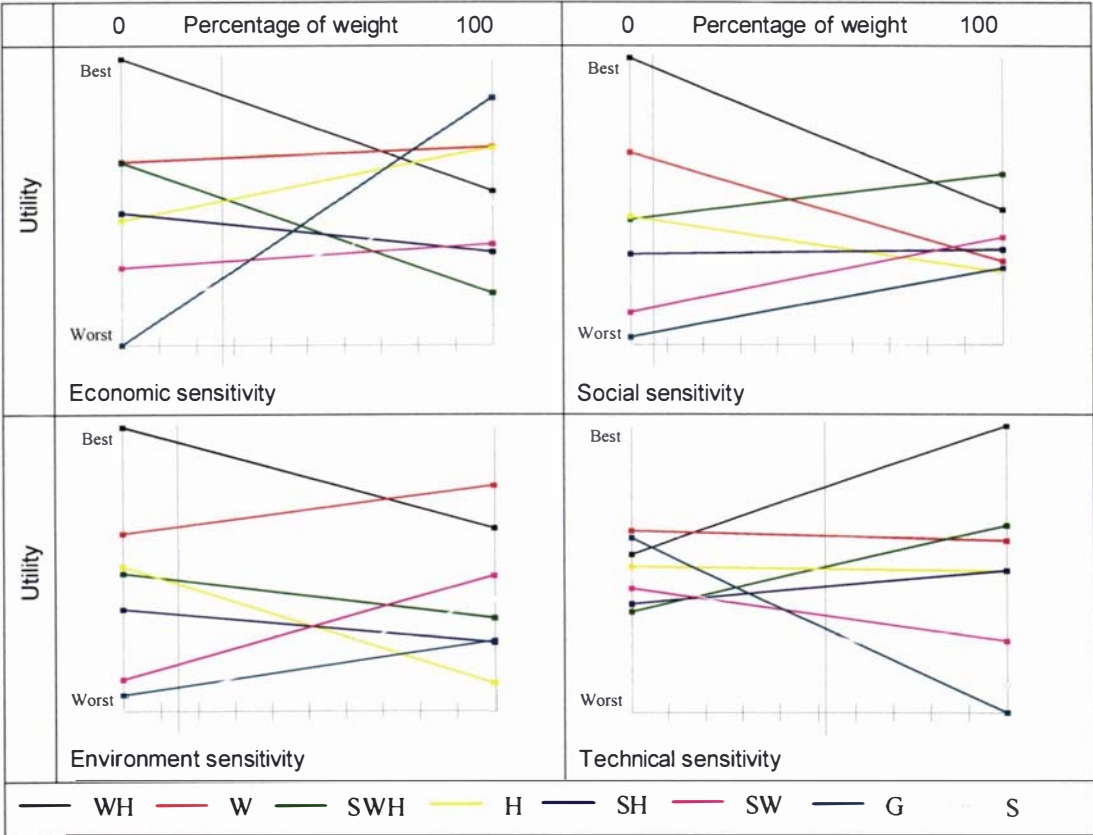


Figure 15.3 Full-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the SMARTER method.

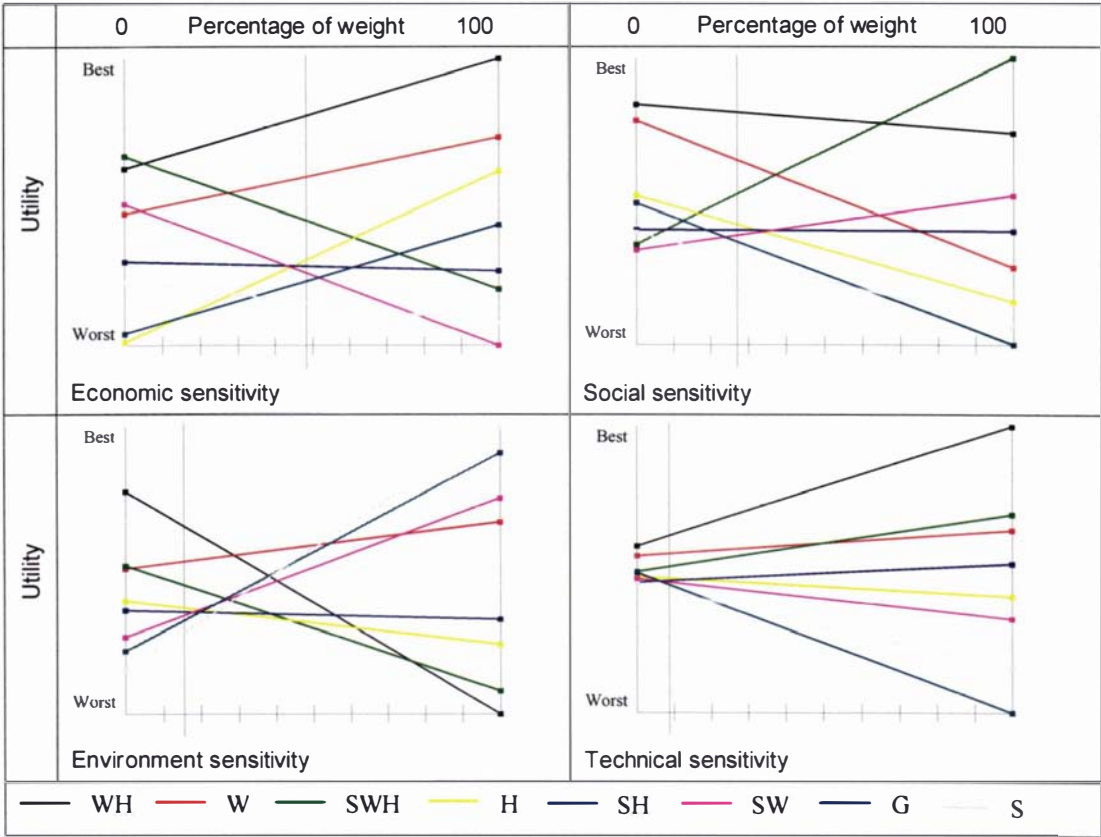


Figure 15.4 Full-term duration sensitivity graphs for the secondary goals using the *individual farm* preference set and the AHP method.

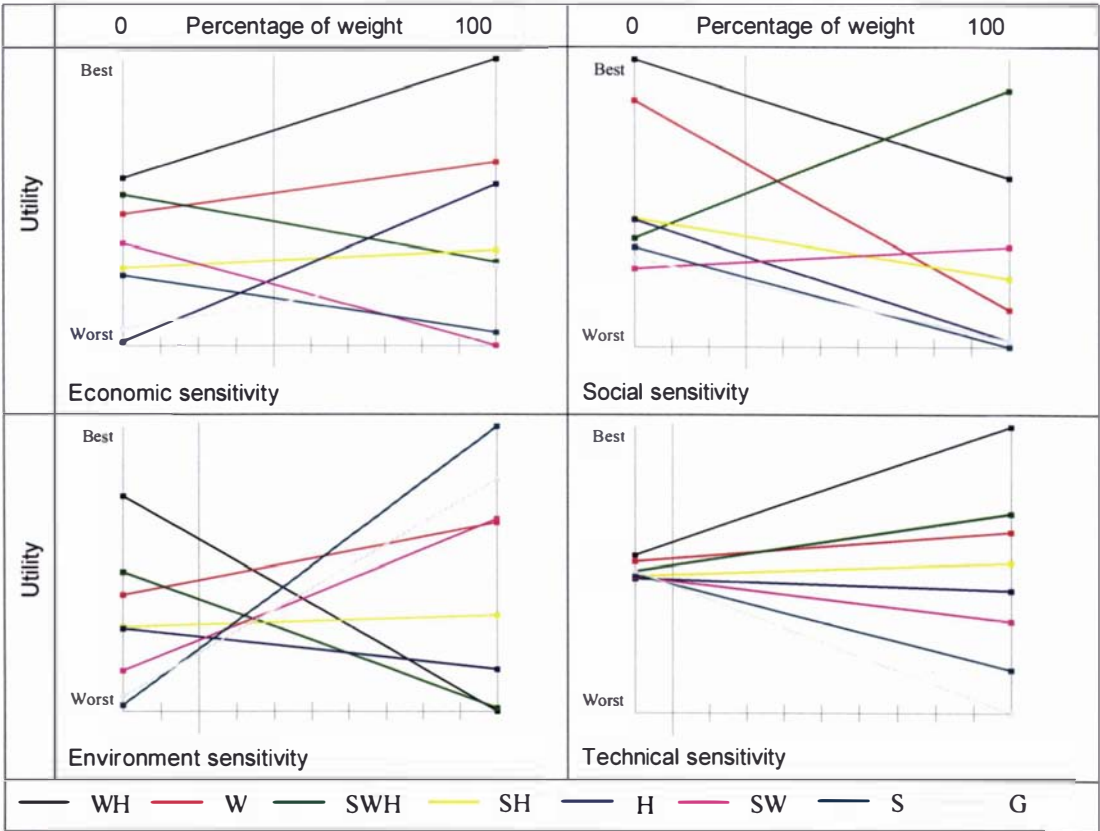


Figure 15.5 Full-term duration sensitivity graphs for the secondary goals using the *individual farm* preference set and the SMARTS method.

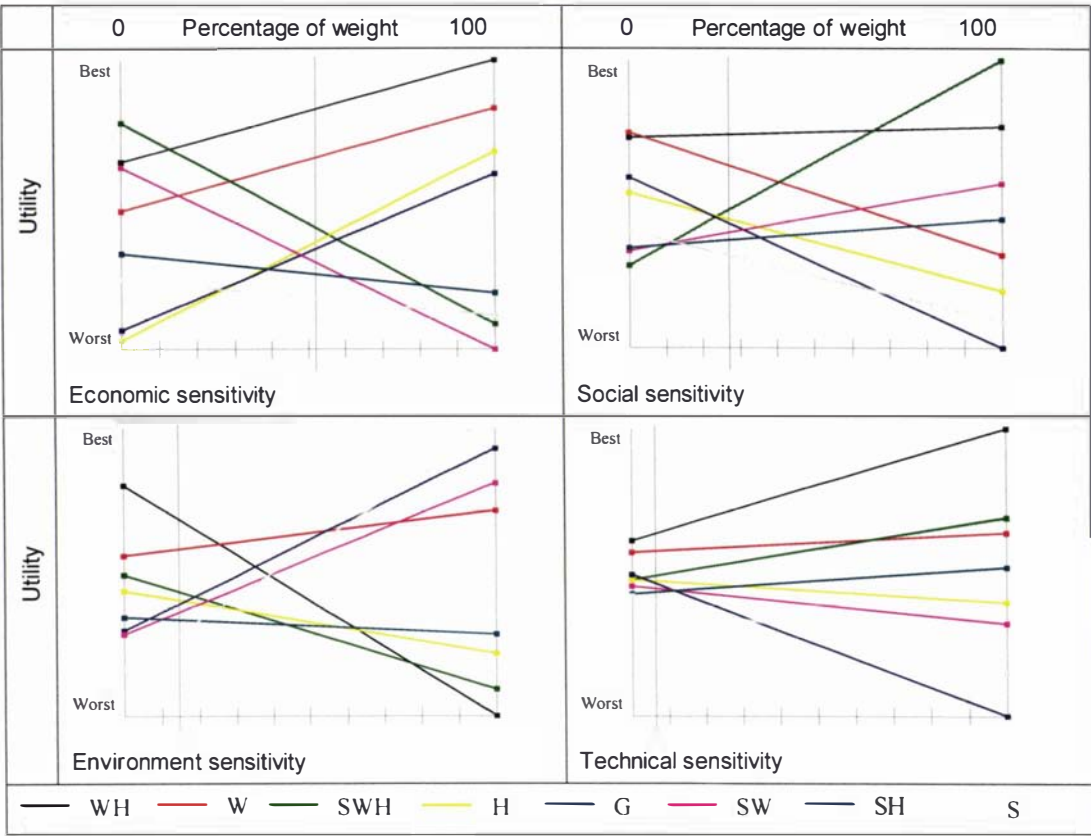


Figure 15.6 Full-term duration sensitivity graphs for the secondary goals using the *individual farm* preference set and the SMARTER method.

15.2.2 Short-Term Duration

The short-term duration sensitivity results should be read in conjunction with section 10.3.2. The sensitivity analysis results for the short-term duration (Figure 15.7 to Figure 15.12) were derived from the same preferences and hence weights as the full-term duration.

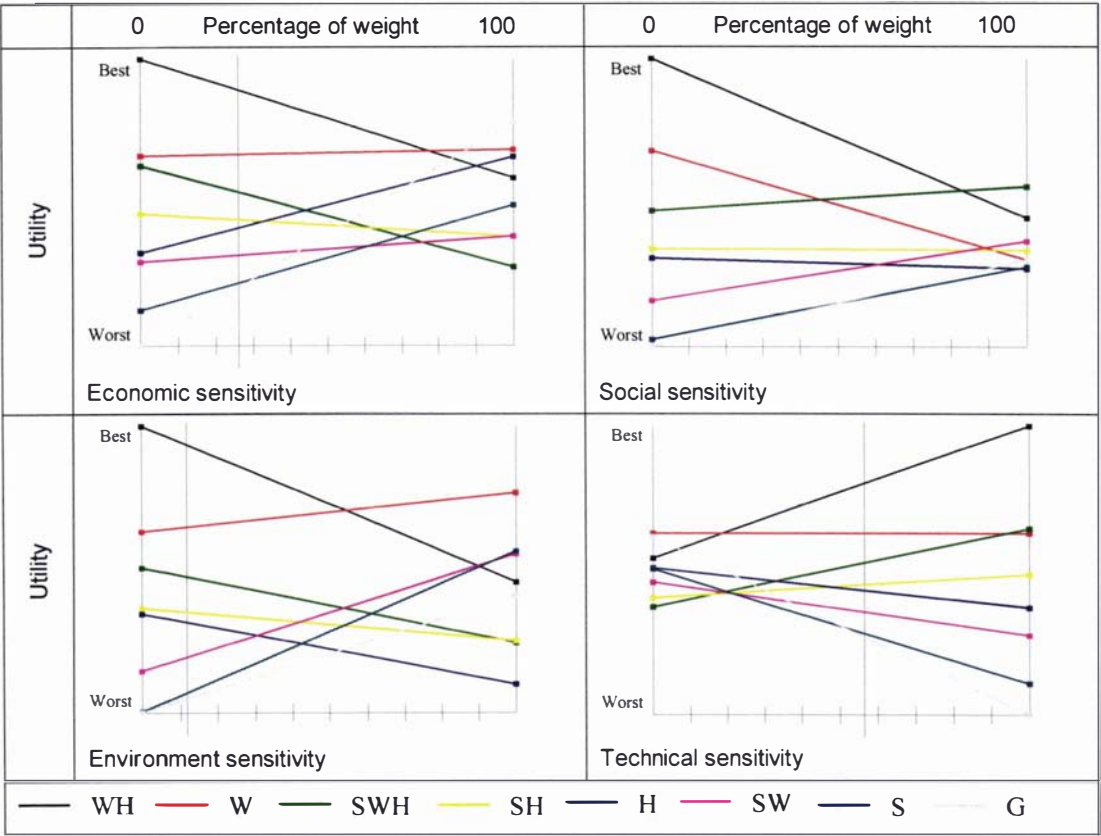


Figure 15.7 Short-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the AHP method.

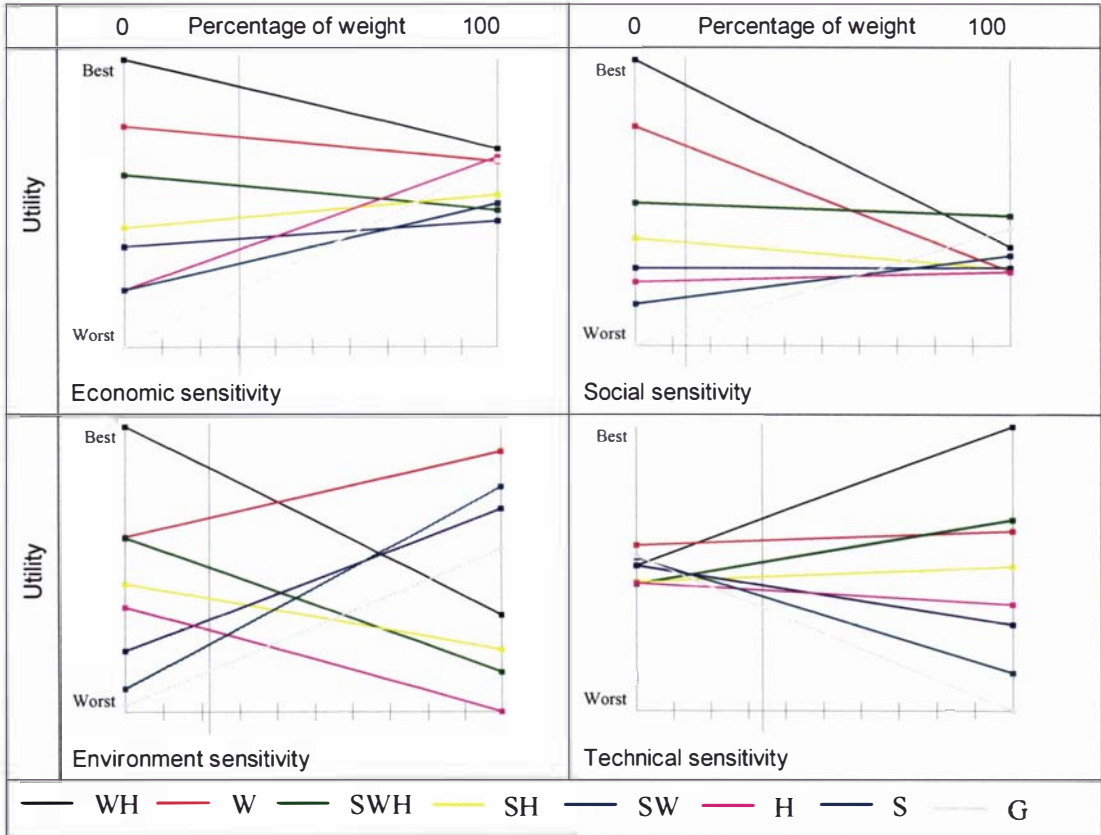


Figure 15.8 Short-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the SMARTS method.

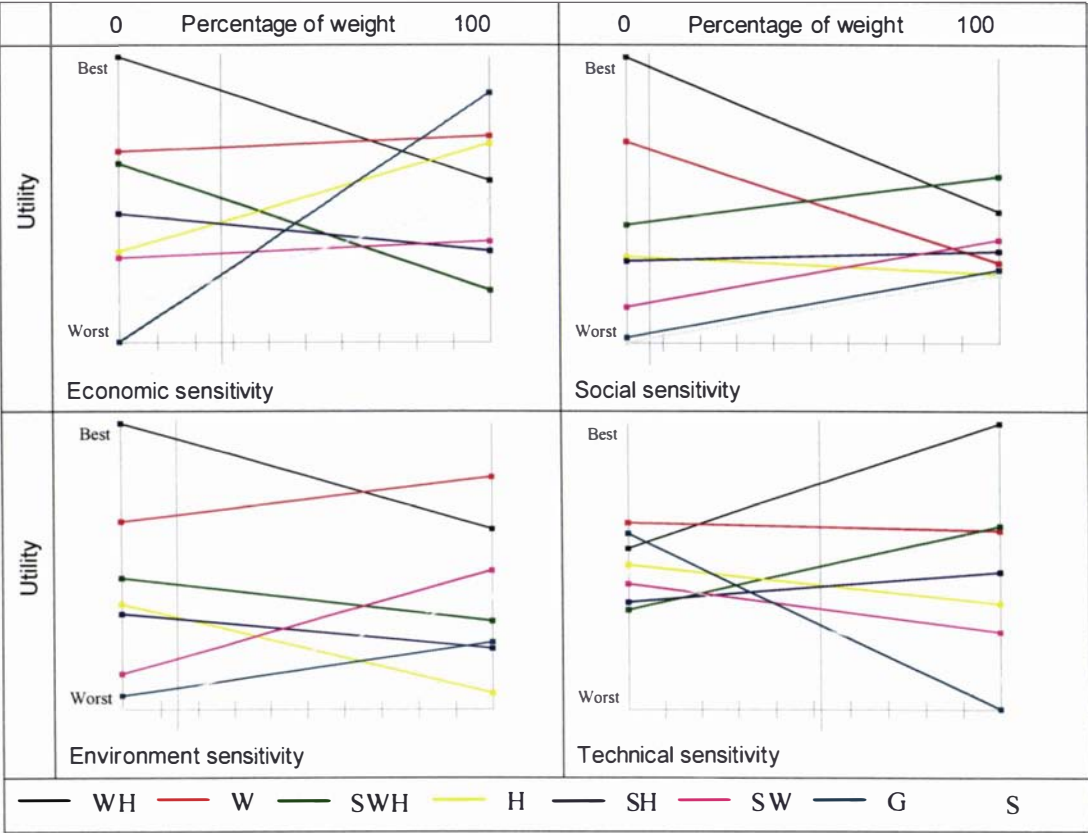


Figure 15.9 Short-term duration sensitivity graphs for the secondary goals using the *distribution network* preference set and the SMARTER method.

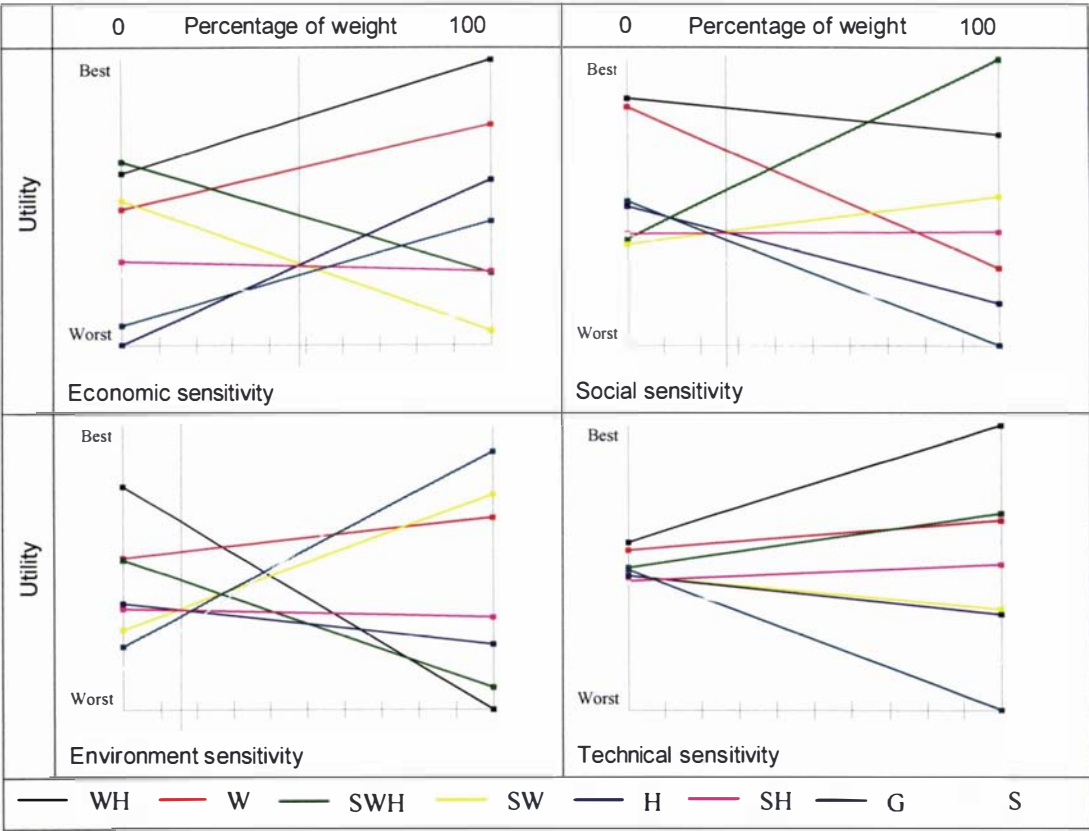


Figure 15.10 Short-term duration sensitivity graphs for the secondary goals using the *individual farm* preference set and the AHP method.

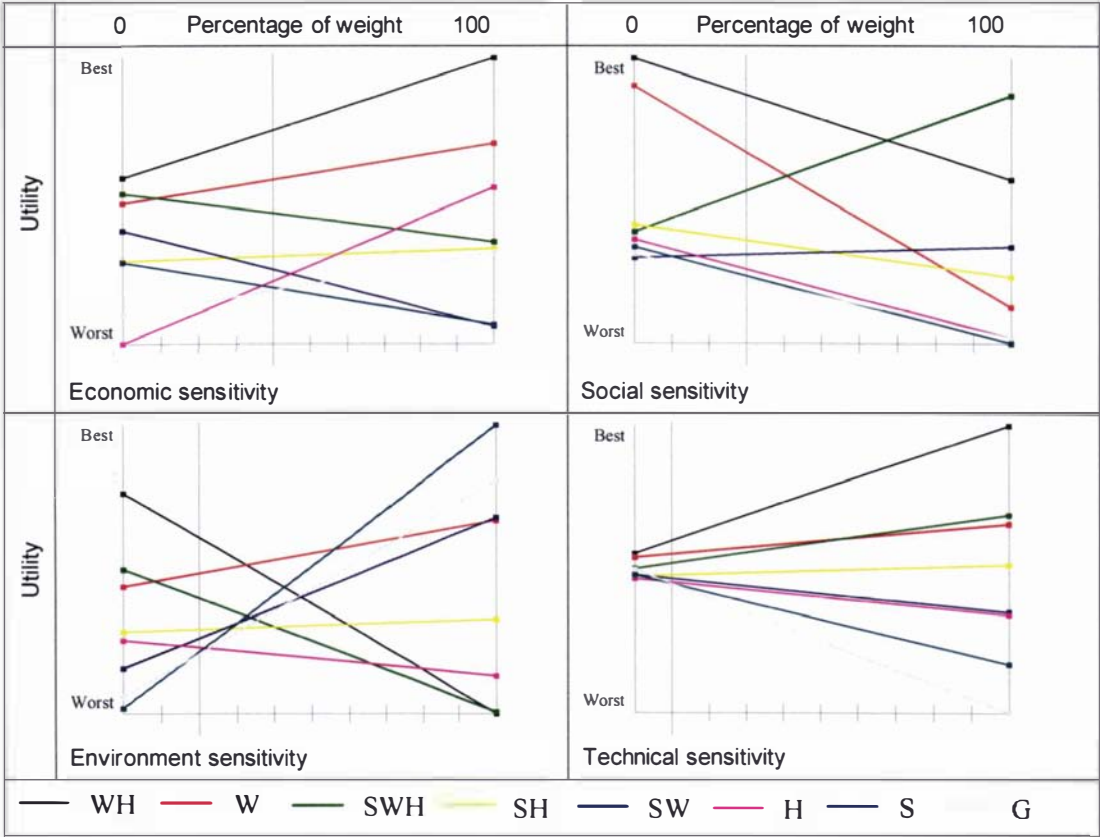


Figure 15.11 Short-term duration sensitivity graphs for the secondary goals using the *individual farm preference set* and the SMARTS method.

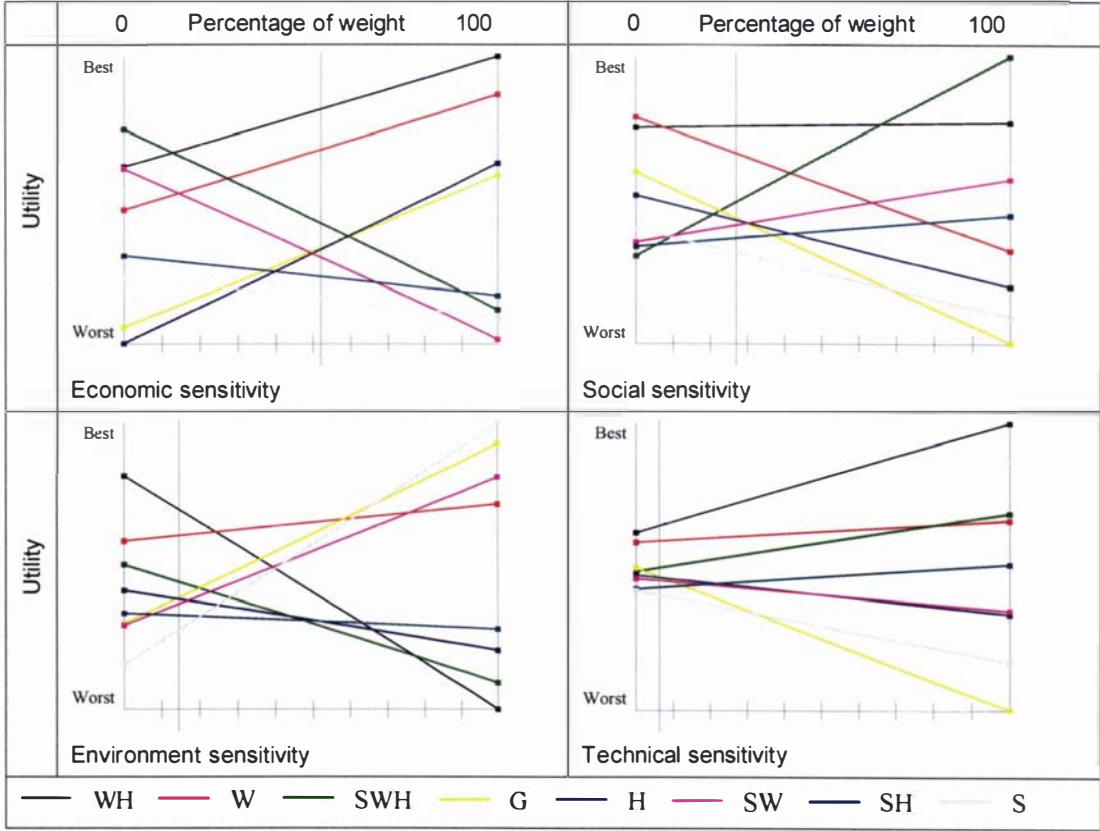


Figure 15.12 Short-term duration sensitivity graphs for the secondary goals using the *individual farm preference set* and the SMARTER method.

Appendix D

16 The Limestone Downs Case Study Site

This section expounds on the second case study site. This study was undertaken in parallel to the study at Totara Valley but was not utilised in the decision analysis study. It is presented in this section to present the valuable shearing shed electricity loads data obtained.

Limestone Downs, a large sheep and beef station, is located on the northern Waikato coastline approximately 120 kilometres south of Auckland (Figure 16.1). It is a 3,129 hectare (or 7,954 acres) sheep and beef station and carries a variable seasonally-dependant workforce, with a permanent staff of two shepherds and their families, a manager and family and up to three single shepherds. A large seven-stand shearing shed was the dominant feature of the commercial load at this site (Figure 16.2) and this forms the basis of this case study.



Figure 16.1 The location of Limestone Downs.

The electricity usage of several shearing sessions is presented in detail in Section 16.1. It includes unique measures of sheep farm energy use such as sheep shorn per kWh. This analysis led to the modelling of electricity loads for sheep shearing (Section 16.1.2). Another key task relative to sheep shearing is the 'maintenance' shear called crutching. This is the practice of clearing the wool from around the anus and tail area of the sheep in order to avoid excessive excrement build-up in the wool. Such a crutching session was monitored and the unique data is presented in Section 16.1.3. The solar and wind resources of Limestone Downs were monitored and the results are presented in Section 16.2.

16.1 The Electricity Load at the Limestone Downs Shearing Shed

At Limestone Downs, the shearing shed (Figure 16.2) was monitored using a Siemens S2A-100 single-phase meter on each of the individual shearing stands (Figure 16.3) and the wool press machine. Each shear session was monitored and the data recorded. The number of sheep shorn per session was noted in order to assess energy use per sheep. A Seaward MD300 three-phase meter was used to record the total shed demand simultaneously with the individual demands of the shearing machines and recorded the other shed loads.

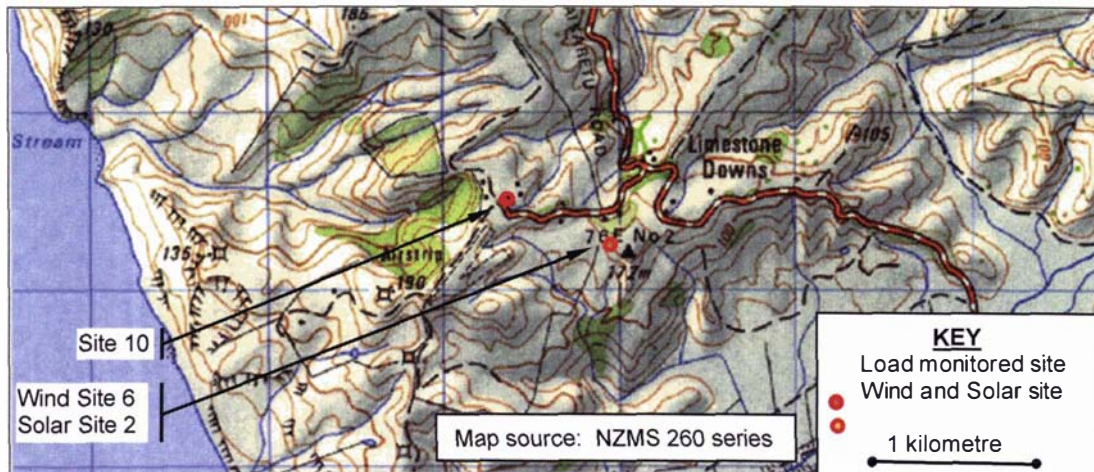


Figure 16.2 The Limestone Downs region and the shearing load site location.

The shearing shed at Limestone Downs is a large shed at seven stands, and provided a unique opportunity to monitor a the large number of sheep being handled (up to 10,000 ewes over a five-day period). The total load of the site was monitored from 7th October 2000 to 19th July 2001 inclusive using a Seawards MD-300 meter (Figure 16.3 B), while the seven individual shearing machine loads were monitored using individual Siemens S2A-100 meters mounted beside each shearing machine (Figure 16.3 A).

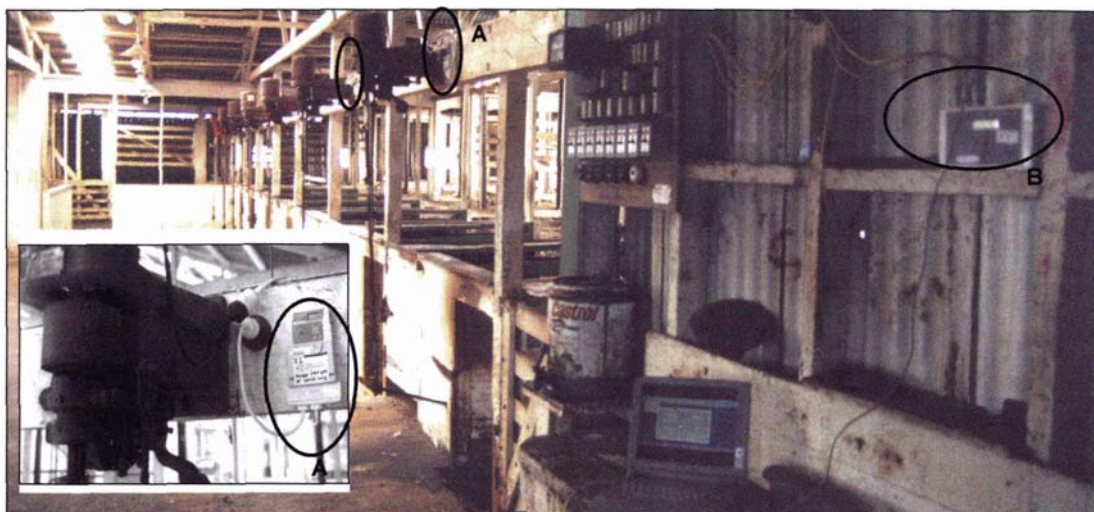


Figure 16.3 The shearing stand area showing the location of the meters.

16.1.1 The Sheep Shearing Electricity Load

The electric motors on stands one through to six had the nameplate rating of one half horsepower (3.6 Amps) but the nameplate rating of the electric motor on stand seven was 750

watts (5.2 Amps). The maximum electricity load for any one-hour period in the monitoring duration was noted (Figure 16.4) and indicated some of the very high individual hourly load levels evident through the duration of summer shearing and crutching (December 2000 – February 2001), and winter shearing.

The mean and standard deviation of the shearing shed profile (Figure 16.5 and Figure 16.6) showed three distinct shear periods, December 2000 to February 2001, and May – June 2001. The standard deviation and the coefficient of variation of the shearing shed load indicated a large variability about the mean (Figure 16.6 and Figure 16.7).

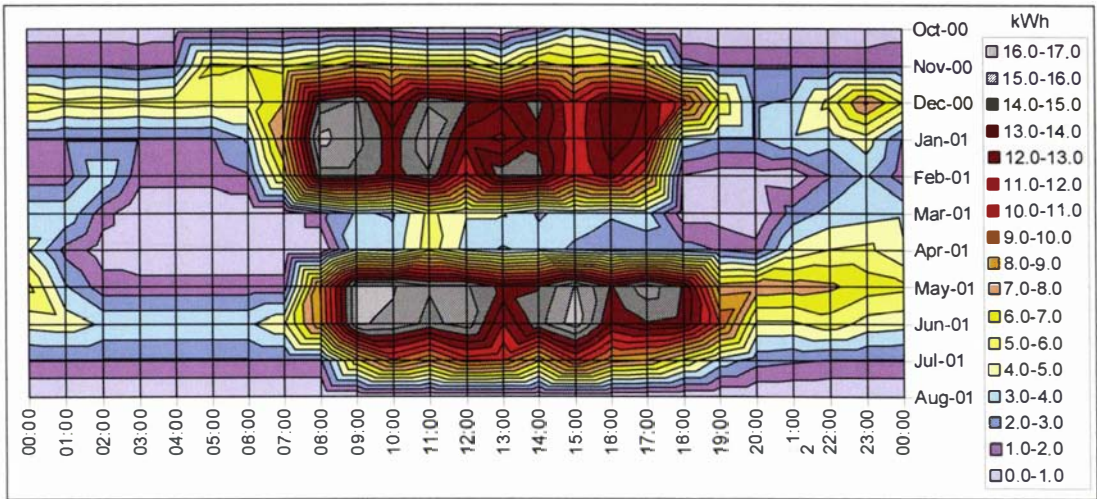


Figure 16.4 The maximum electricity use of any one hour in the months of monitoring.

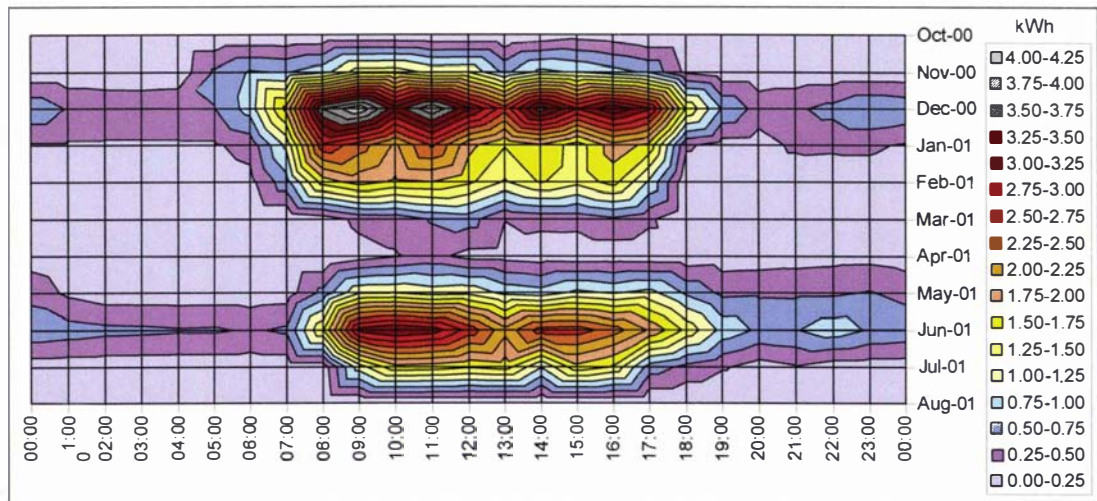


Figure 16.5 The mean diurnal – monthly shearing shed load profile.

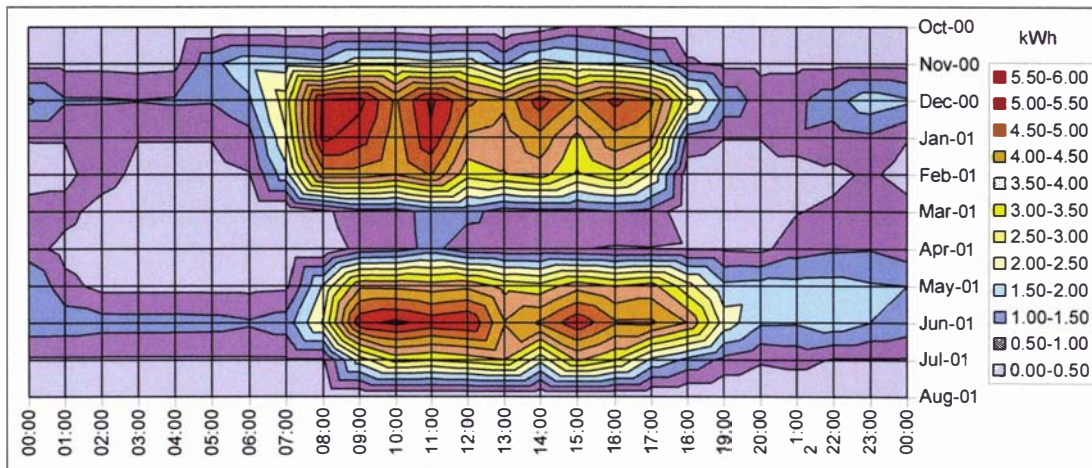


Figure 16.6 The standard deviation of the diurnal – monthly shearing shed load profile.

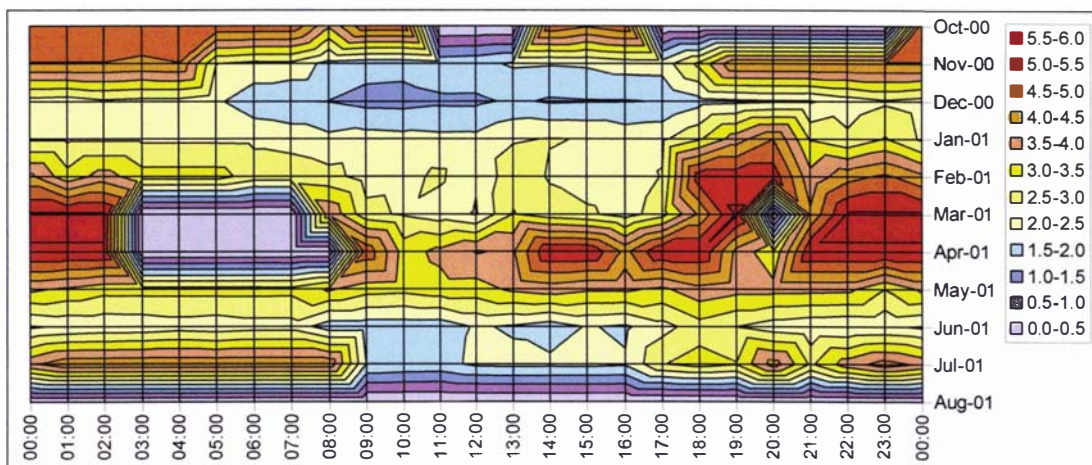


Figure 16.7 The coefficient of variation of the shearing shed load profile over the duration of monitoring.

16.1.2 The Sheep Shearing Load Model

The work of seven shearers at Limestone Downs was observed and closely monitored over a six-day period from the 11th to 17th December 2000. Over this duration, a high level of documented shearer output (sheep shorn) in conjunction with electricity use was recorded. The shearing work was broken by bad weather over this duration (12th December) so five days of shearing were recorded. From this, an analysis of the electricity load relative to the number and type of sheep shorn was conducted. A large level of variation of skills existed between the seven shearers ranging from the highly skilled (large turnover of sheep) through to the 'novice' (moderate numbers of sheep but large variability in this). The effect this and the electric motor size had on the electricity load levels was evident in the mean number of sheep shorn per shearer per shear session (Figure 16.8).

The mean number of sheep shorn by each shearer over each two-hour shear session varied over the five-day period (Figure 16.8). The numerical insert at the base of each column was the standard deviation of the mean number of sheep shorn per shearer per session. The high – low lines indicate the mean and standard deviation of the electricity used per session by each shearer. It should be noted that the shearing machine on stand seven was the bigger

motor and therefore had a higher level of energy consumption. It was also the stand used by the novice shearer so there was more variation in this.

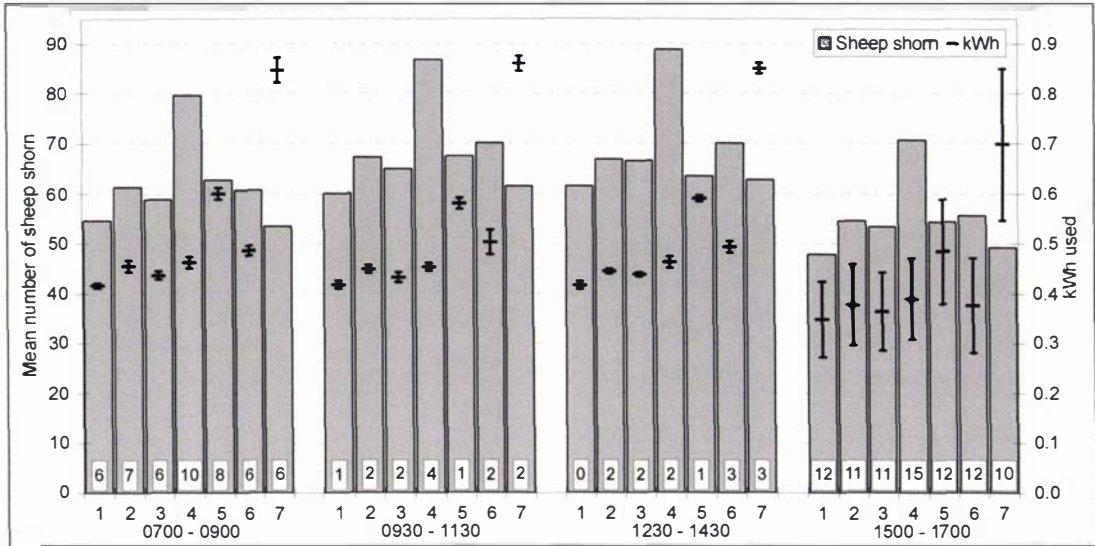


Figure 16.8 The mean number of sheep shorn per session over a five-day period, and the mean amount of electricity used ± 1 standard deviation.

A regression analysis of the data indicated each shearer's ability to work consistently through each session and provided a comparative analysis of the number of sheep shorn per kWh (Figure 16.9). The most experienced shearer used stand four, and the other stands were all approximately level with the number of sheep shorn. The effect of the larger electric motor being used by the novice shearer on stand seven can be seen clearly.

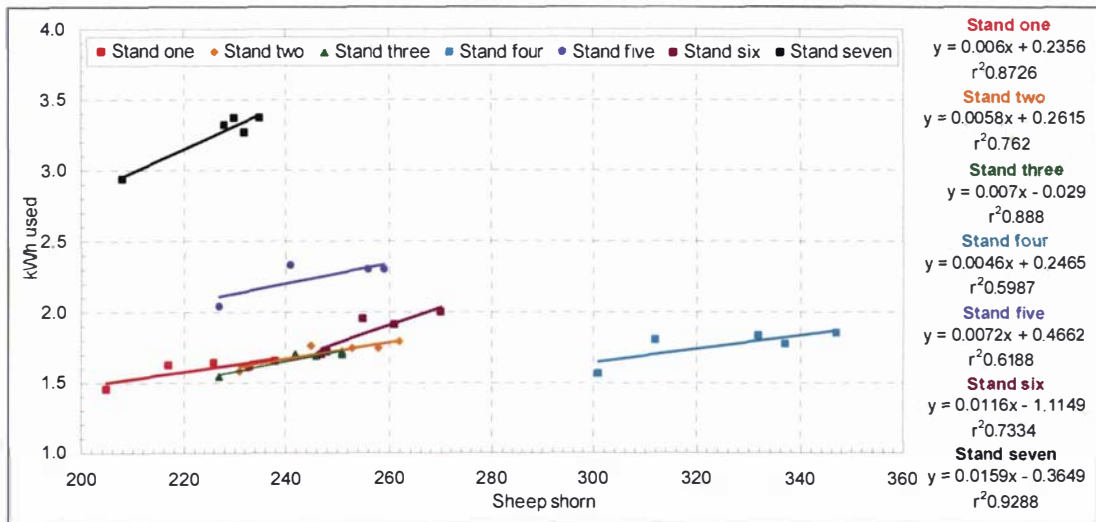


Figure 16.9 A regression analysis of the number of sheep shorn by each shearer each session and the amount of electricity used.

This analysis was continued to produce a model from which the amount of energy required to shear a given number of sheep could be estimated (Figure 16.10), if the skill level (equated by the number of sheep shorn per day) of the shearer was known and the size of the motor was similar to those used in this shearing shed.

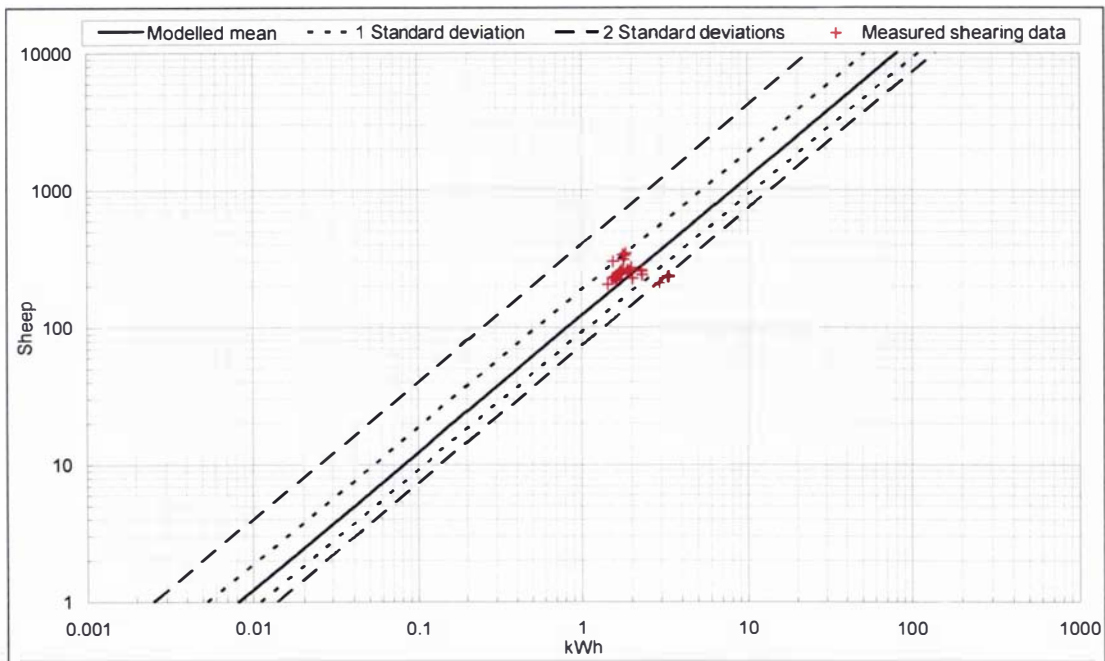


Figure 16.10 The modelled electricity requirement dependent on the number of sheep to be shorn.

16.1.3 The Sheep Crutching Electricity Load

The large variability observed in the shearing shed loads was due to shearer ability, shearing machine size and condition, wool length, and sheep age and size. This variability was evident again in the crutching data gathered over a three-day period from the 13th – 15th February 2001 when 10,000 ewes were ring-crutched²⁸. This analysis was to assess the number of sheep able to be crutched per kWh.

While the crutching took place over a three-day period, the second of the three days was disrupted due to the implementation of major electricity line refurbishment of the distribution network from 11,000 to 22,000 volts. The interruption to the power supply occurred on the second day of a three-day crutching period. Mid-way through the second day the existing power supply was interrupted, a large diesel generator was connected, and the shearing continued.

After the line voltage upgrade, there was a distinct reduction in the amount of energy used between day-one and day-three (Figure 16.11). This was assumed to be due to the increase of voltage quality as there had been issues with this in the past. This can be noted in this analysis where approximately the same numbers of sheep were crutched per day, but on day three, the number of sheep crutched per kWh has increased markedly.

²⁸ This action was to remove the wool from around the anus and tail area of the sheep to prevent a manure build-up. This is a common practice in order to avoid fly-strike.

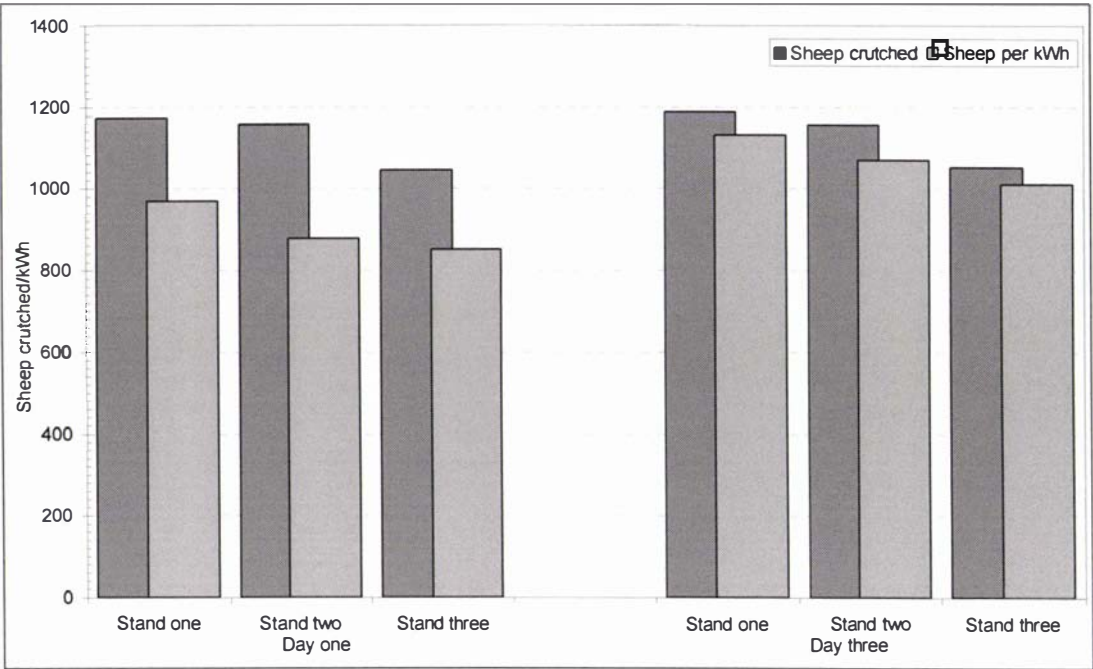


Figure 16.11 The numbers of sheep crutched and sheep crutched per kWh before and after a distribution network line upgrade.

The individual days crutching electricity use is given in Figure 16.12 to Figure 16.14. The transition day from 11,000 volts to 22,000 can be seen where a diesel generator supplied the load for part of the day in order to maintain a supply of electricity to the shearing shed.

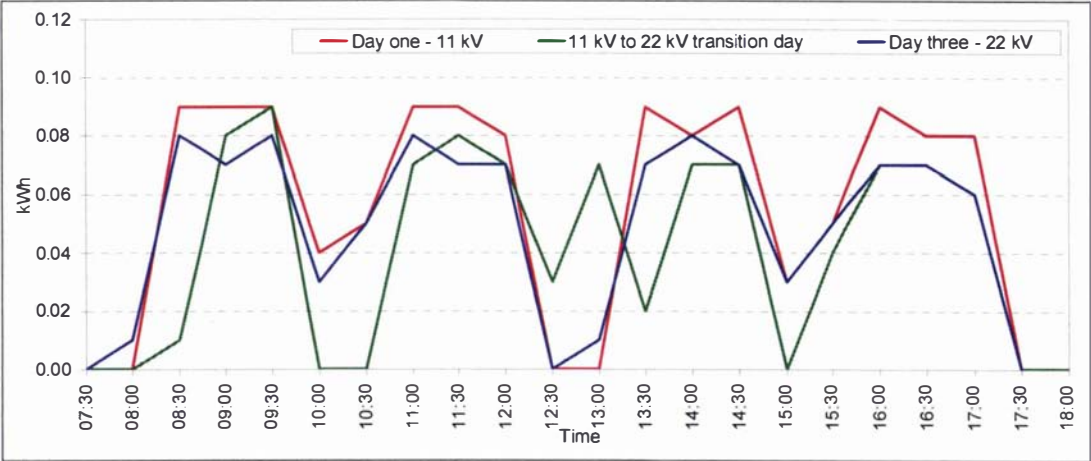


Figure 16.12 The mean electricity load profile for stand one crutching data with power supply voltage transition.

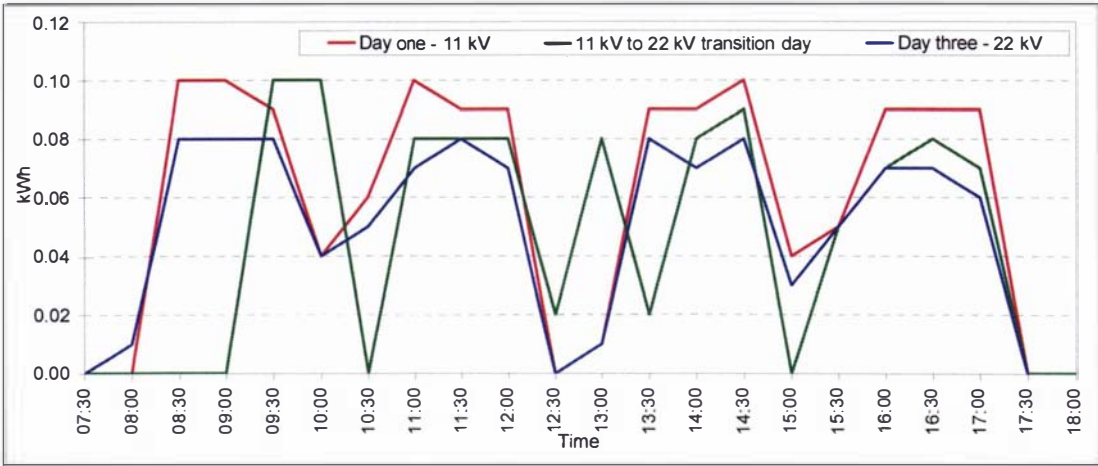


Figure 16.13 The mean electricity load profile for stand two crutching data with power supply voltage transition.

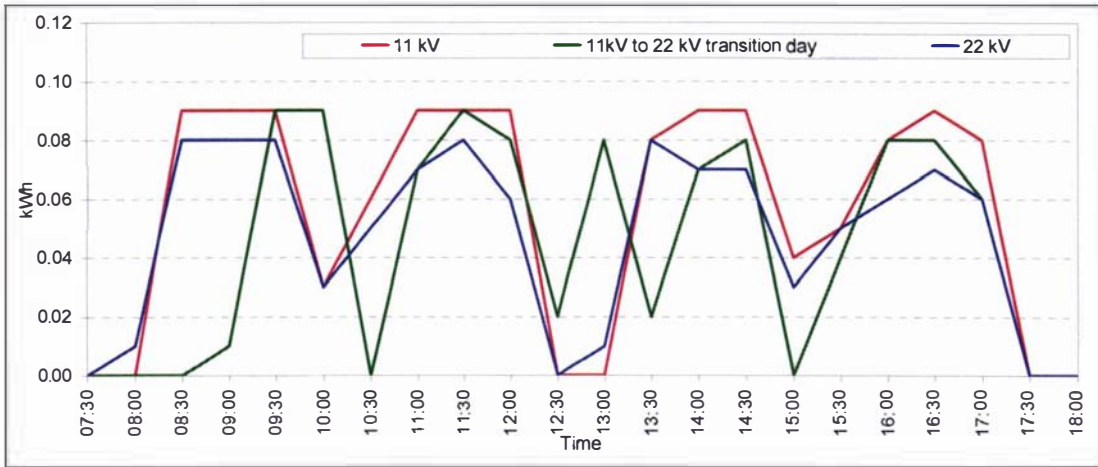


Figure 16.14 The mean electricity load profile for stand three crutching data with power supply voltage transition.

The crutching of a sheep required far less electricity than full shearing due to the smaller area of wool being removed and so the number of sheep crutched per session was accordingly a lot larger. This had the effect of requiring a smaller amount of electricity to be used. The mean and standard deviation of the number of sheep shorn and the mean and standard deviation of the energy required to do so in a two-hour period is given in Figure 16.15. The data shown is from four two-hour shearing sessions per day over a two-day period.

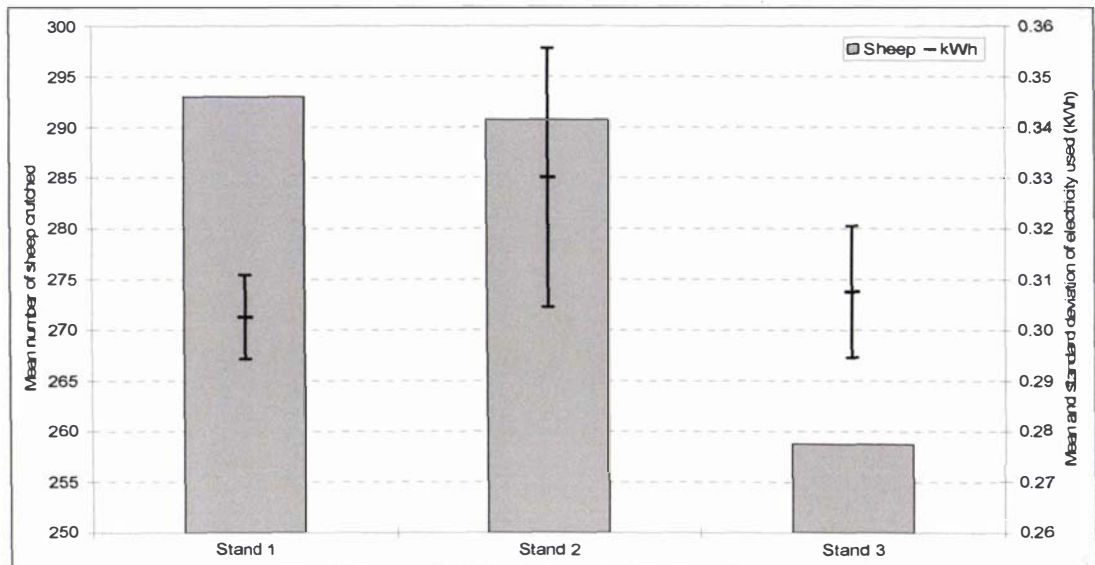


Figure 16.15 The mean numbers of sheep crutched per session, and the mean and standard deviation of the electricity used.

16.2 Limestone Downs Renewable Energy Resource Assessment

16.2.1 Wind Energy Resource Data

The renewable energy resources of wind and solar were monitored at Limestone Downs from 10th October 2000 to 21st October 2001. The site of the wind monitoring was approximately 600 metres south east of the shearing shed complex (Figure 16.16).

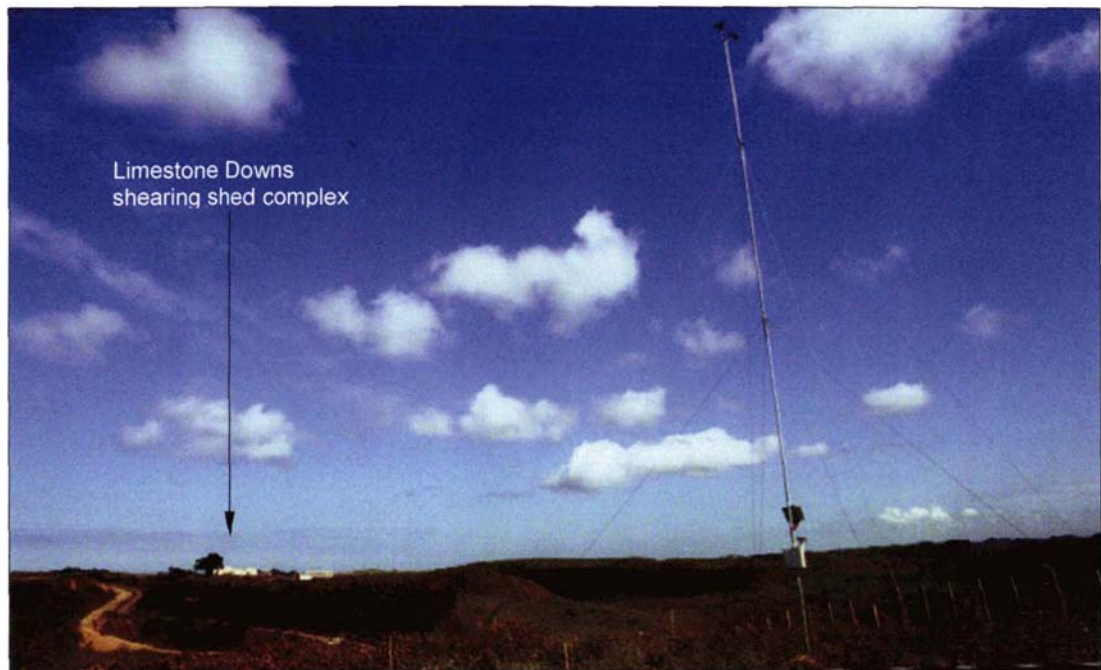


Figure 16.16 Limestone Downs shearing shed (background) and the solar and wind data logging site (foreground).

The windrose in Figure 16.17 indicates the predominant directions as being southerly and north easterly. The mean wind-speed of Wind Site 6 was 6.27 m/s over ten-minute averaging periods. The axial difference between colour-coded inner lines within the windrose

represents the duration of time (in multiples of ten minutes) at which the wind-speed was at the represented wind-speed from the direction indicated.

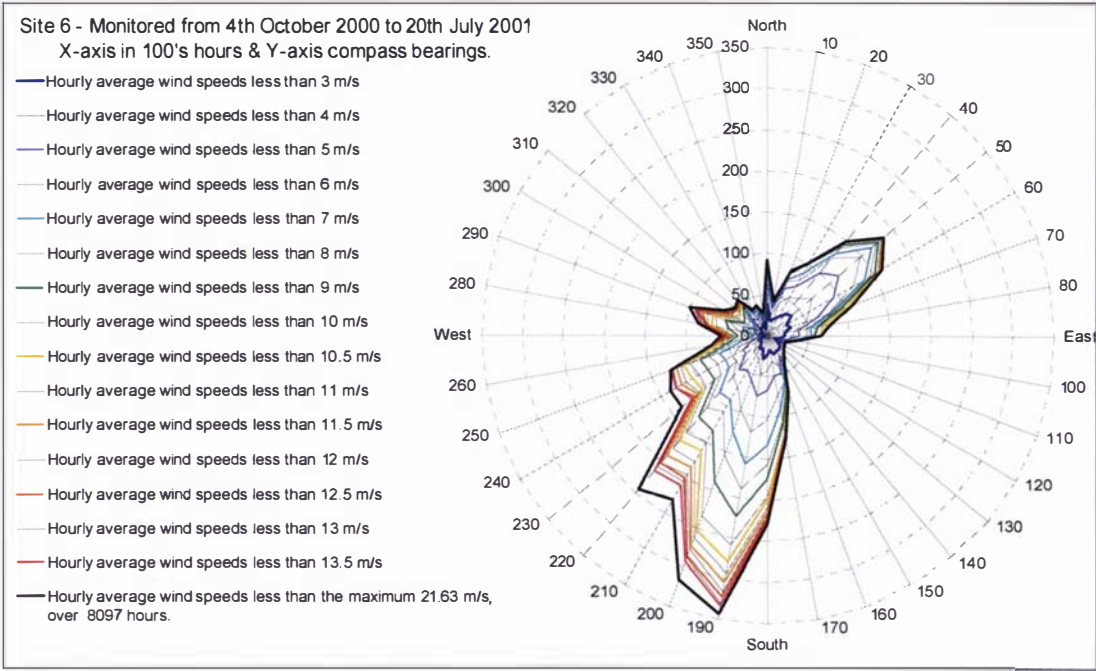


Figure 16.17 Limestone Downs ten-minute mean wind-speed windrose.

The hourly mean diurnal – monthly wind velocity patterns tend to show an increasing wind-speed through the day with the peak mean wind-speed occurring from 1300 hours to 1900 hours through most of the year (Figure 16.18). Five months exhibit obvious differences with March, June/July and September experiencing a distinctly lower mean diurnal wind-speed regime; and May, August, and October/November all having experienced higher mean wind-speeds.

The variation about the mean values is given as a standard deviation (Figure 16.19) and the coefficient of variation (Figure 16.20). In both plots, the afternoon throughout the year appears to be the duration of lower variation. The higher variation occurs in the early morning throughout the year, and in the late evening in March and April.

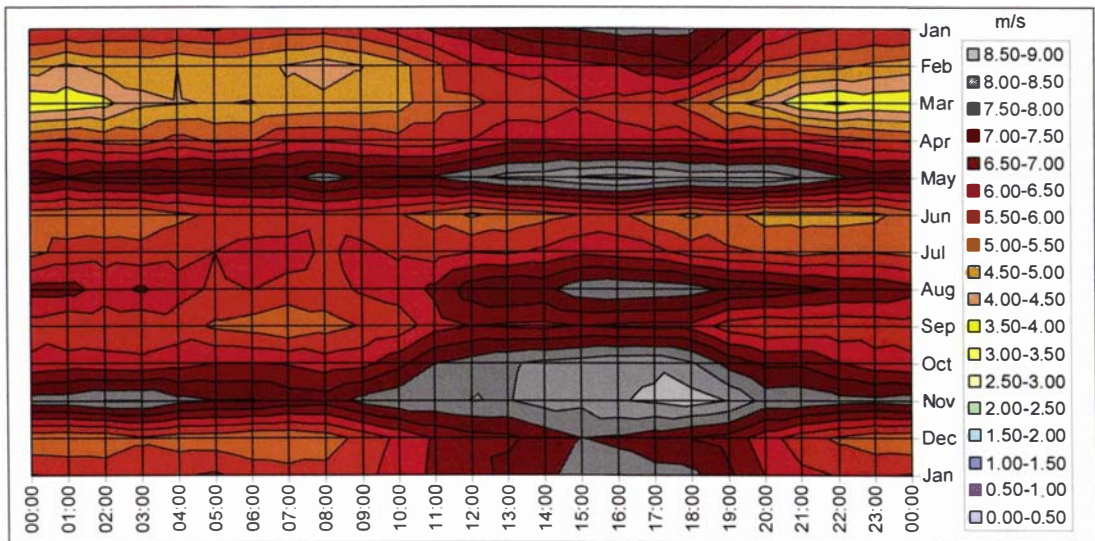


Figure 16.18 The mean hourly diurnal – monthly wind resource for Limestone Downs.

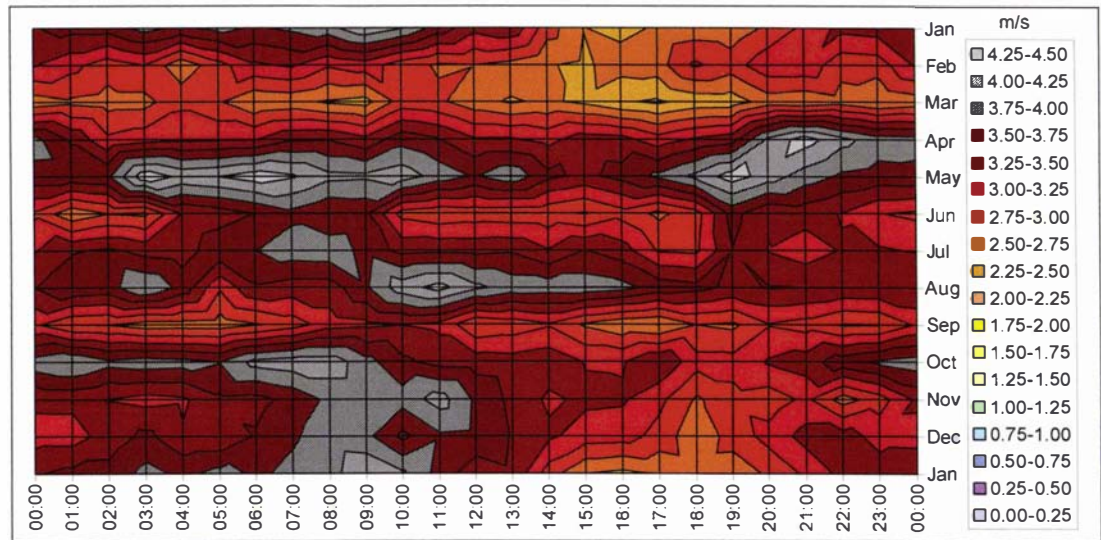


Figure 16.19 The standard deviation of the hourly diurnal – monthly wind resource for Limestone Downs.

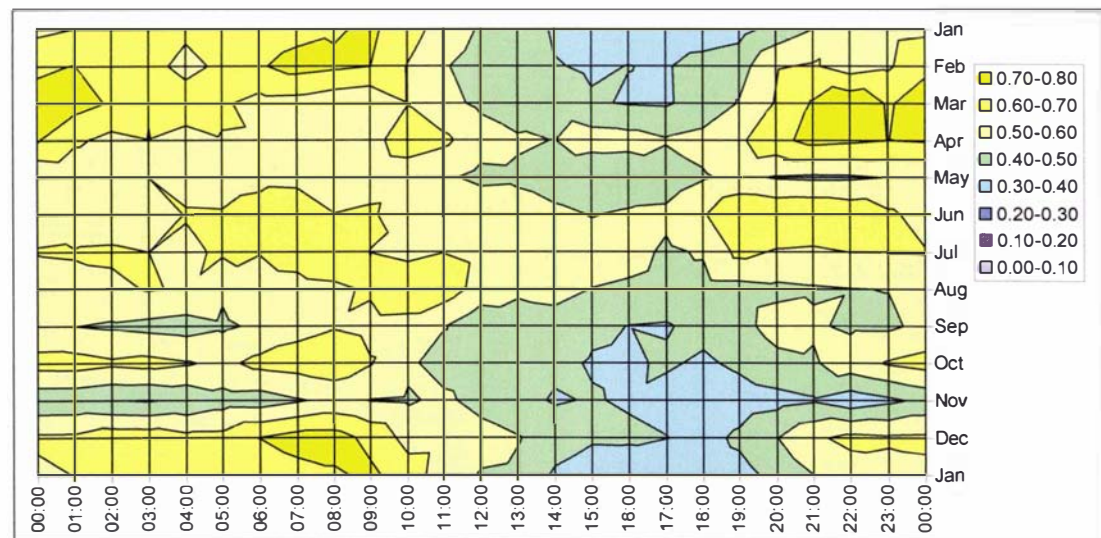


Figure 16.20 The coefficient of variation of the hourly diurnal – monthly wind resource for Limestone Downs.

16.2.2 Solar Energy Resource Data

The mean solar resource data of Limestone Downs (Figure 16.21) indicated an unusual seasonal solar insolation map over the winter period. This could be either an unusual solar insolation occurrence or a pyranometer malfunction apparent at times through the year. The mean peak solar insolation of between 550 – 600 W/m² occurred in January between 1300-hours and 1600-hours. The lowest mean winter peak is 250 – 300 W/m² and occurs between 1200-hours and 1500-hours in August/September. The month of May could have been affected by meter reading problems.

The standard deviation (Figure 16.22) and co-efficient of variation (Figure 16.23) provide an indication of the variation in the solar insolation. The co-efficient of variation is unfiltered in Figure 16.23, but has been reproduced to filter out the very high variation in the early morning and late evening period (Figure 16.24).

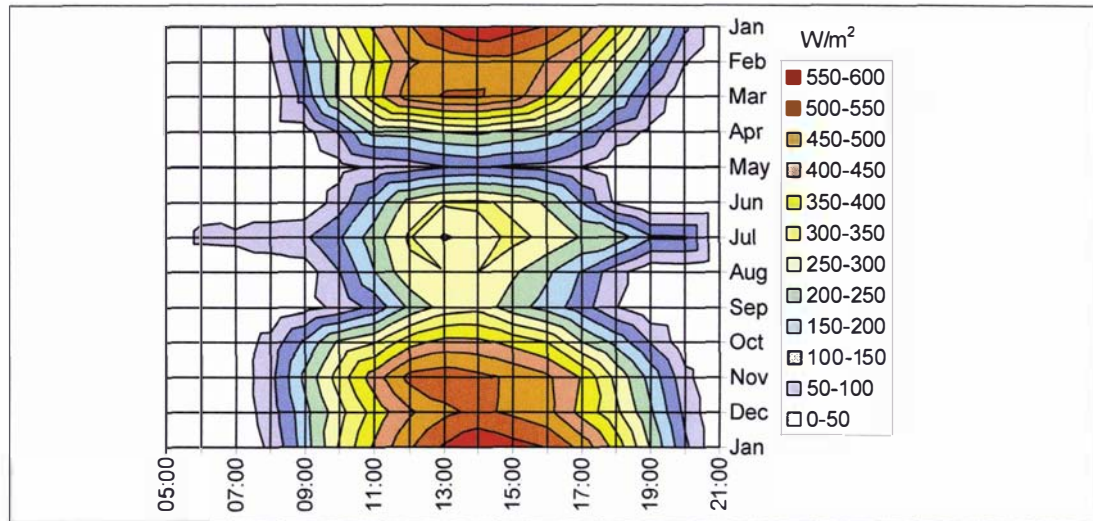


Figure 16.21 The mean hourly diurnal – monthly solar resource.

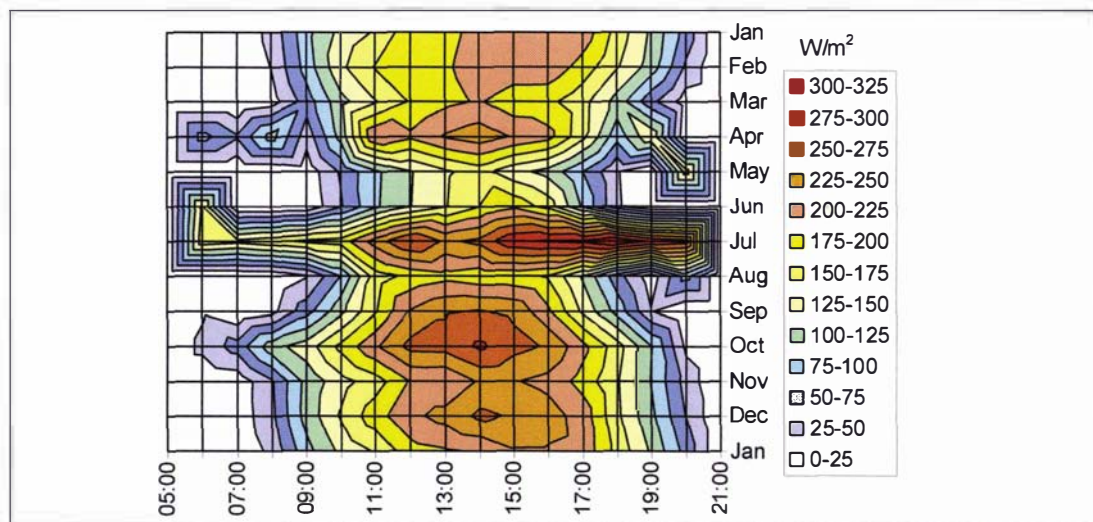


Figure 16.22 The standard deviation of the hourly diurnal – monthly solar resource.

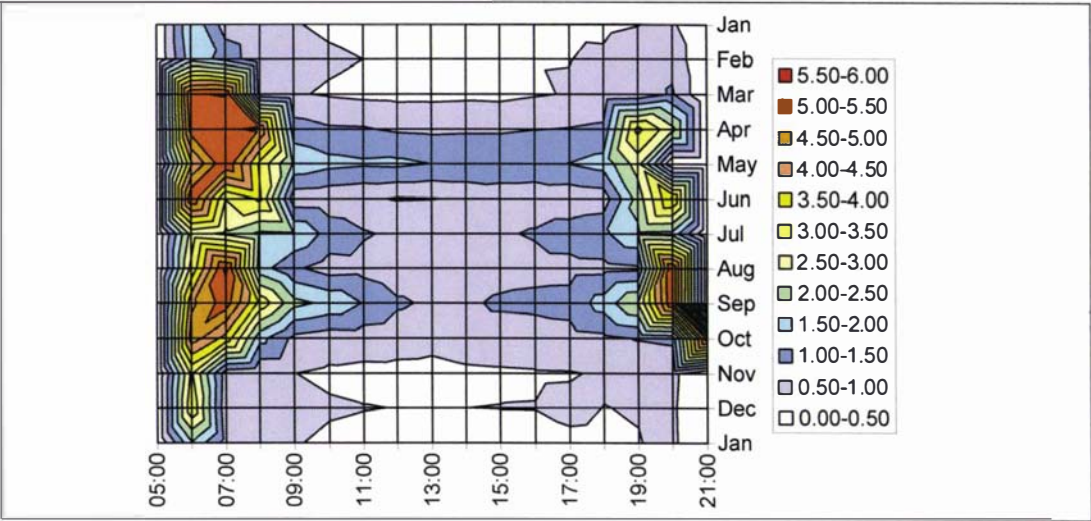


Figure 16.23 The unfiltered coefficient of variation of the hourly diurnal – monthly solar resource.

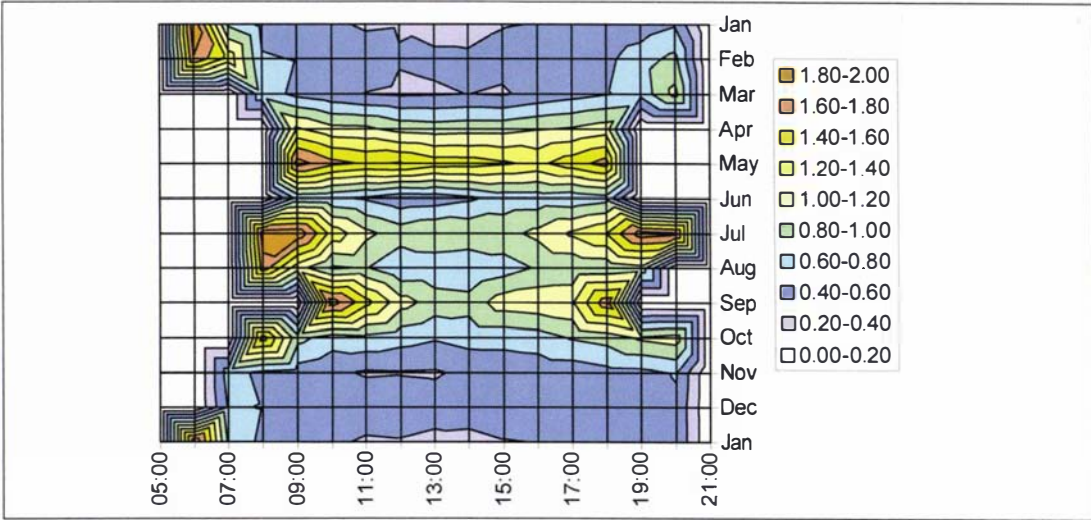


Figure 16.24 The coefficient of variation of the hourly diurnal – monthly solar resource filtered to exclude the very high variation above 2.0.

Appendix E

17 Aerial Photograph of Totara Valley

This photograph (Figure 17.1) is the master copy of many of the small photographs as seen in the text.

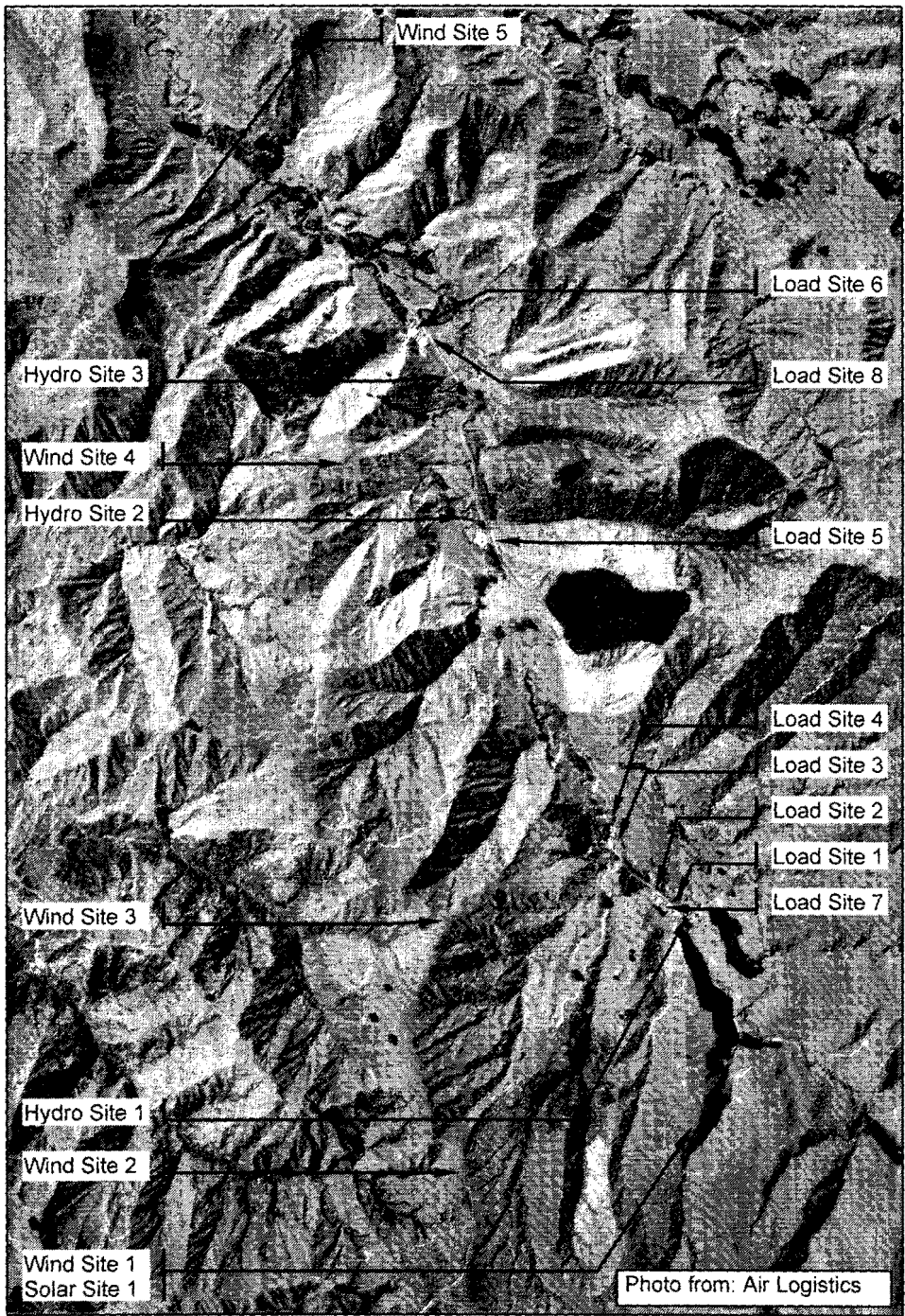


Figure 17.1 Totara Valley aerial photo indicating all resource and load sites locations of interest.

Appendix F

18 Electricity Load Profile Data

This section contains both community and individual electricity load material supplementary to Chapter 6 and 9, and details the individual loads that comprised the community load. A breakdown of the community load profile into domestic (no farm loads) and water heating is given in Section 18.1. The individual sites are presented in Section 18.2. The results from the short-term duration analysis of the electricity loads are given in Section 18.3, and include:

- the daily and hourly statistics of the monitored duration (section 18.3.1),
- a cumulative daily mean electricity load analysis (section 18.3.2), and
- an hourly cumulative mean electricity load analysis (section 18.3.3).

18.1 Electricity Load Profiles – Totara Valley Community

The mean domestic load profile (Figure 18.1) revealed a seasonal trend, peaking at 1900 hours in the winter evenings at the mean level of 7 kWh. The mean base load appeared to be up to 1 kWh with a slight increase in the winter months up to 2 kWh. The standard deviation and the coefficient of variation of the domestic loads (Figure 18.2 and Figure 18.3) indicated the levels of variation of the mean loads, with the highest variation apparently in the July – August period when people took their holidays. There was a period of suspected voltage anomalies in November 1999, which was indicated by a large level of variation (Figure 18.3). The other period of high variation was from December 2000 onwards when the rate of data downloading slowed as noted in the data solidity (Figure 18.4).

The mean water-heating load for the community illustrated the 'ripple' control of the water-heating load over the summer months of November 1999 to February 2000 (Figure 18.5). Of note was the high level of electricity used after the 'ripple' control turned the water heating back on. The levels of variation about the mean again indicated the suspected voltage anomaly (Figure 18.6 and Figure 18.7). The data solidity of the water heating loads as profiled is given in Figure 18.8.

The farm electricity load (Figure 18.9) indicated the shearing shed and freezer shed loads from Farm 1 and 3, and the workshop load of Farm 2. The January shearing profile was clearly visible but the July shear was only notable in the plotted standard deviation (Figure 18.10). The coefficient of variation (Figure 18.11) indicated a slightly higher variation over the shearing durations. The very high levels of variation from December 2000 stemmed from low levels of data monitoring and data collected seen as a low level of data solidity (Figure 18.12).

18.1.1 Community Domestic Load Profile Only

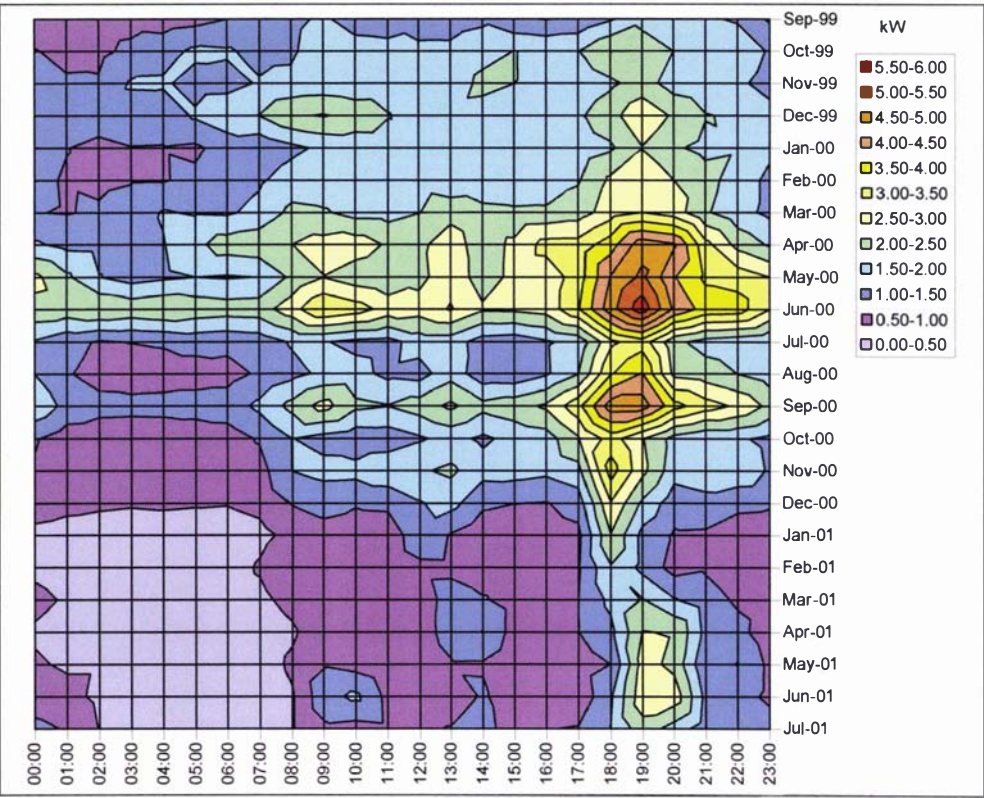


Figure 18.1 The mean monthly – diurnal domestic load profile over the duration of the monitoring for the whole community.

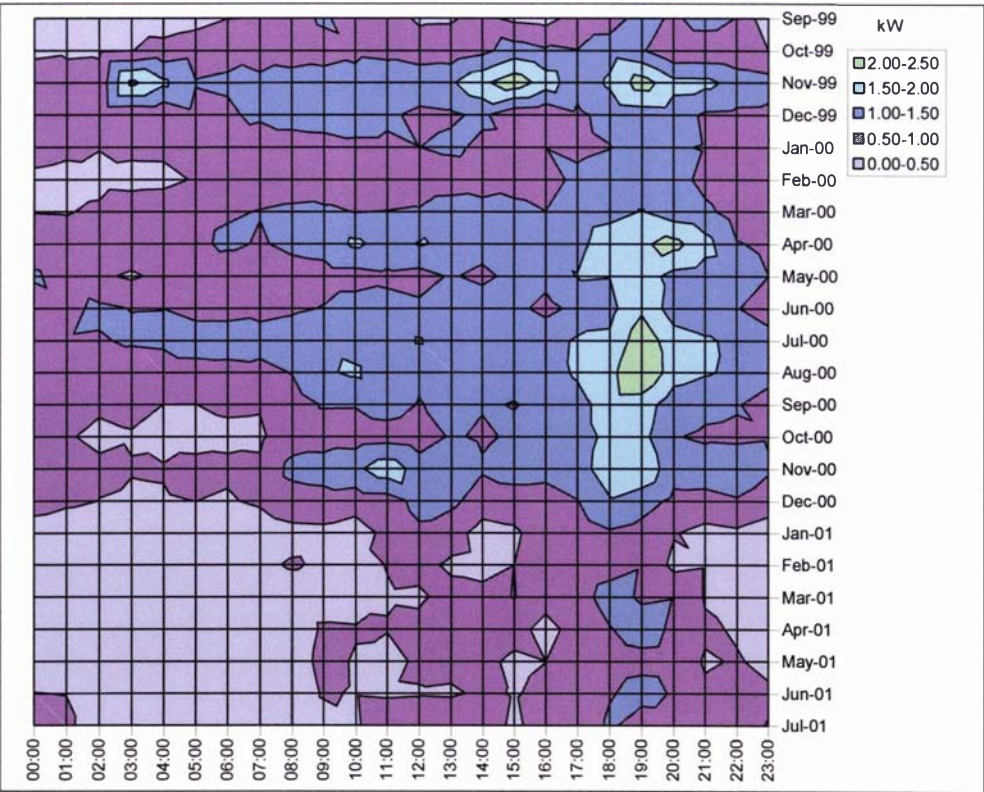


Figure 18.2 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for the whole community.

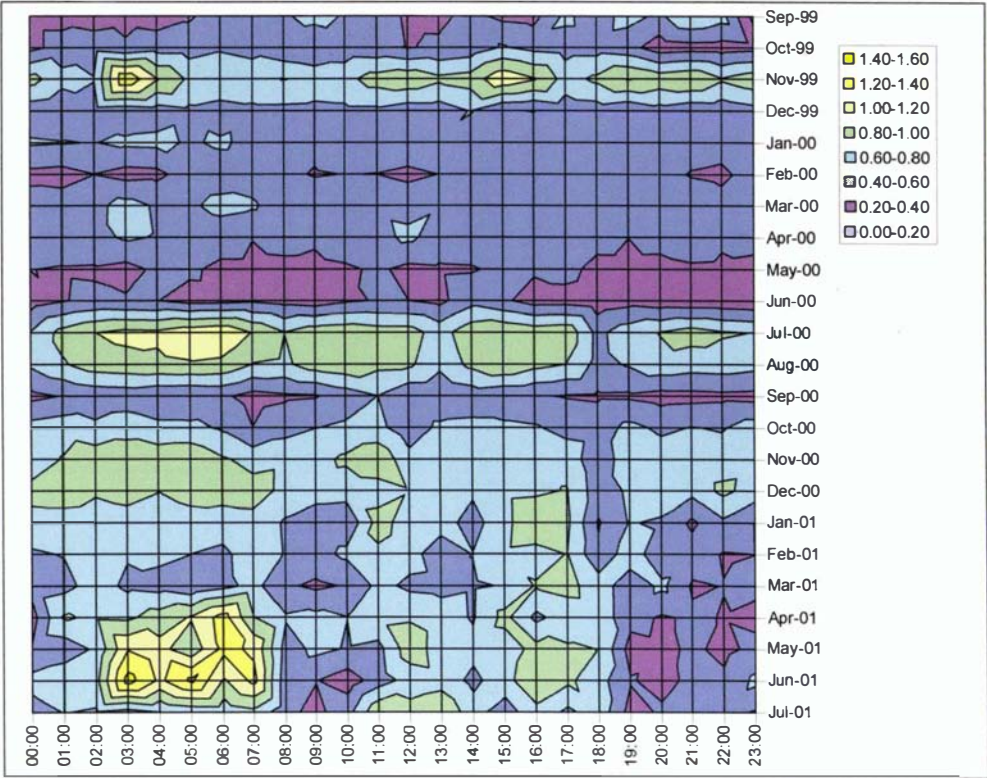


Figure 18.3 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for the whole community.

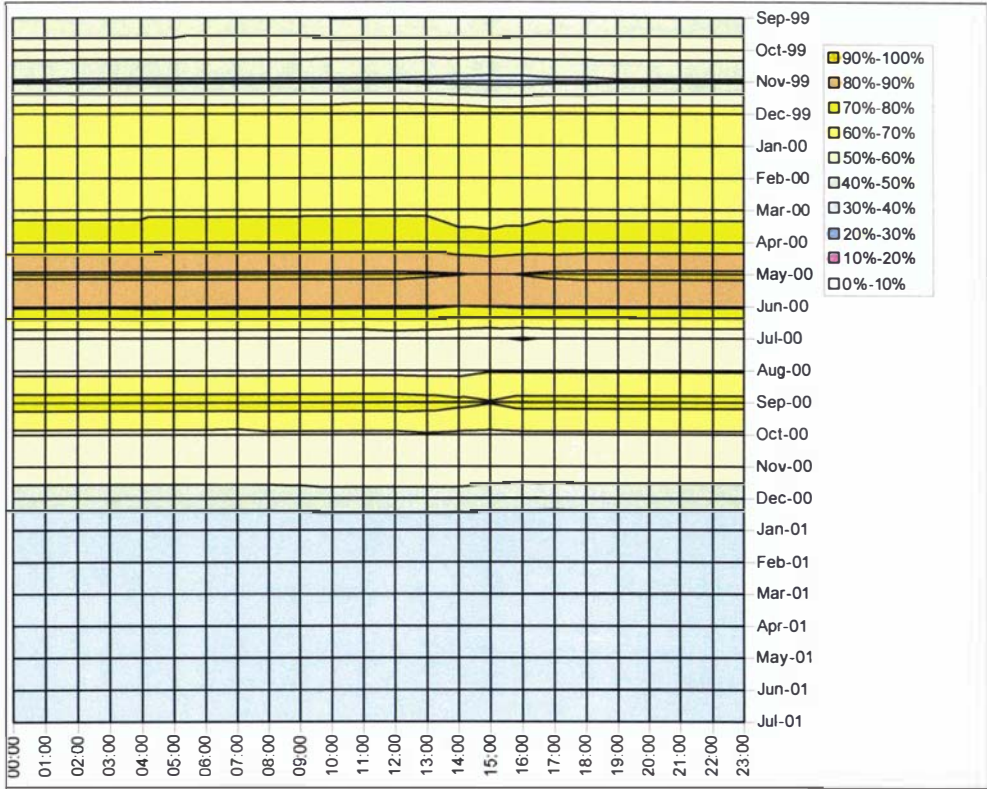


Figure 18.4 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for the whole community.

18.1.2 Community Water Heating Load Profile Only

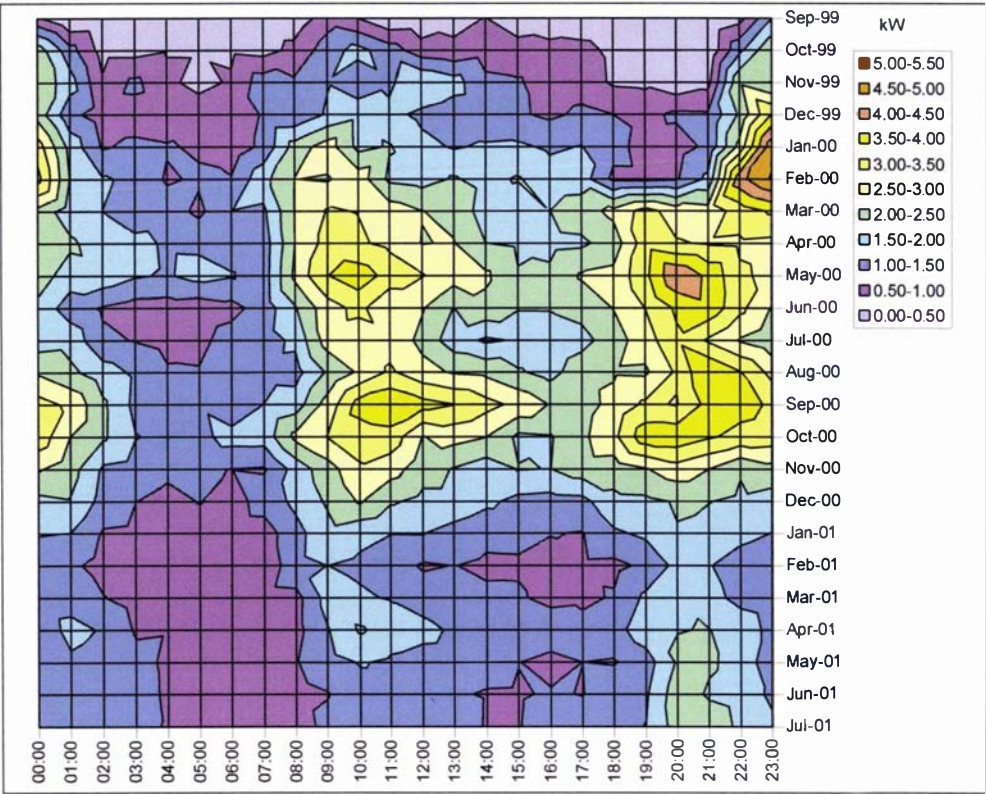


Figure 18.5 The mean monthly – diurnal water heating load profile over the duration of the monitoring for the whole community.

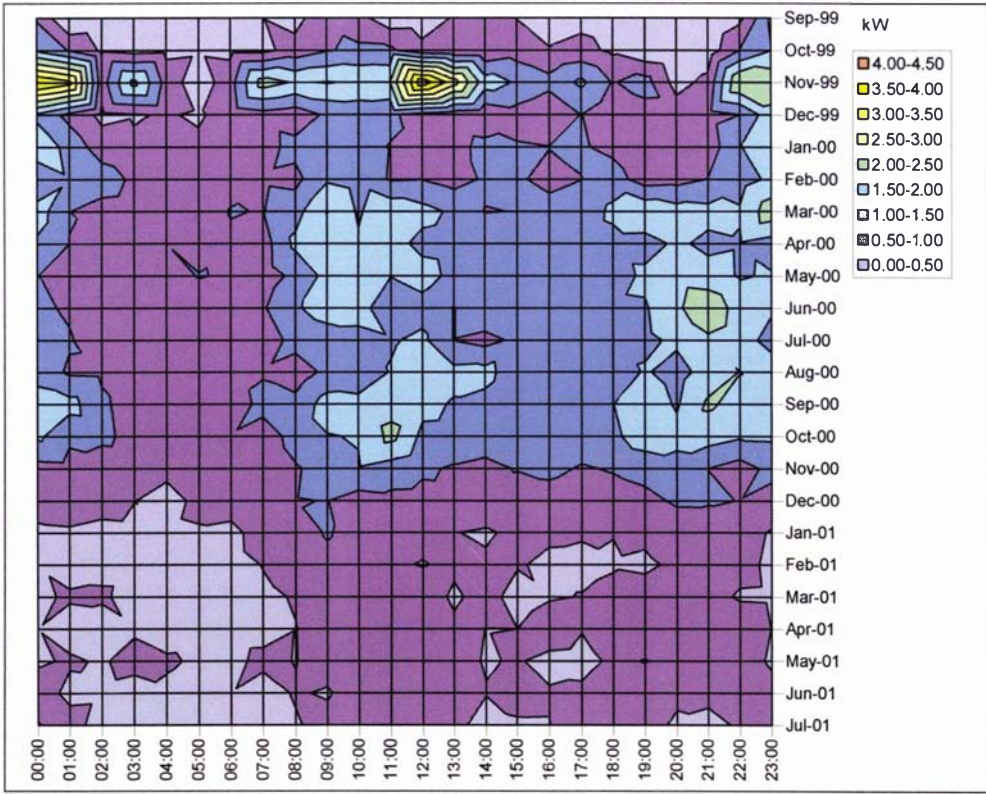


Figure 18.6 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for the whole community.

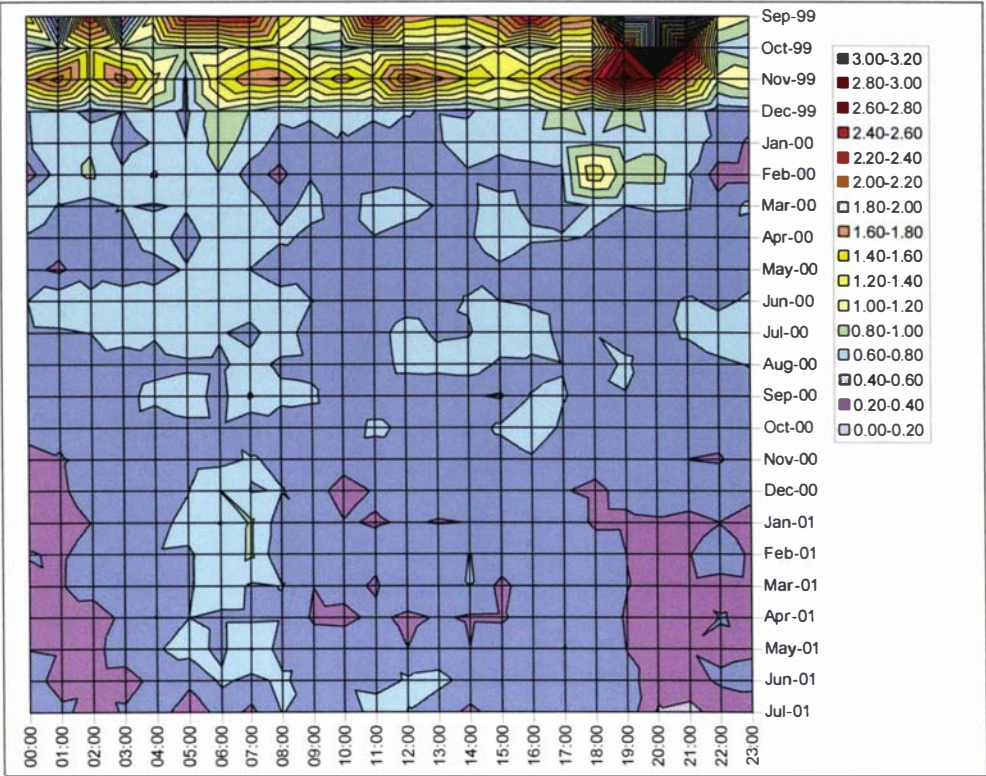


Figure 18.7 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for the whole community.

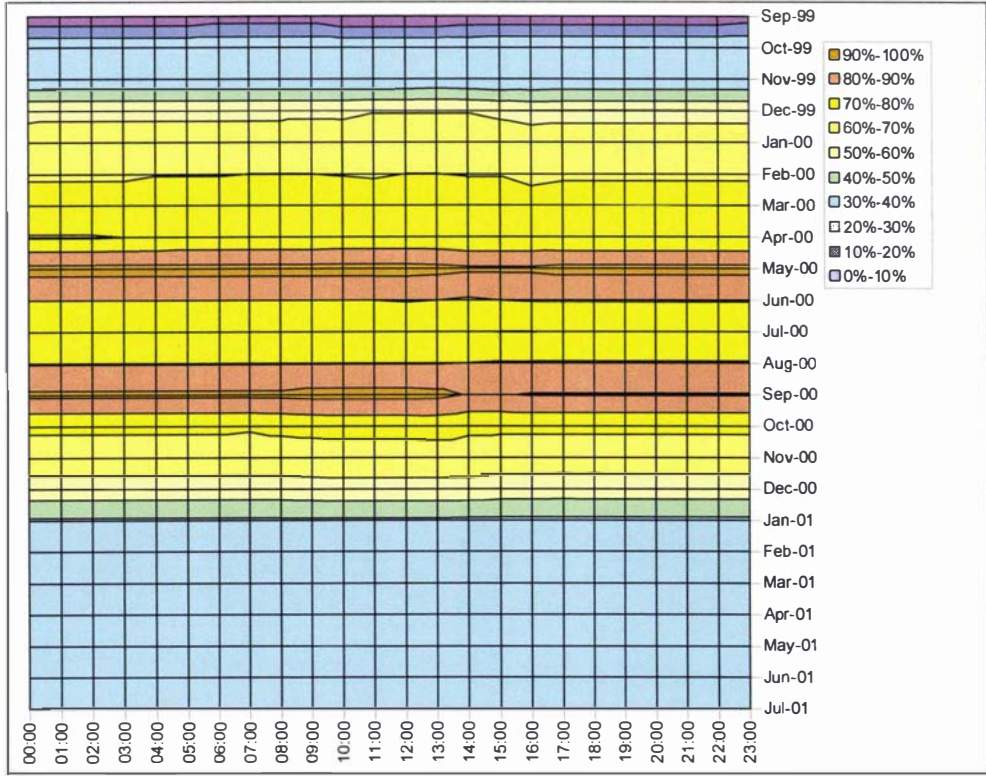


Figure 18.8 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for the whole community.

18.1.3 Community Farm Load Profile Only

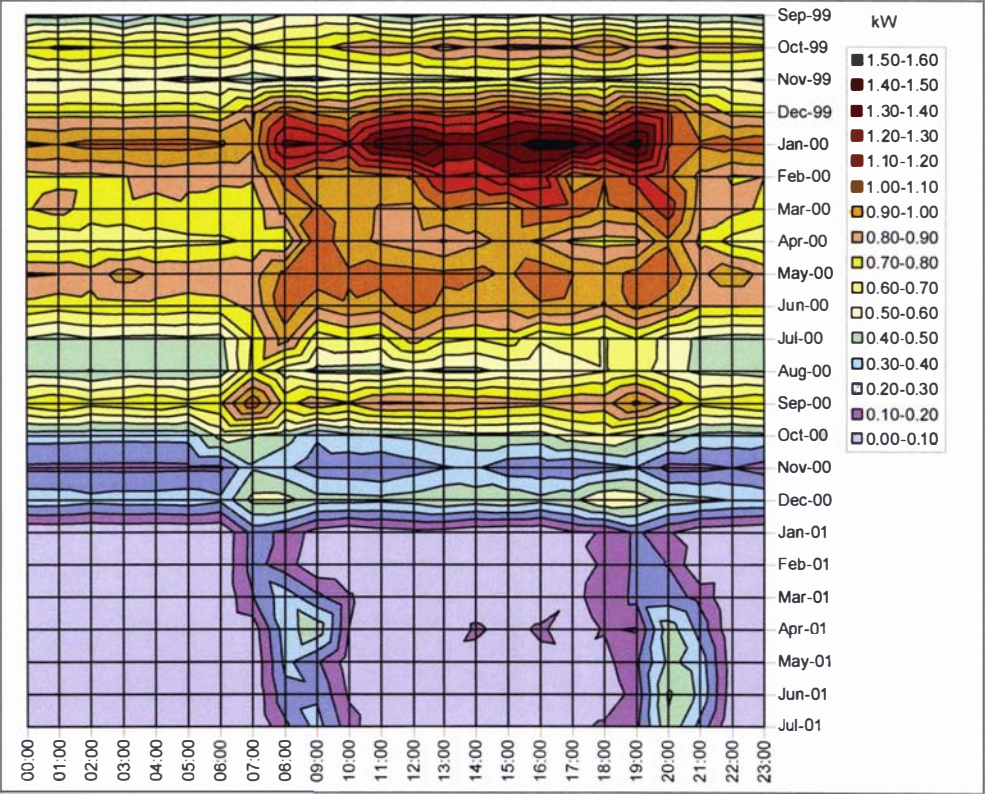


Figure 18.9 The mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for the whole community.

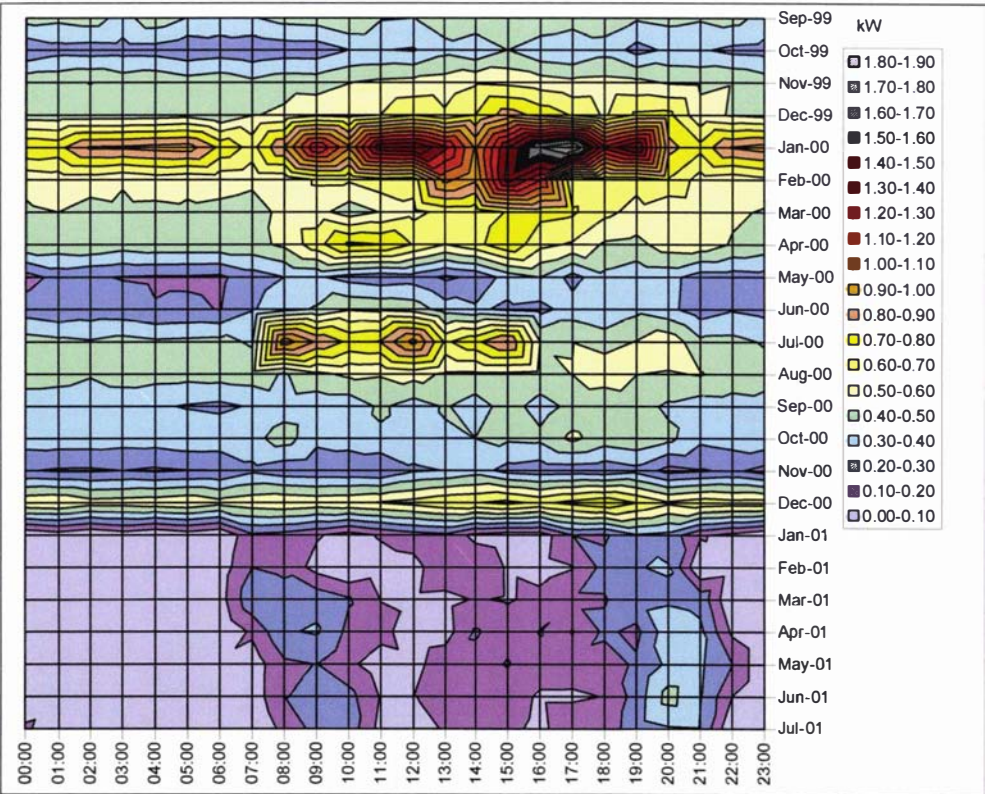


Figure 18.10 The standard deviation of the mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for the whole community.

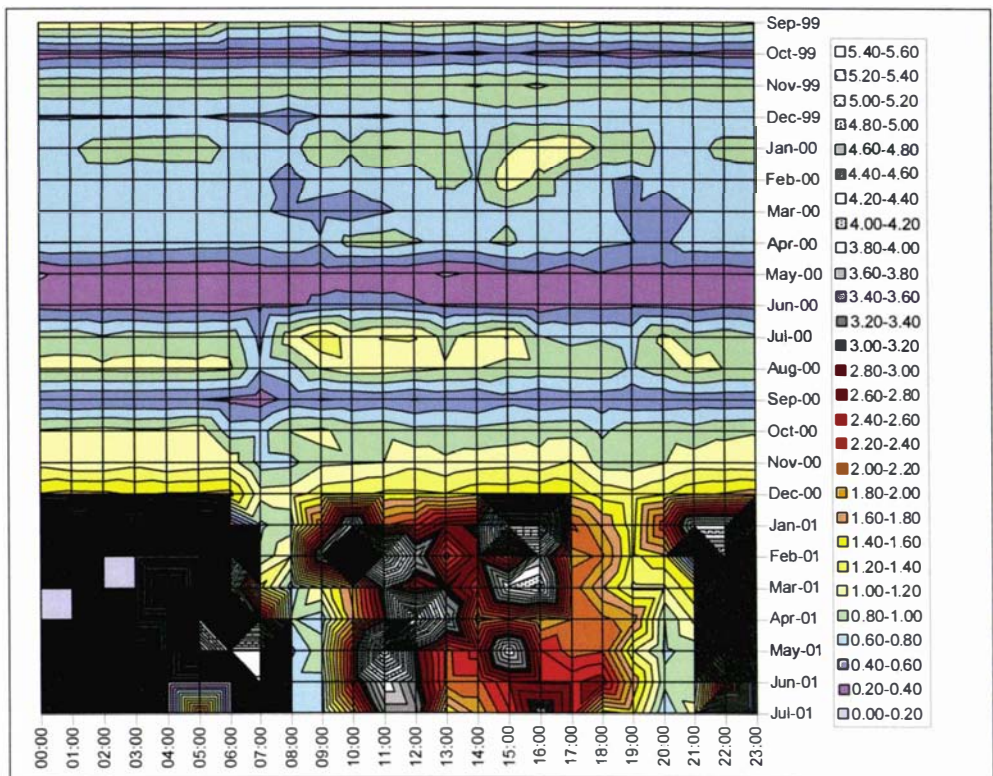


Figure 18.11 The coefficient of variation of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for the whole community.

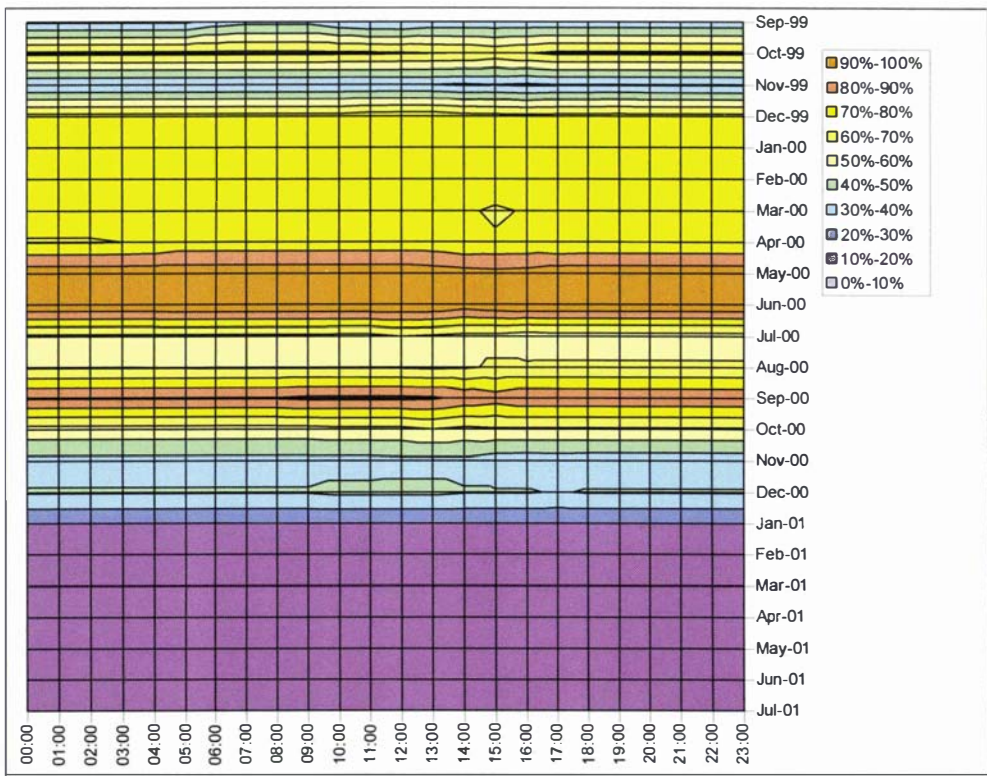


Figure 18.12 The data solidity of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for the whole community.

18.2 Electricity Load Profiles – Individual Sites

This section should be read with Chapter 6. The electricity loads for Sites 1 to 8 are presented separately as plots of mean diurnal – monthly energy use magnitudes (kWh), standard deviation, coefficient of variation, and data solidity (Figure 18.13 to Figure 18.112). A general feature of the load profiles presented in this section was the presence of a large level of variation in some of the loads, and an episode of ‘ripple’ control for the water heating loads. Voltage quality was not assessed at the time of monitoring and so the cause of the large variations in November 1999 has been assumed to be from a voltage anomaly. This was visible in the monitored loads for Site 3 (Figure 18.39), Site 5 (Figure 18.67 and Figure 18.71), and Site 6 (Figure 18.77). ‘Ripple’ controlled water heating was clearly seen in Site 1 (Figure 18.21), Site 3 (Figure 18.45), Site 5 (Figure 18.73), and Site 6 (Figure 18.85). Metering problems are presented in detail in tabular form in section 18.2.9.

The loads of Site 1 (Figure 18.13 to Figure 18.24) were monitored from September 1999 to December 2000 using three Siemens S2A-100 meters. The combined domestic and water heating electricity loads for Site 1 indicated a non-regular late morning and early evening peak (Figure 18.13). The occupant of Site 1 left for holidays during July and August 2000 and the subsequent effect of this on the combined profile can be noted (Figure 18.13). This can also be seen in the domestic only profile (Figure 18.17) where the remaining load could be considered base load, in the coefficient of variation where the level of variation was clearly higher (Figure 18.19), and in the data solidity where it was lower due to a lower level of monitoring (Figure 18.20). The combined mean profile of Site 1 (Figure 18.13) indicates not only a lower summer and a higher winter diurnal profile but also an hourly trough throughout the year between 1500 – 1800 hours. The very high levels of load in the September 1999 to January 2000 2100 – 0100 hours was due to the water heating load being turned on again after being off through ‘ripple’ control mechanism. This is clearly seen in Figure 18.21.

The loads of Site 2 (Figure 18.25 to Figure 18.36) were monitored from September 1999 to July 2001 using one Seaward MD-300 meter. However, due to metering problems, data could only be retrieved from the meter from April 2000 to July 2001. The occupants of Site 2 took their holidays in June 2000, and this can clearly been seen in Figure 18.25, where the base load only is visible. The midday and evening peaks are very clear in the domestic only profile where the cooking loads and (in the evening) the lighting loads prevail (Figure 18.29). The water heating load peak occurs very late in the night between 2300 and 0200 hours. This period also displays a very low level of variation (Figure 18.35).

The Site 3 loads (Figure 18.37 to Figure 18.48) were monitored from different start dates due to metering problems (section 18.2.9). The domestic loads were monitored from October 1999 to November 2000 using two Siemens S2A-100 meters. The water heating load was monitored from January 2000 to October 2000 using a Seaward MD-300 meter. Despite the setback of metering problems, the profiles from the monitoring still indicated distinct patterns of use. The predominant domestic peak occurred in the evening through winter (Figure 18.41), while the water heating peaks occurred progressively later in the morning and evening, with a

diurnal trough occurring through winter due to the solid-fuel wood burner displacing the electricity (Figure 18.45).

The Site 4 loads of domestic, water heating and farm workshop were monitored from December 1999 to July 2001 (Figure 18.49 to Figure 18.64), using one Seaward MD-300 meter. This meter was the most reliable of the Seaward meters used at Totara Valley. Accordingly, there was an unbroken level of data recorded (Figure 18.52), and this clearly indicated a very regular pattern of use. It was interesting to note the change in the water heating load profiles from November 2000 onwards with the arrival of a baby into the household (Figure 18.57).

The loads of Site 5 (Figure 18.65 to Figure 18.76) were monitored from September 1999 to December 2000 using two Siemens S2A-100 meters. The combined load indicates a variation in the load profile from July 2000 onwards with a distinctly lower level of electricity use (Figure 18.65). This was also reflected in the higher coefficient of variation levels of the domestic load profile (Figure 18.71) and the data solidity of this period for both domestic and water heating loads (Figure 18.72 and Figure 18.76). This lower profile resulted from the residents being away for various lengths of time, seen in the higher variation of the domestic load but not the water heating, which remained turned on though the absences.

The Site 6 loads of domestic and water heating were monitored from September 1999 to December 2000 (Figure 18.77 to Figure 18.88), using three Siemens S2A-100 meters. These combined profiles indicate a very regular seasonal pattern with high morning and evening electricity levels recorded in the winter months of May and June with a tapering profile either side of this period. This is also seen in both the domestic profile (Figure 18.81), and the water heating profile (Figure 18.85).

The shearing shed and freezer shed loads of Site 7 were monitored from September 1999 to December 2000 (Figure 18.89 to Figure 18.100), using four Siemens S2A-100 meters. The Site 7 shearing shed was not only used for shearing with farm equipment maintenance work being undertaken using the electricity from this site also. Farm equipment like electric fence energisers were also run from this site. January, May and September were the months that displayed variability associated with shearing loads (Figure 18.95). The freezer shed indicated a regular pattern of use.

The shearing shed and freezer shed loads of Site 8 were monitored from September 1999 to December 2000 (Figure 18.101 to Figure 18.112), using three Siemens S2A-100 meters. The shearing shed of Site 8 was solely used for shearing and there were no other loads from this site. The shear periods were in January and July (Figure 18.105). The freezer shed loads indicated a higher level of use and some of these load levels were from farm maintenance work from this site.

18.2.1 Site 1 – Electricity Load Profiles

Site 1 Domestic and Water Heating Load Profiles

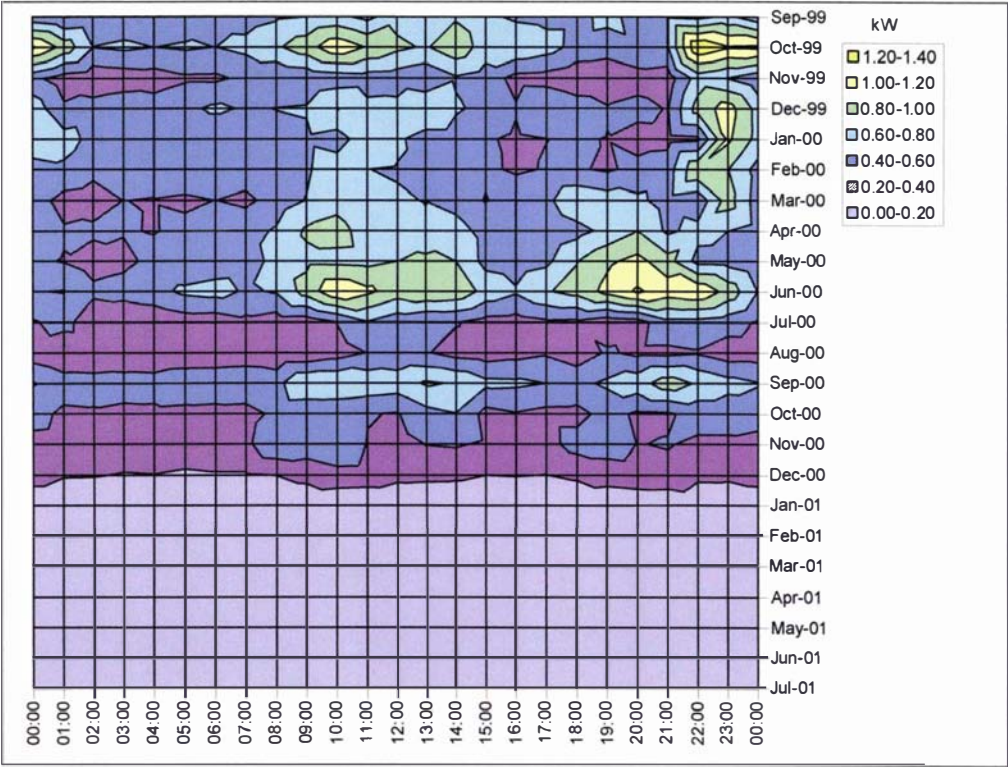


Figure 18.13 The mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 1.

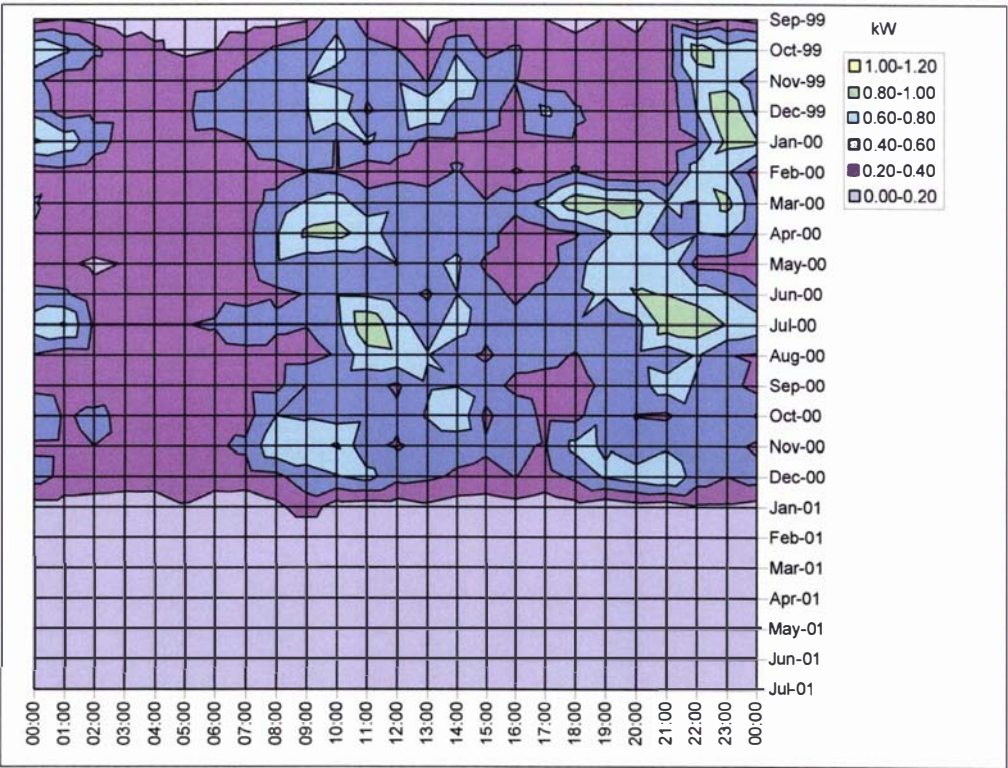


Figure 18.14 The standard deviation of the mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 1.

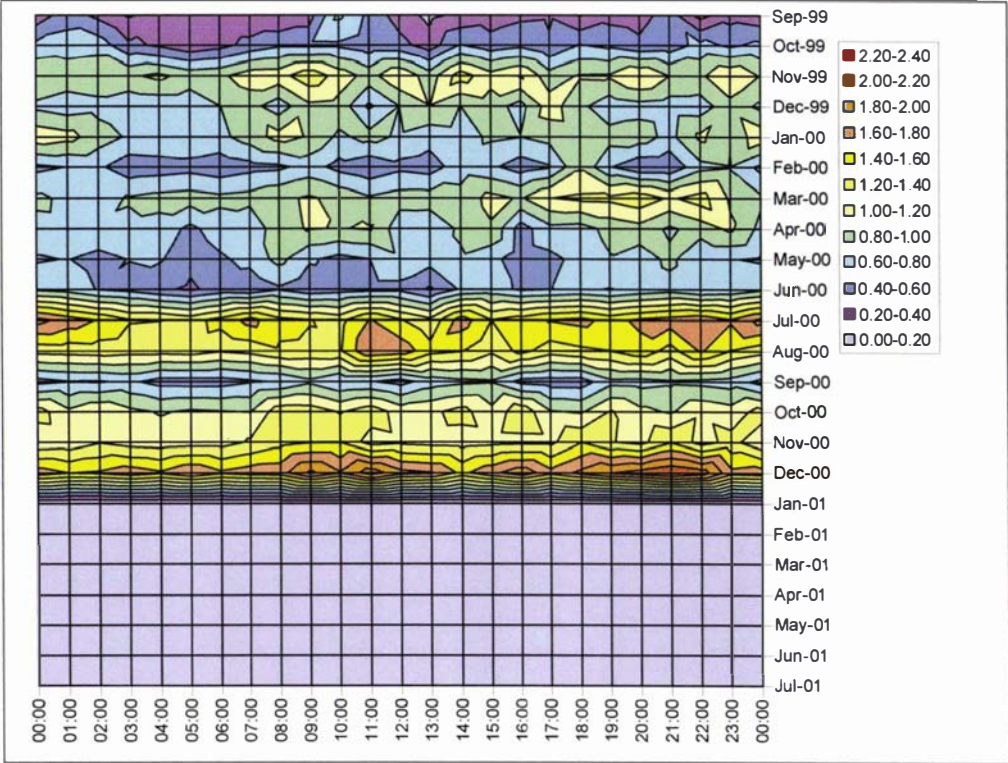


Figure 18.15 The coefficient of variation of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 1.

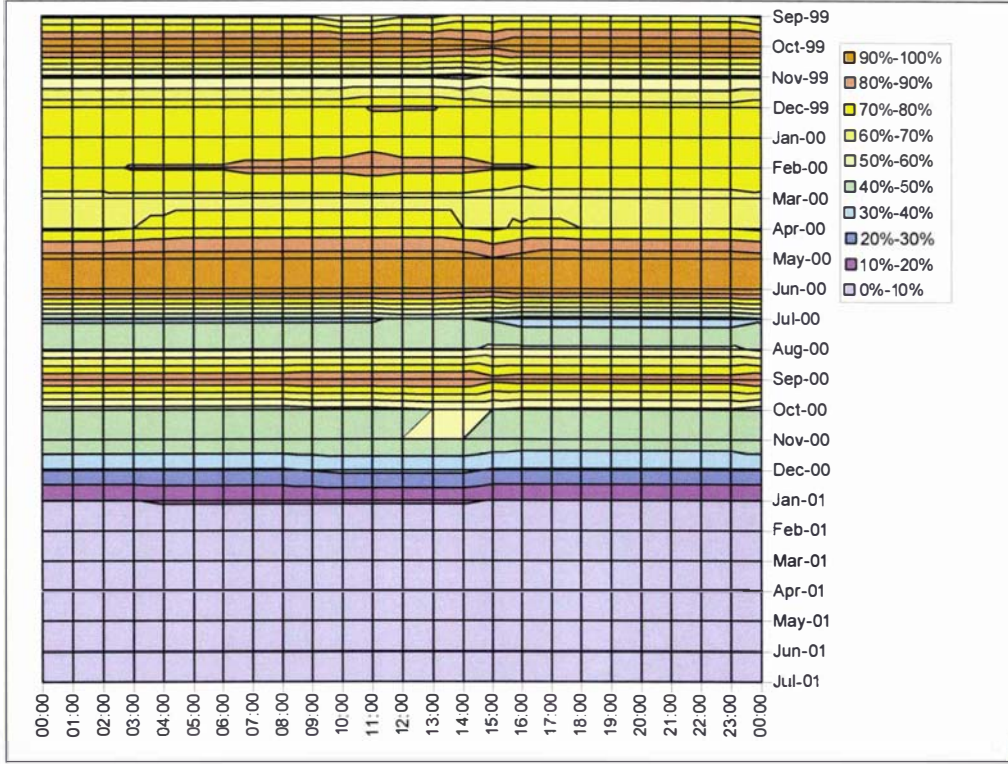


Figure 18.16 The data solidity of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 1.

Site 1 Domestic Load Profile Only

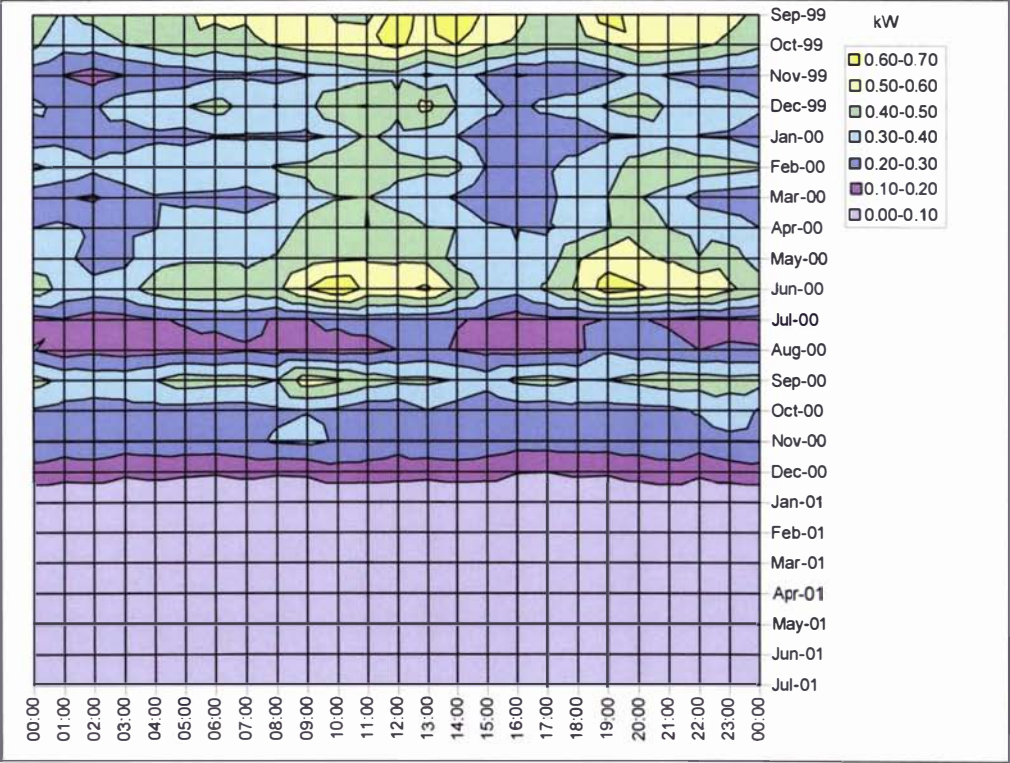


Figure 18.17 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 1.

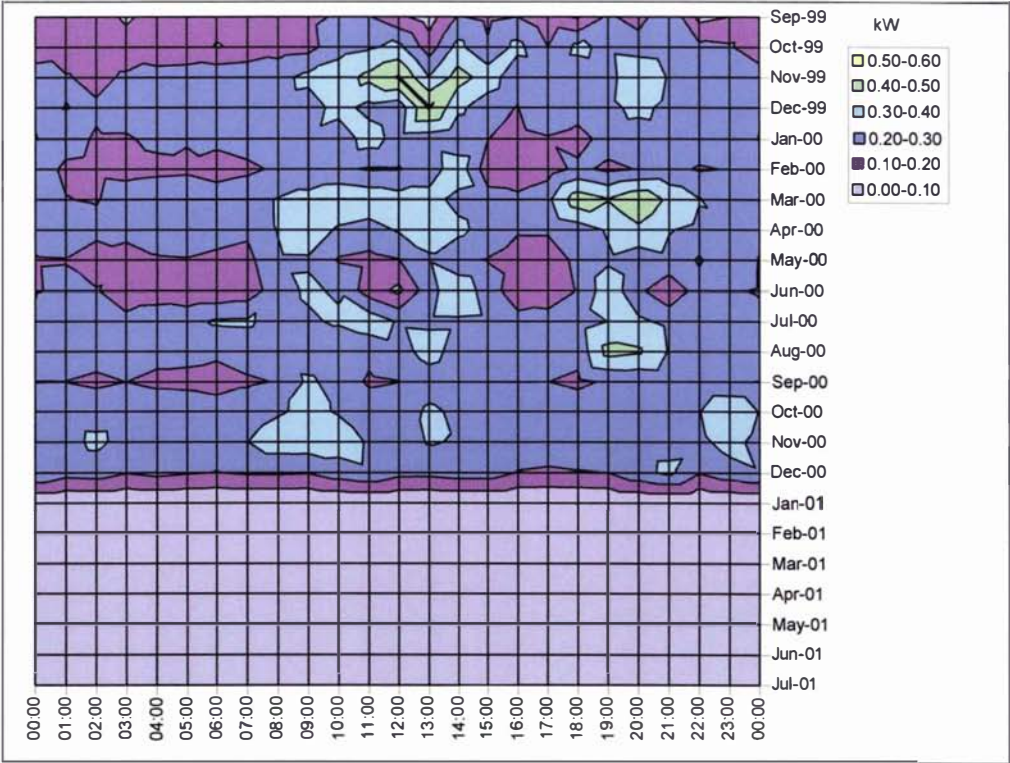


Figure 18.18 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 1.

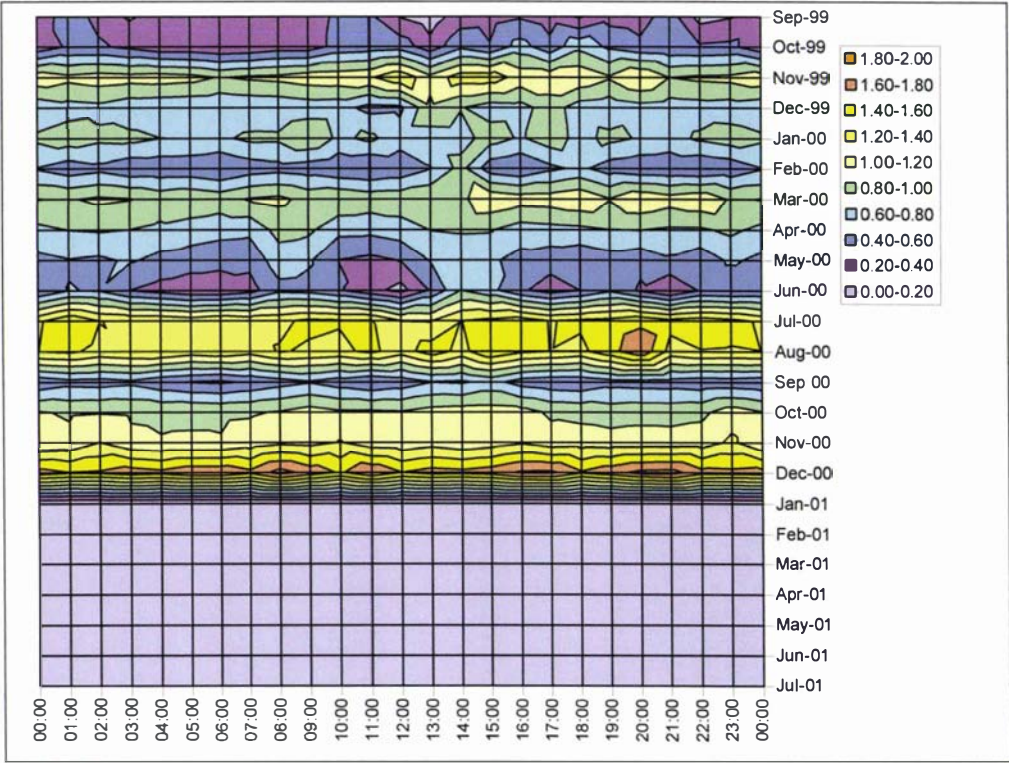


Figure 18.19 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 1.

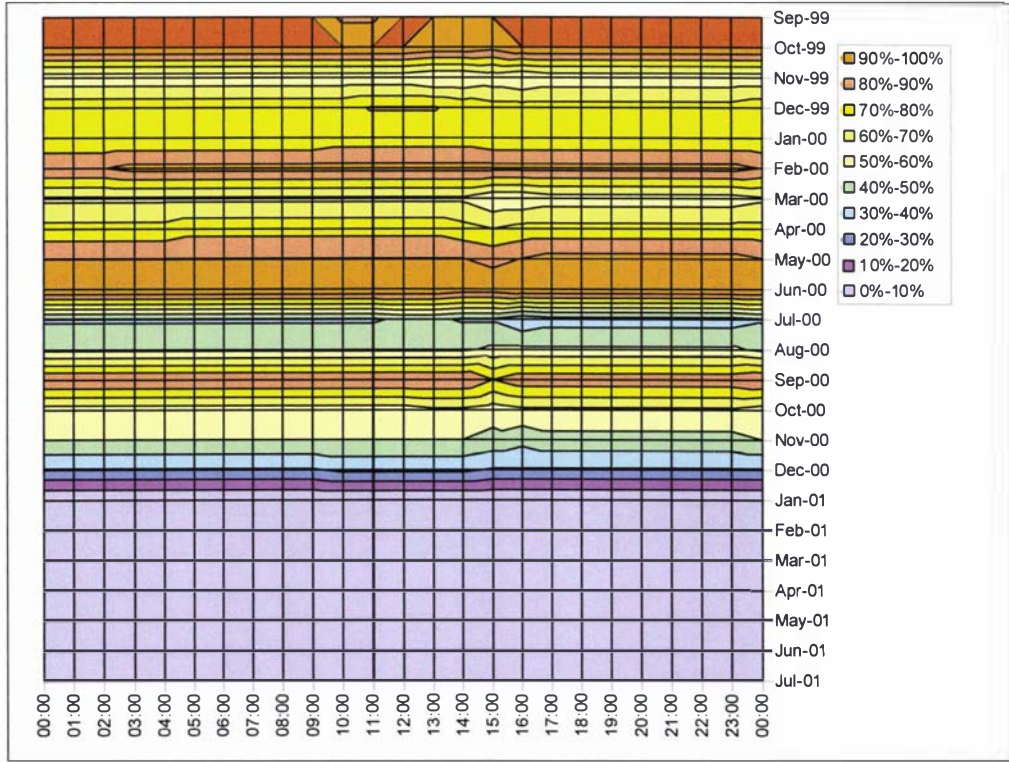


Figure 18.20 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 1.

Site 1 Water Heating Load Profile Only

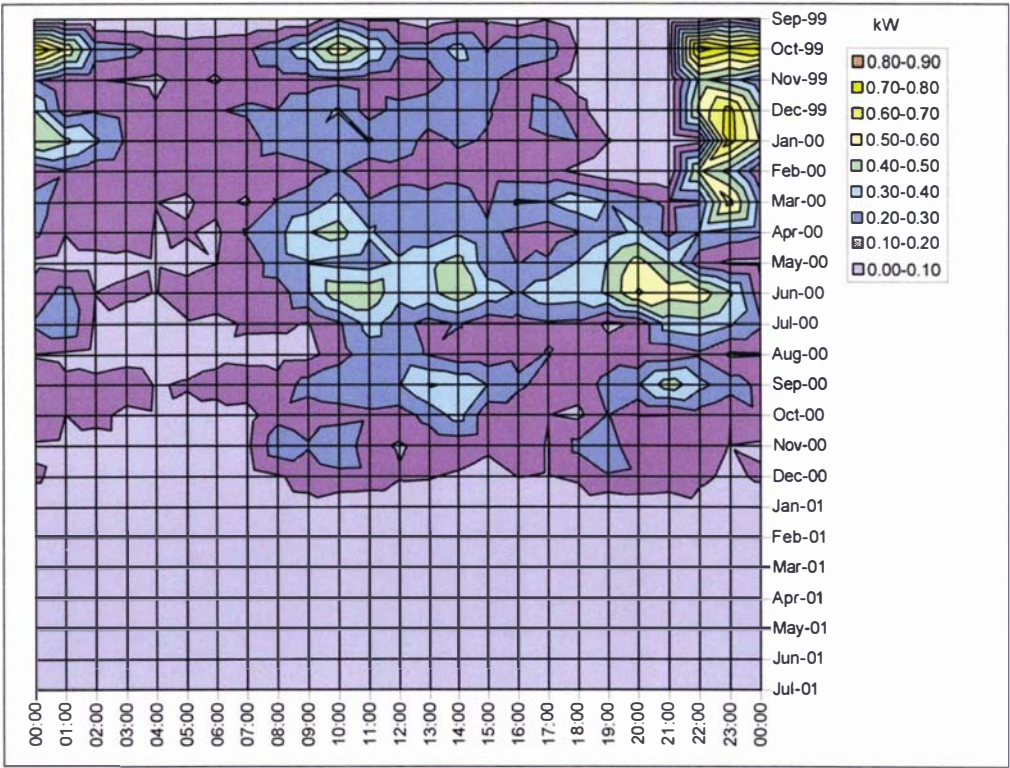


Figure 18.21 The mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 1.

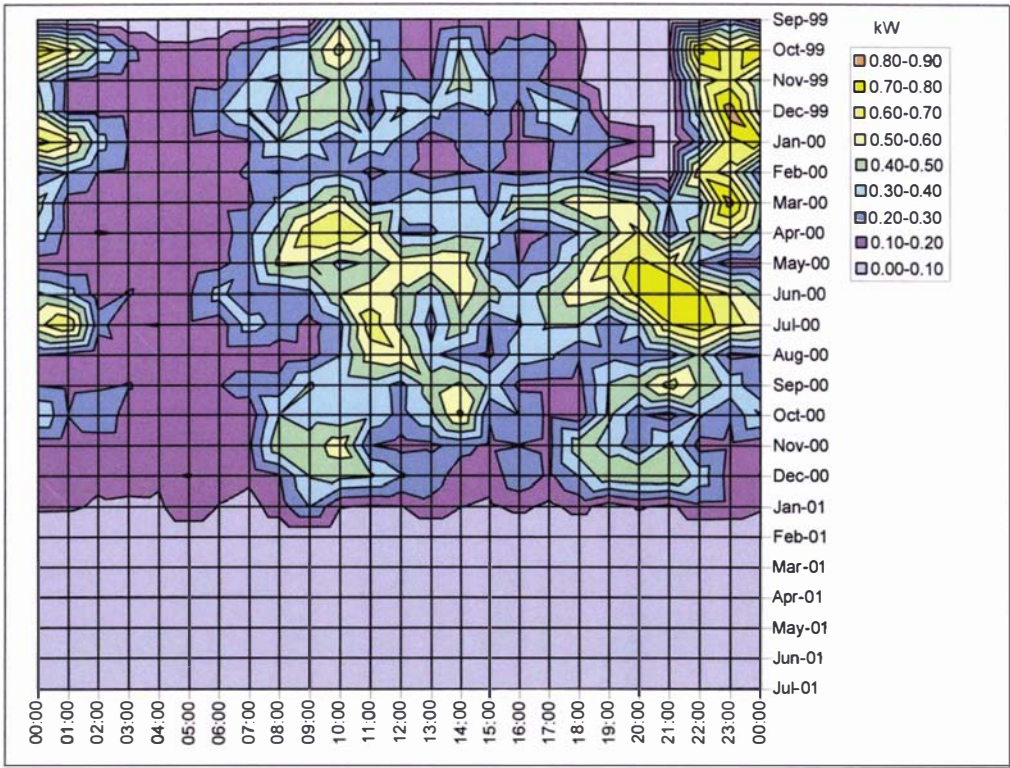


Figure 18.22 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 1.

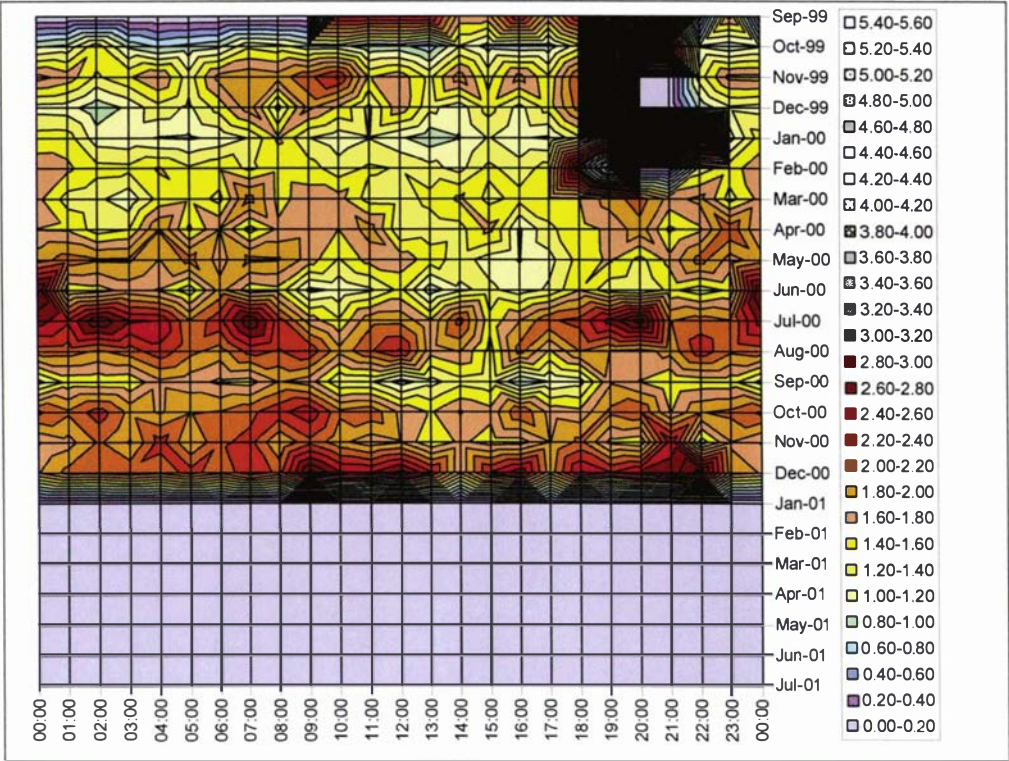


Figure 18.23 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 1.

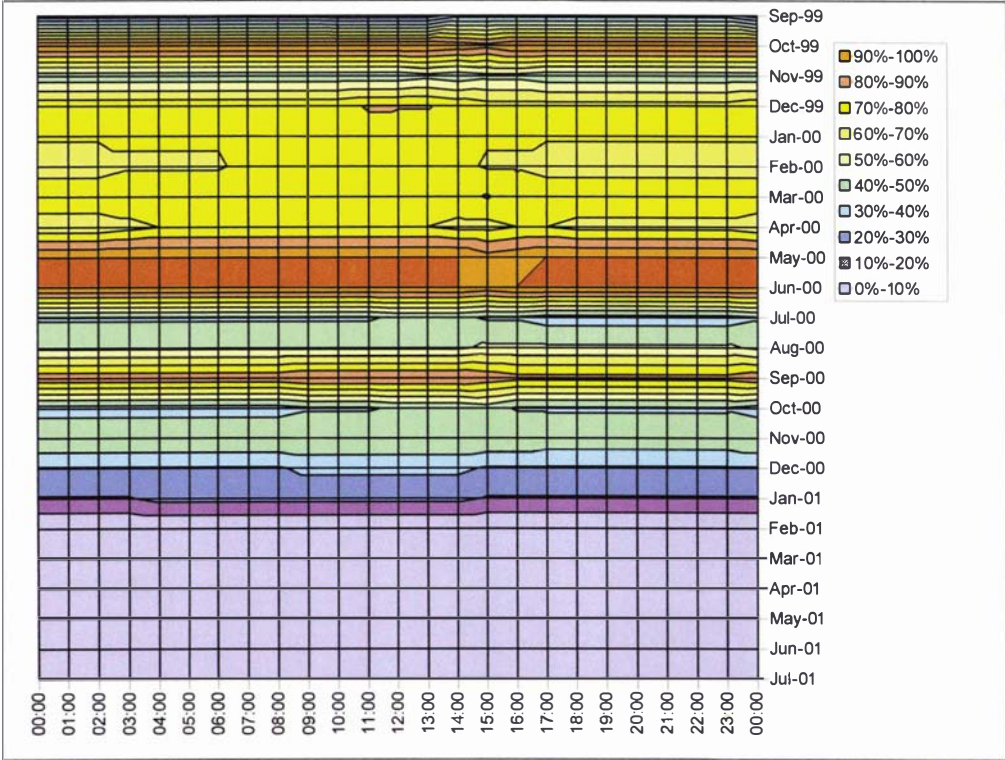


Figure 18.24 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 1.

18.2.2 Site 2 – Electricity Load Profiles

Site 2 Domestic and Water Heating Load Profiles

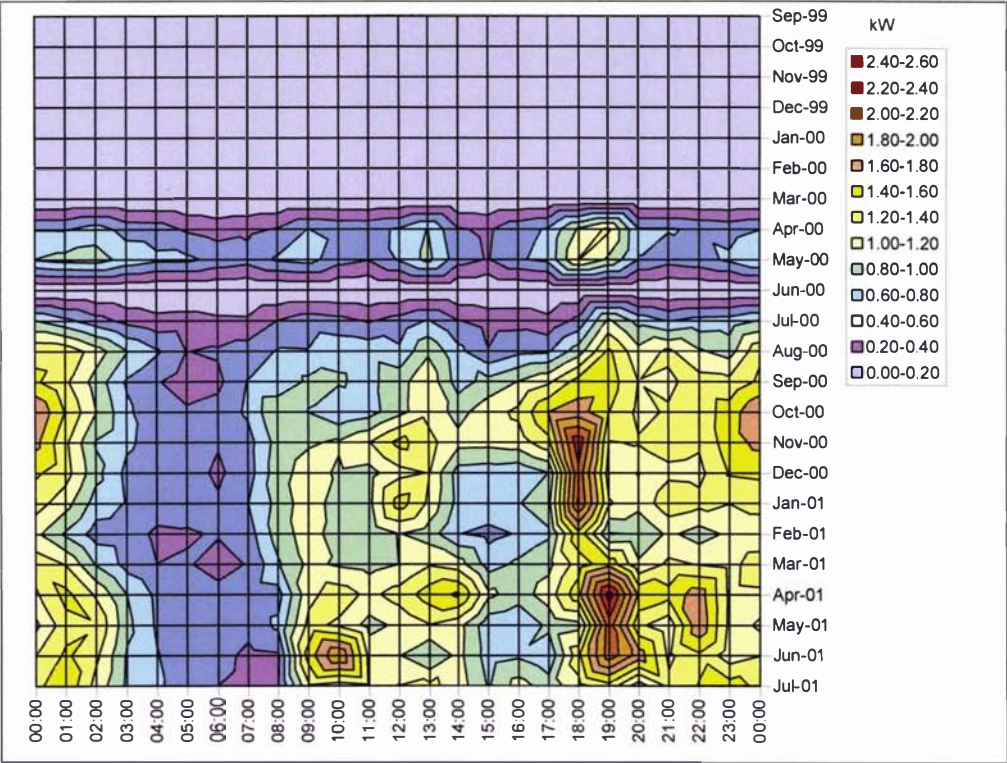


Figure 18.25 The mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 2.

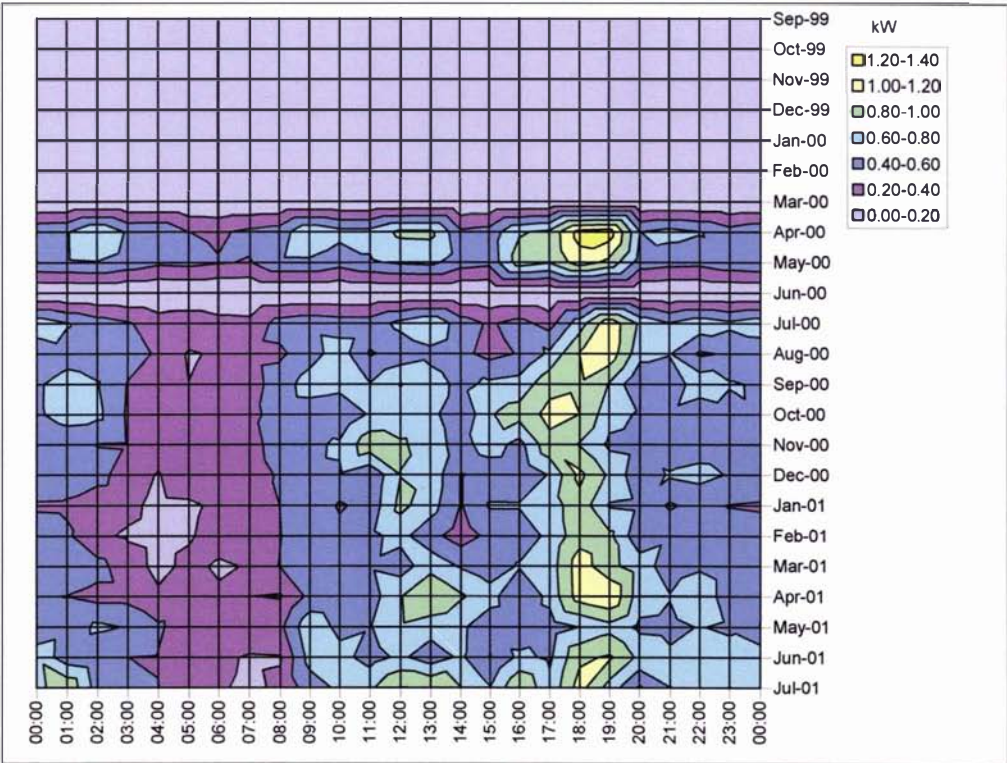


Figure 18.26 The standard deviation of the mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 2.

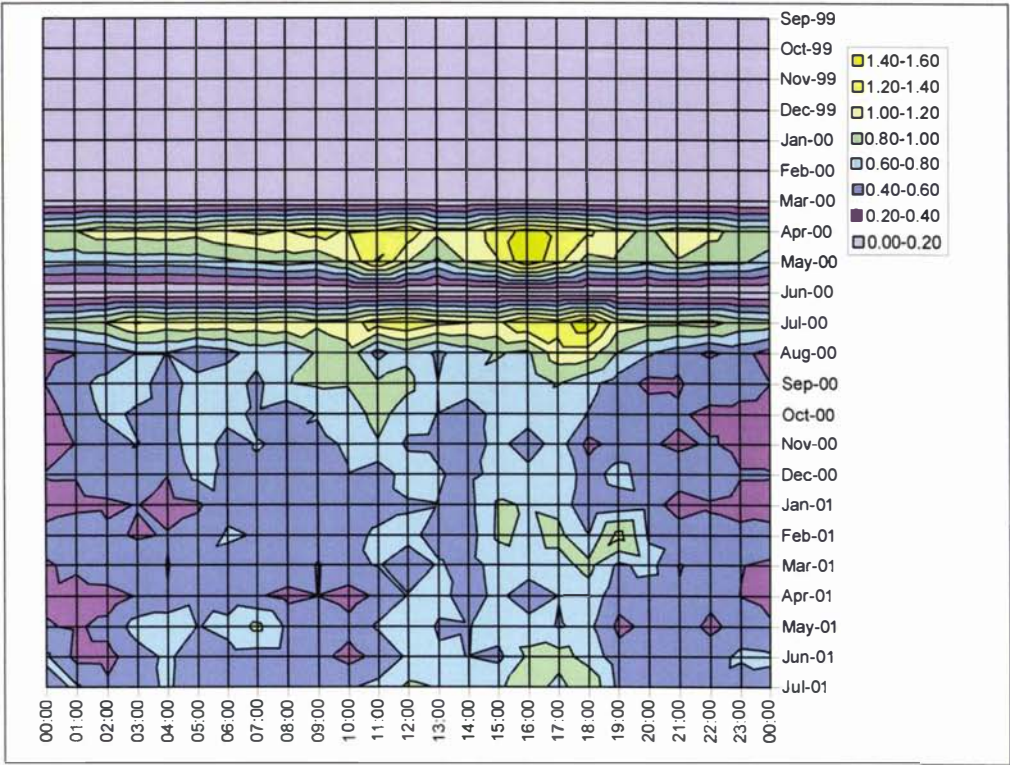


Figure 18.27 The coefficient of variation of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 2.

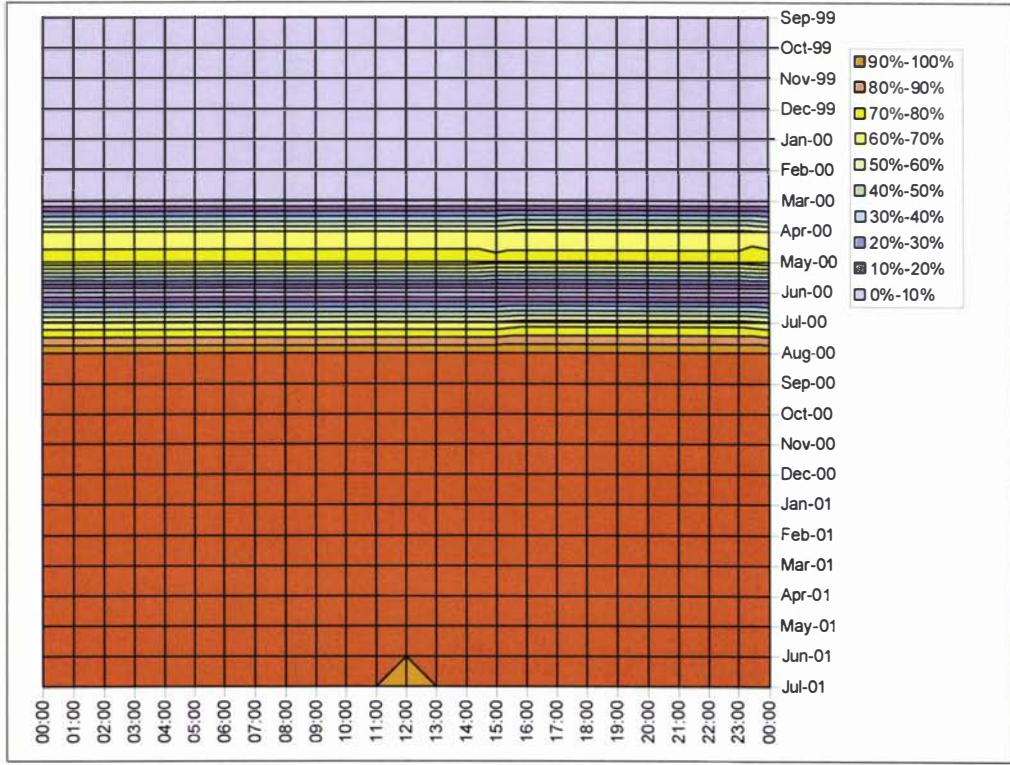


Figure 18.28 The data solidity of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 2.

Site 2 Domestic Load Profile Only

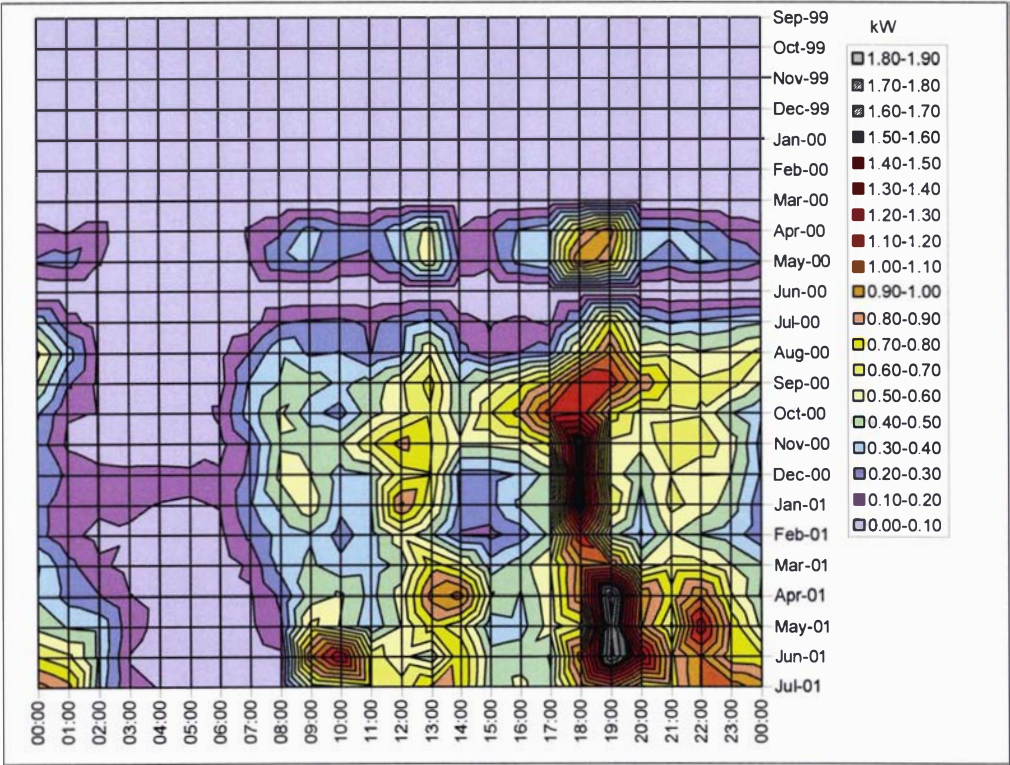


Figure 18.29 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 2.

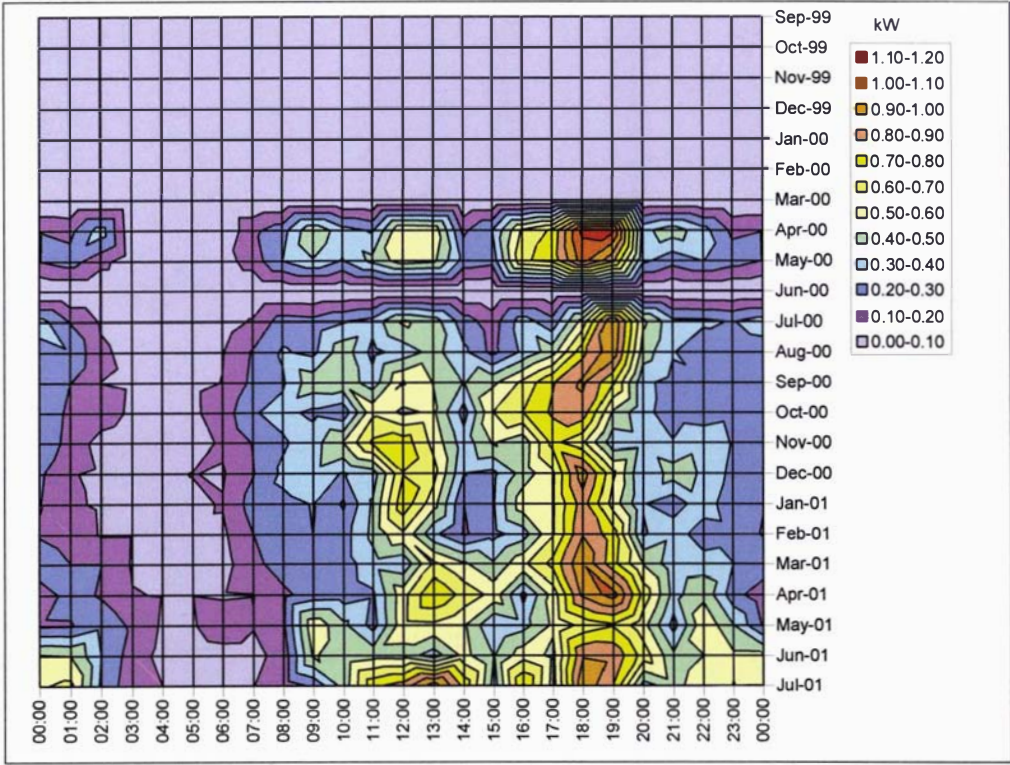


Figure 18.30 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 2.

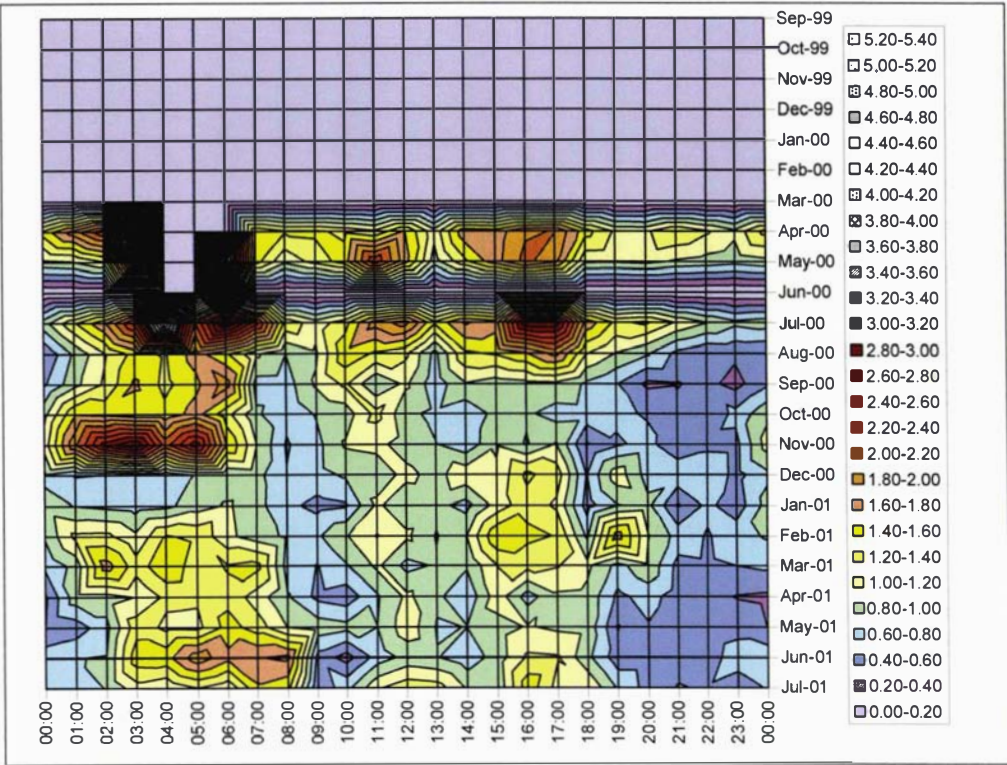


Figure 18.31 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 2.

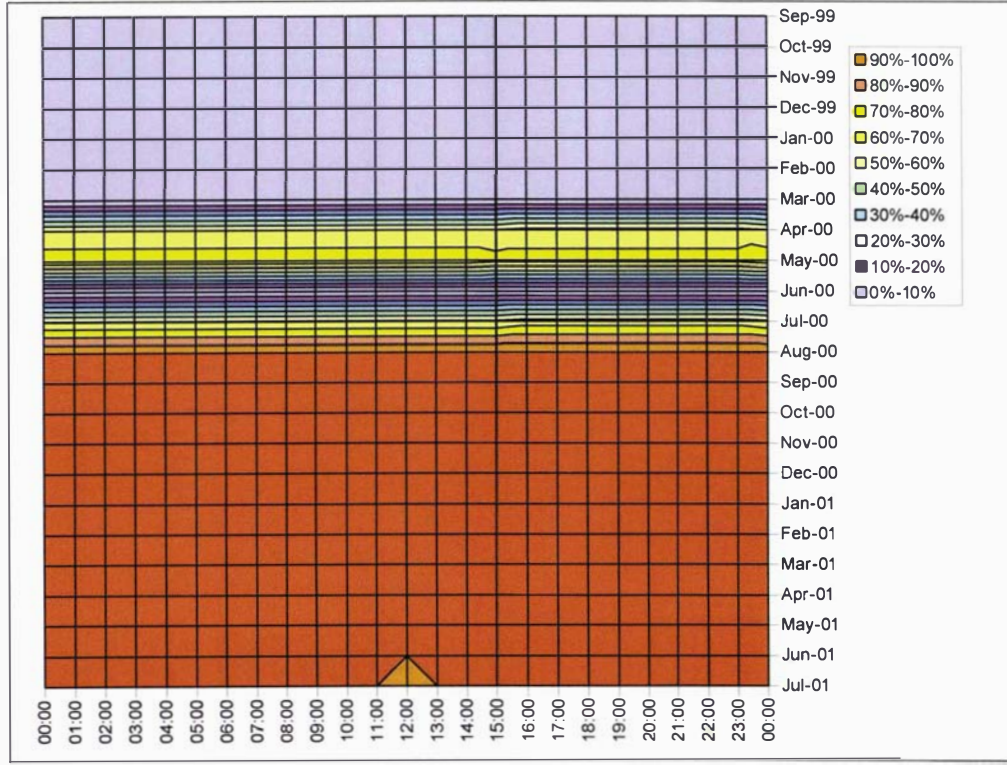


Figure 18.32 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 2.

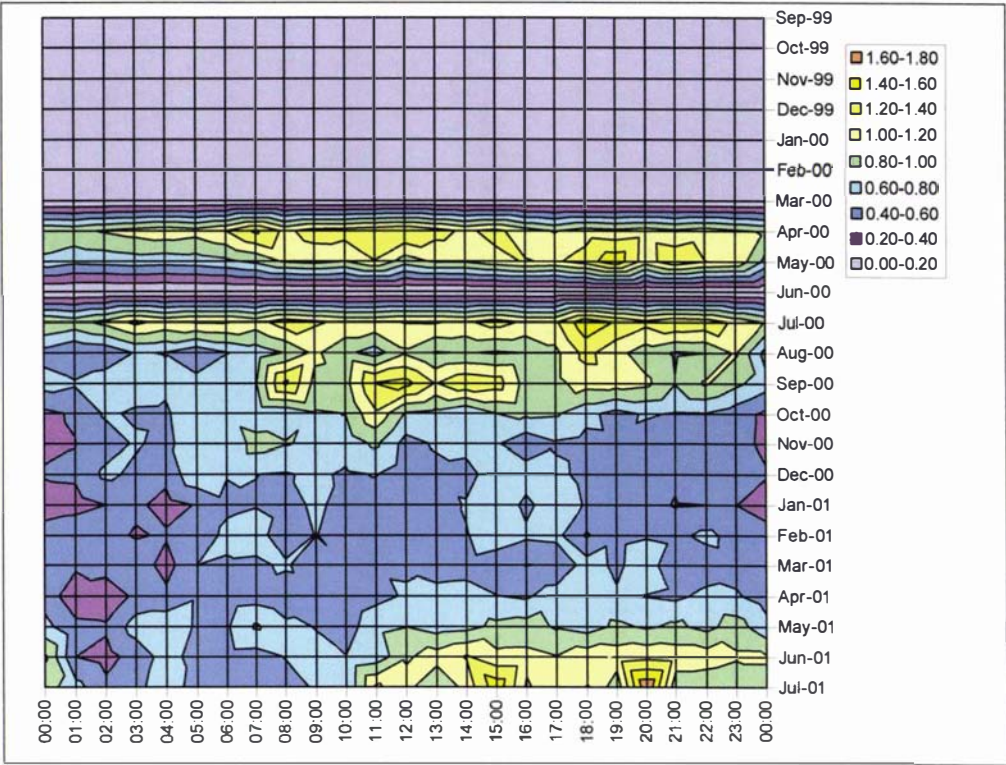


Figure 18.35 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 2.

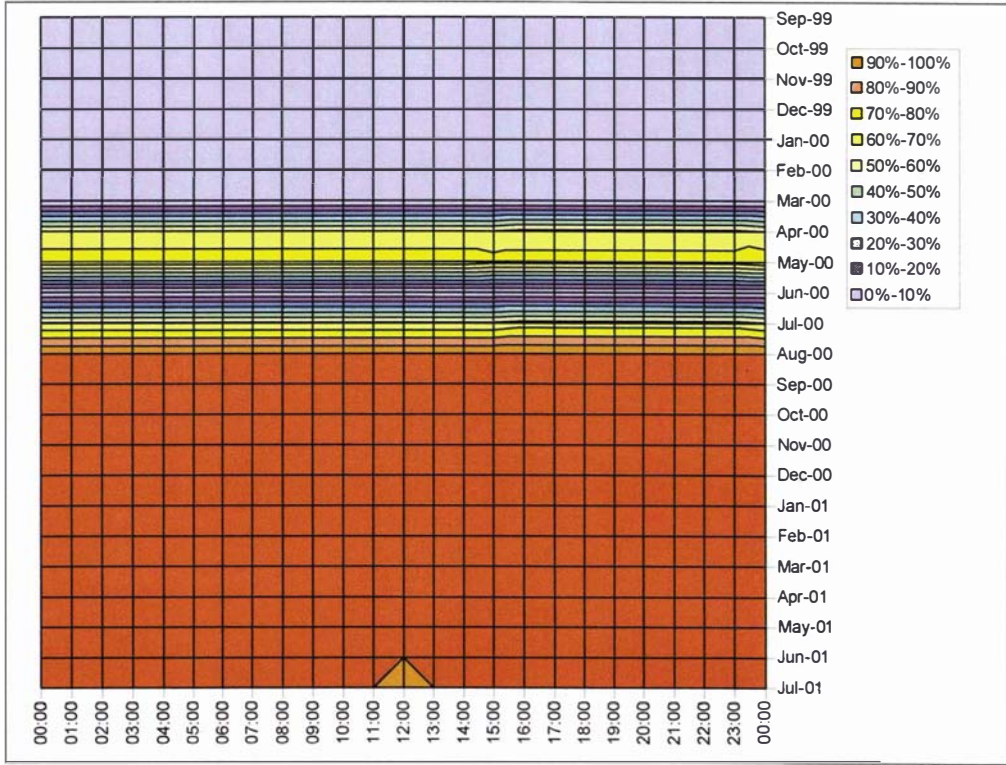


Figure 18.36 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 2.

18.2.3 Site 3 – Electricity Load Profiles

Site 3 Domestic and Water Heating Load Profiles

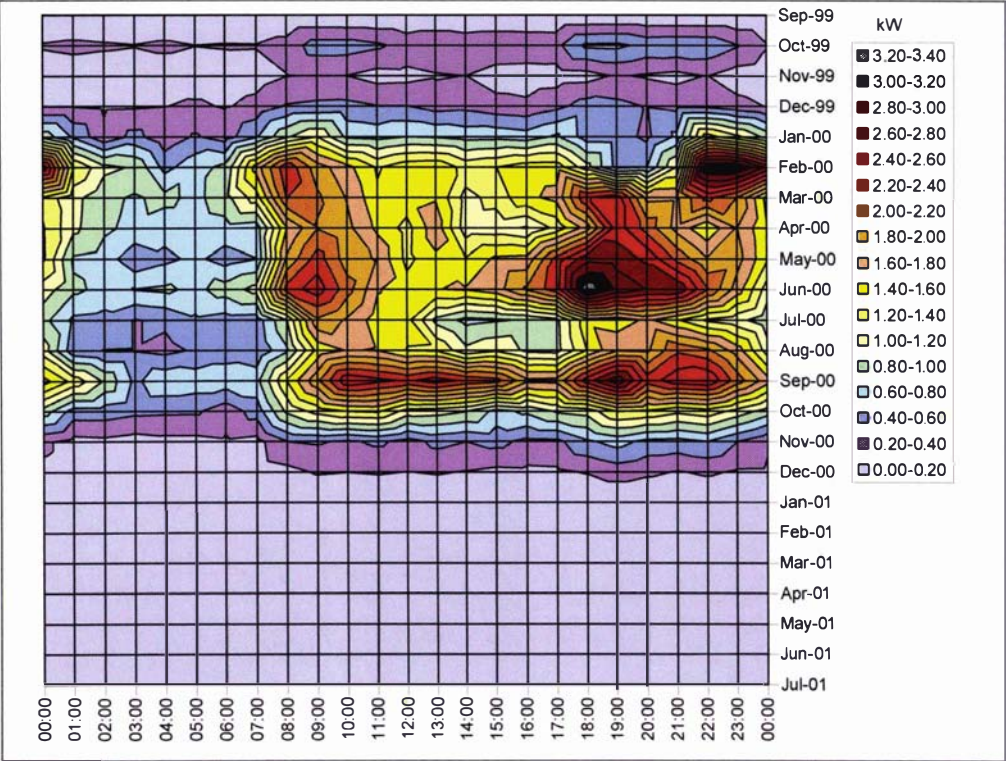


Figure 18.37 The mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 3.

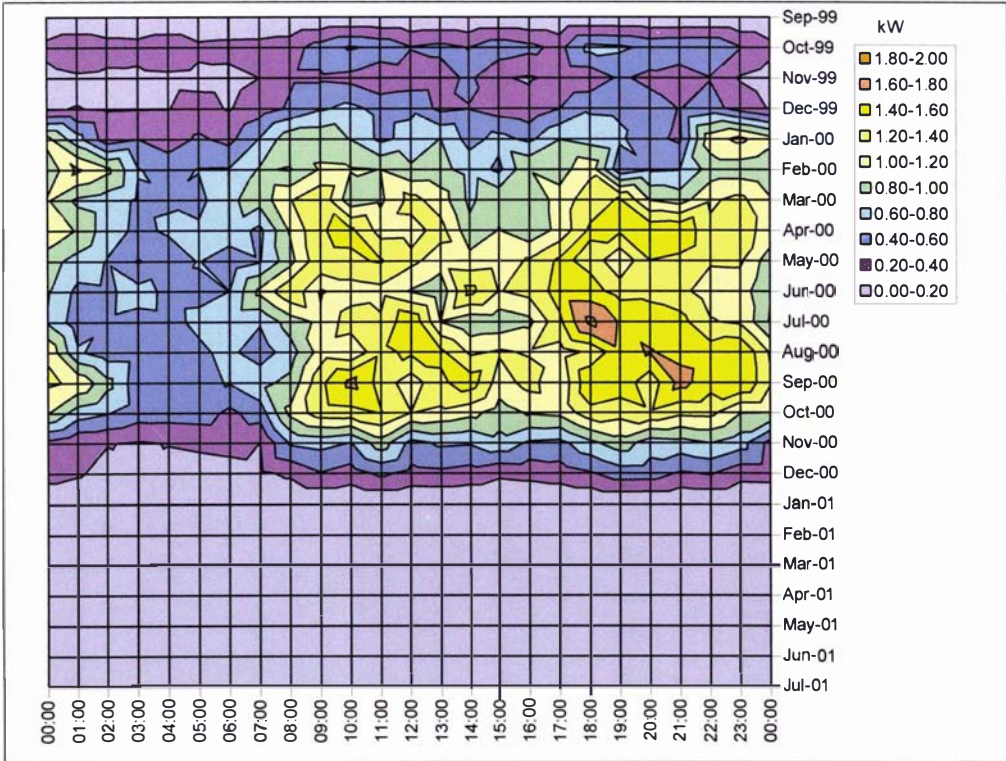


Figure 18.38 The standard deviation of the mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 3.

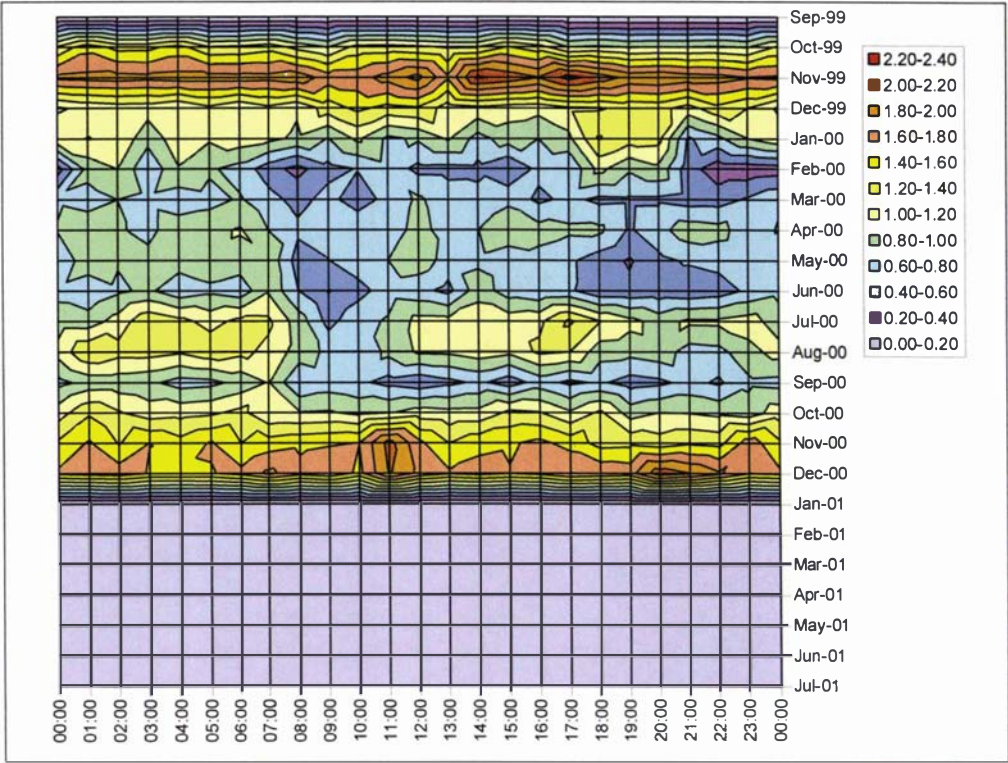


Figure 18.39 The coefficient of variation of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 3.

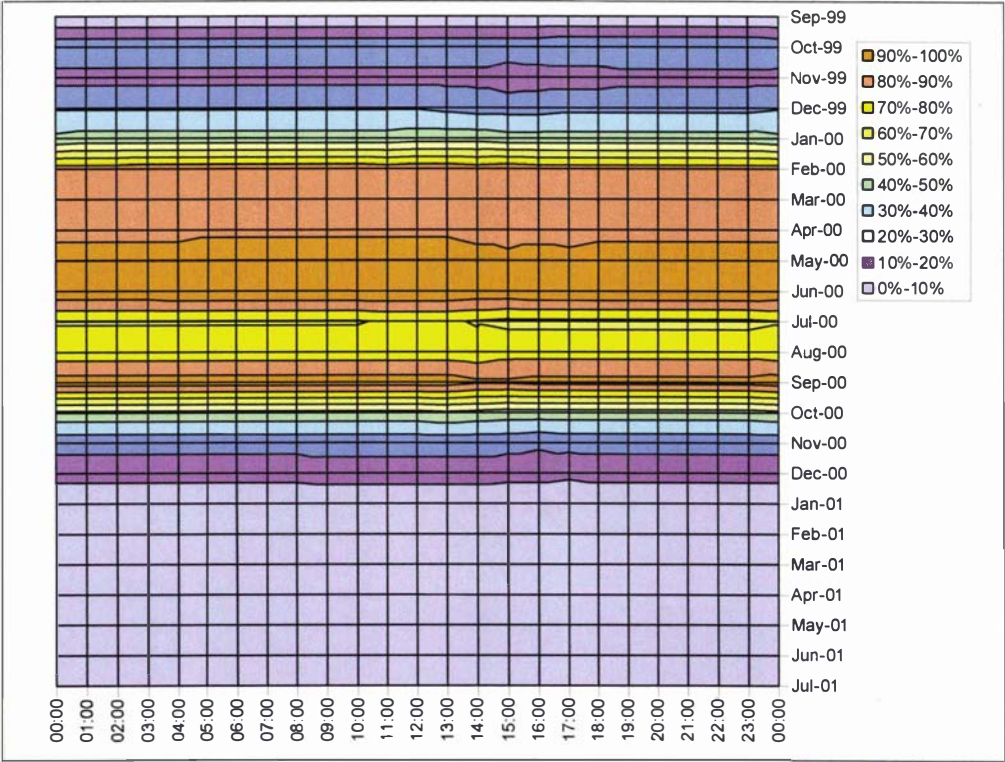


Figure 18.40 The data solidity of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 3.

Site 3 Domestic Load Profile Only

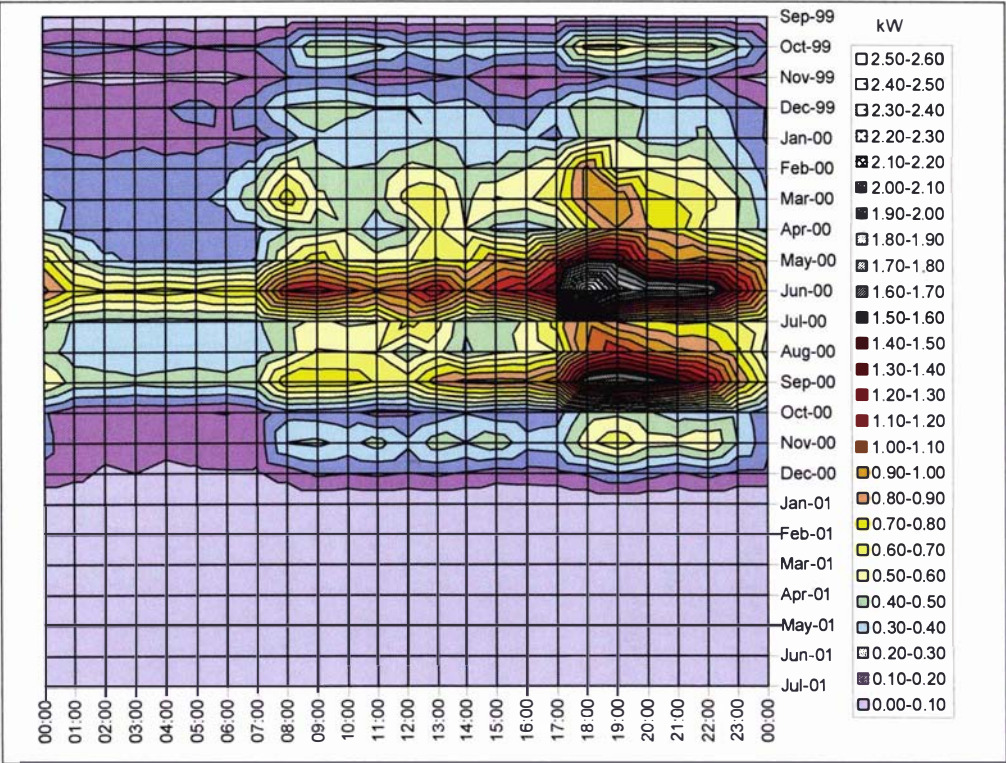


Figure 18.41 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 3.

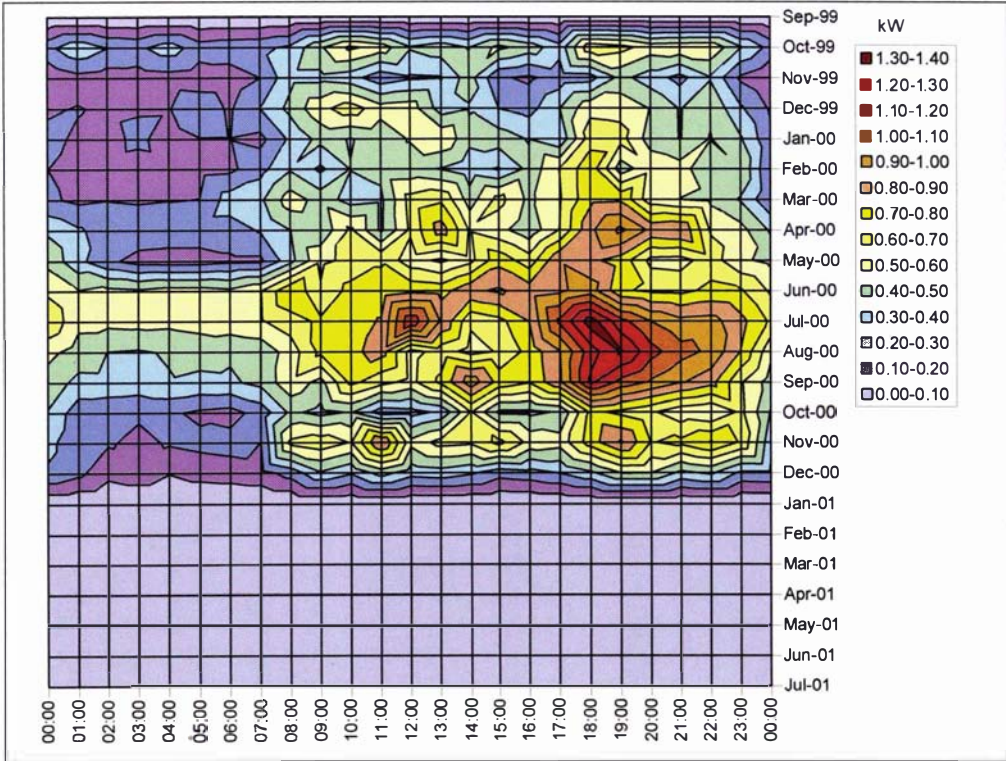


Figure 18.42 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 3.

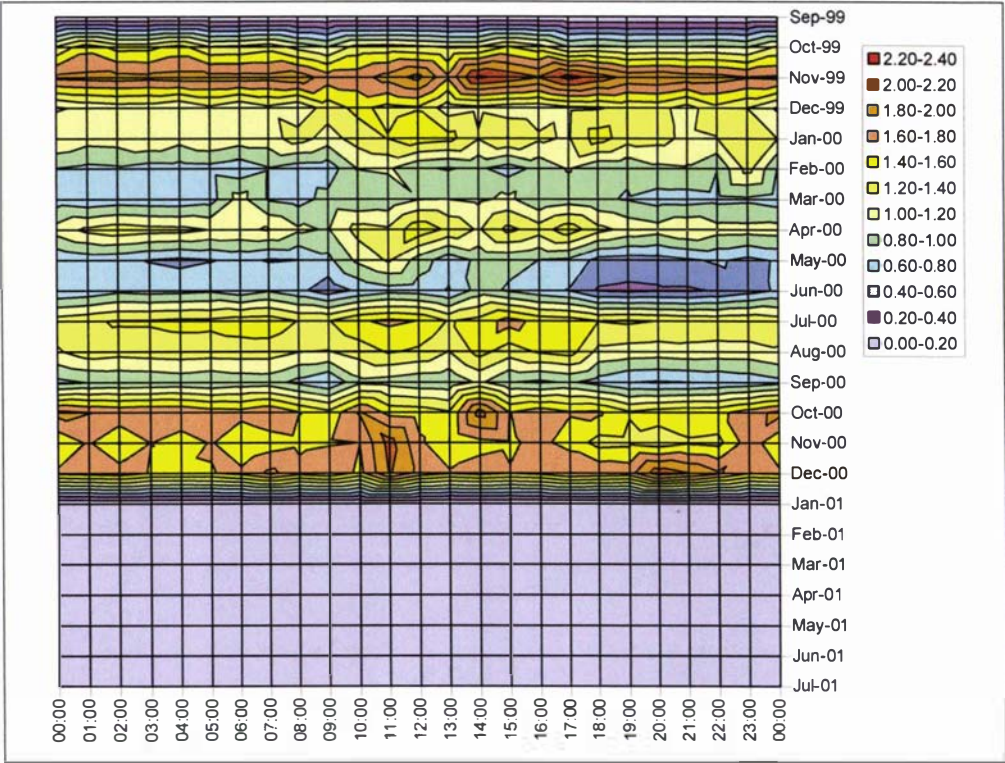


Figure 18.43 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 3.

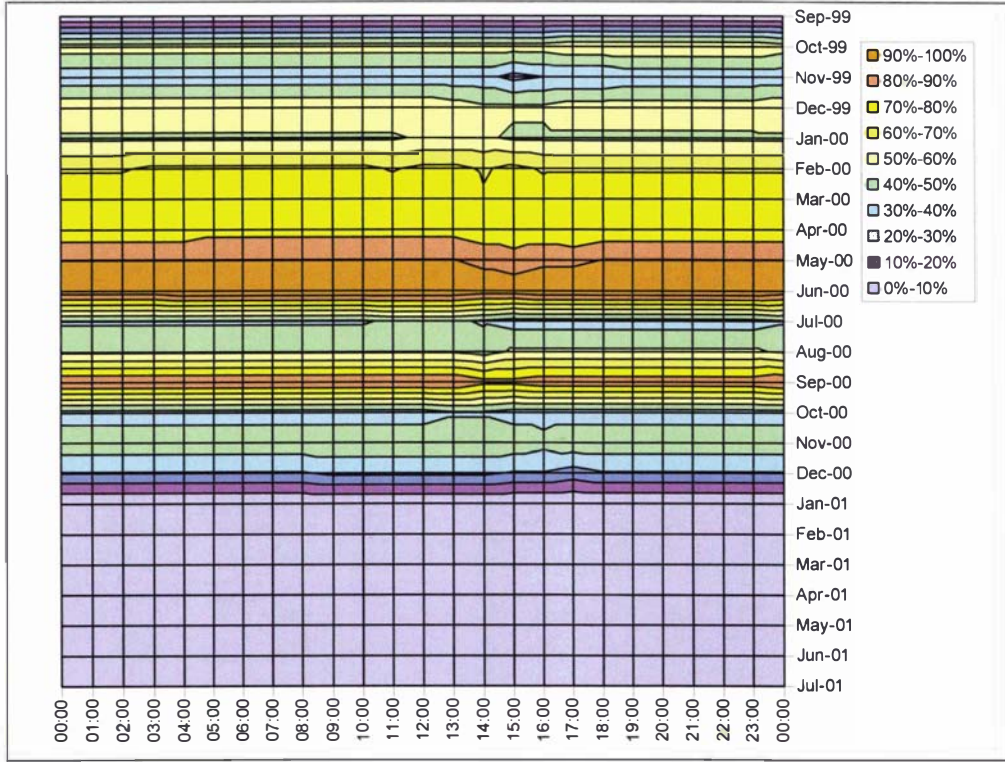


Figure 18.44 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 3.

Site 3 Water Heating Load Profile Only

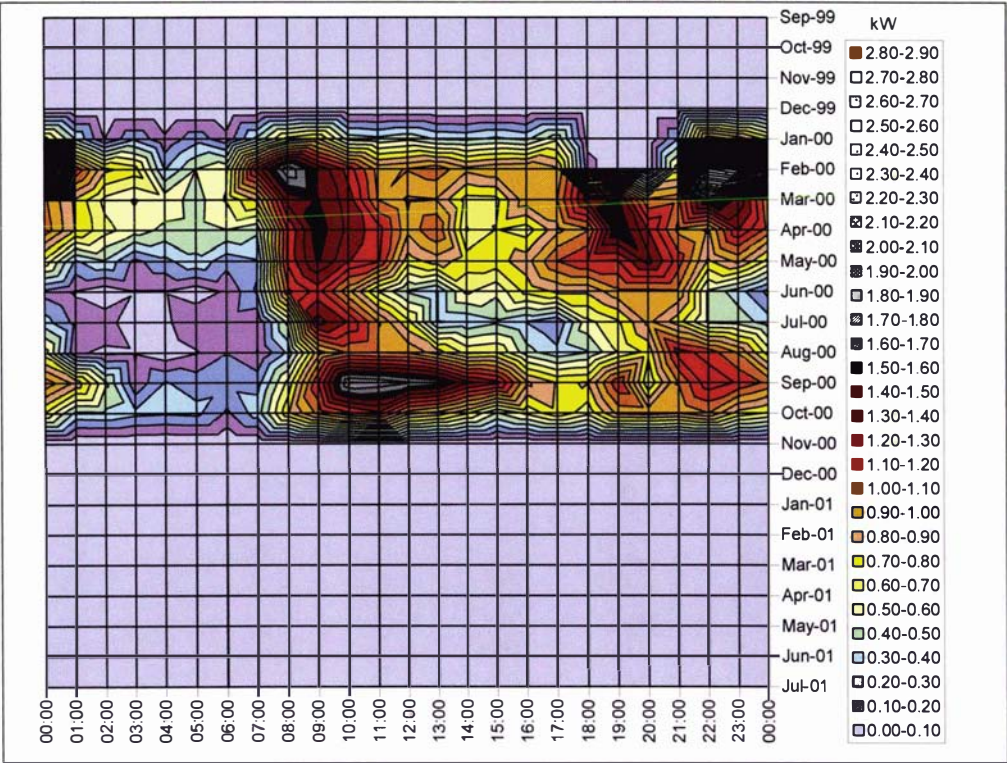


Figure 18.45 The mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 3.

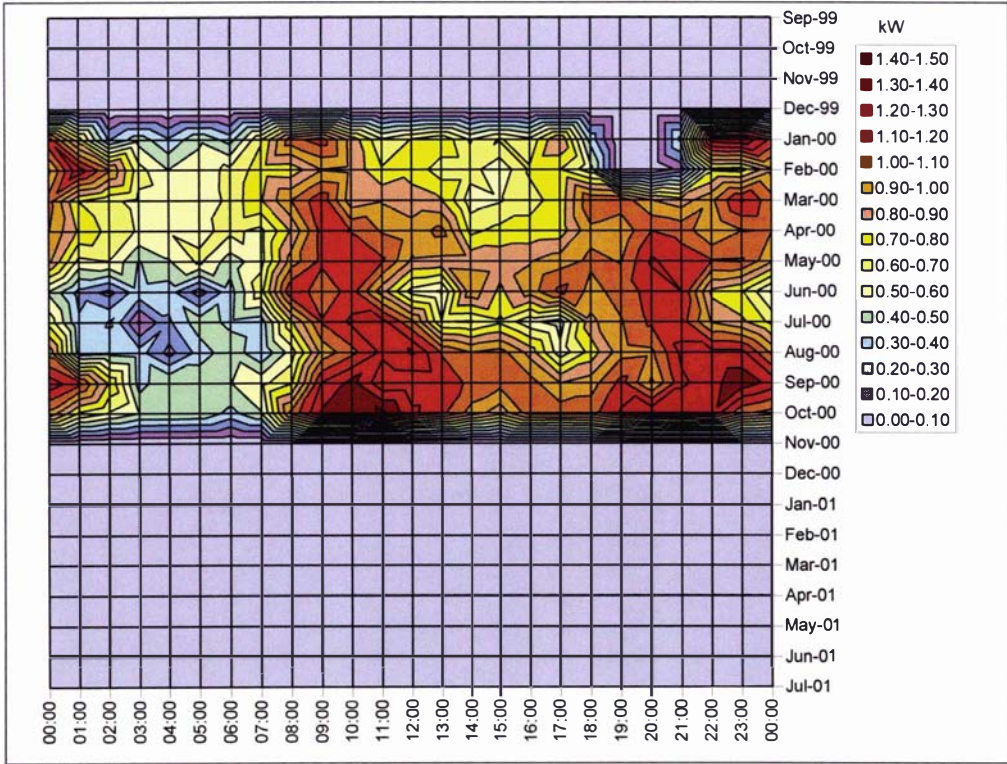


Figure 18.46 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 3.

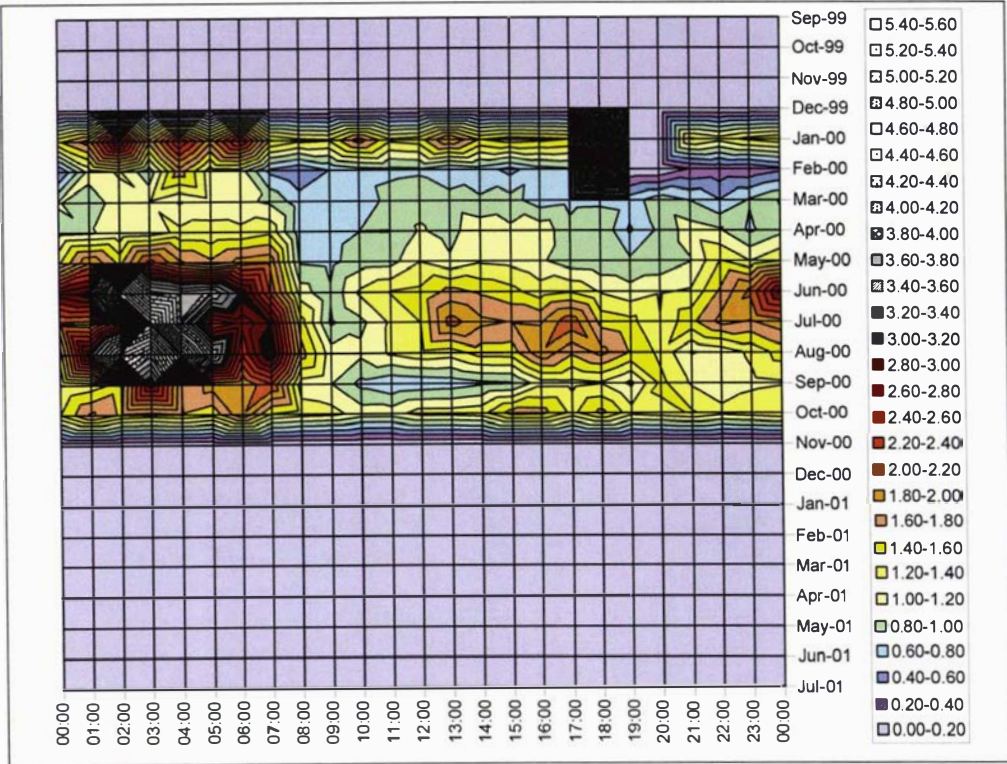


Figure 18.47 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 3.

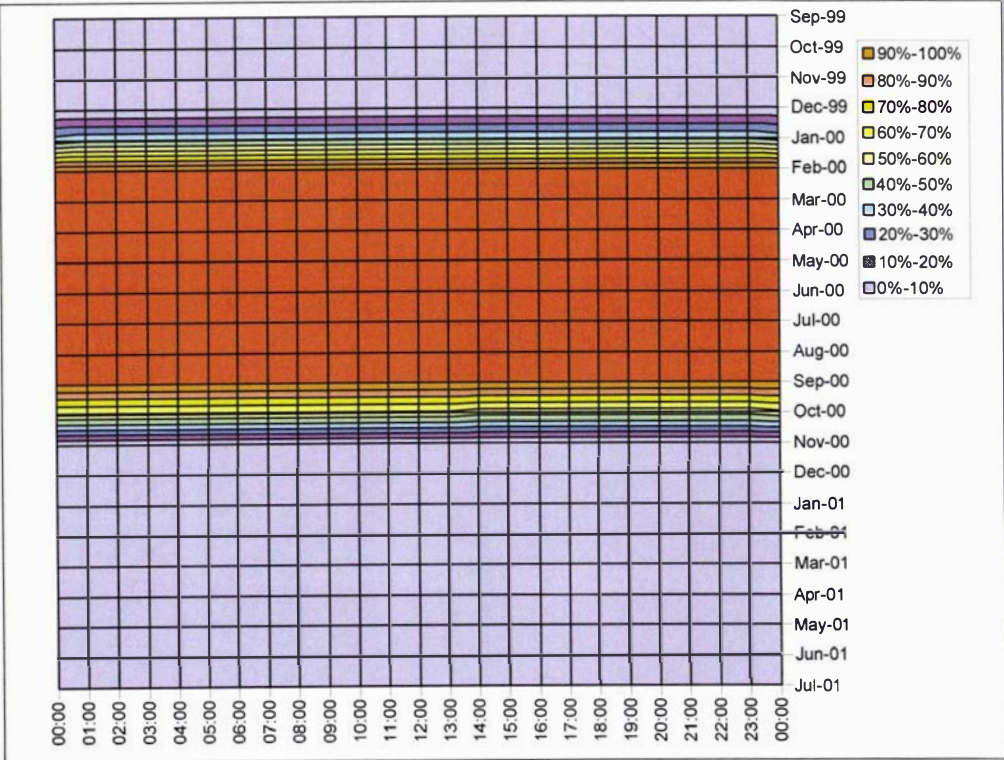


Figure 18.48 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 3.

18.2.4 Site 4 – Electricity Load Profiles

Site 4 Domestic, Water Heating and Workshop Load Profiles

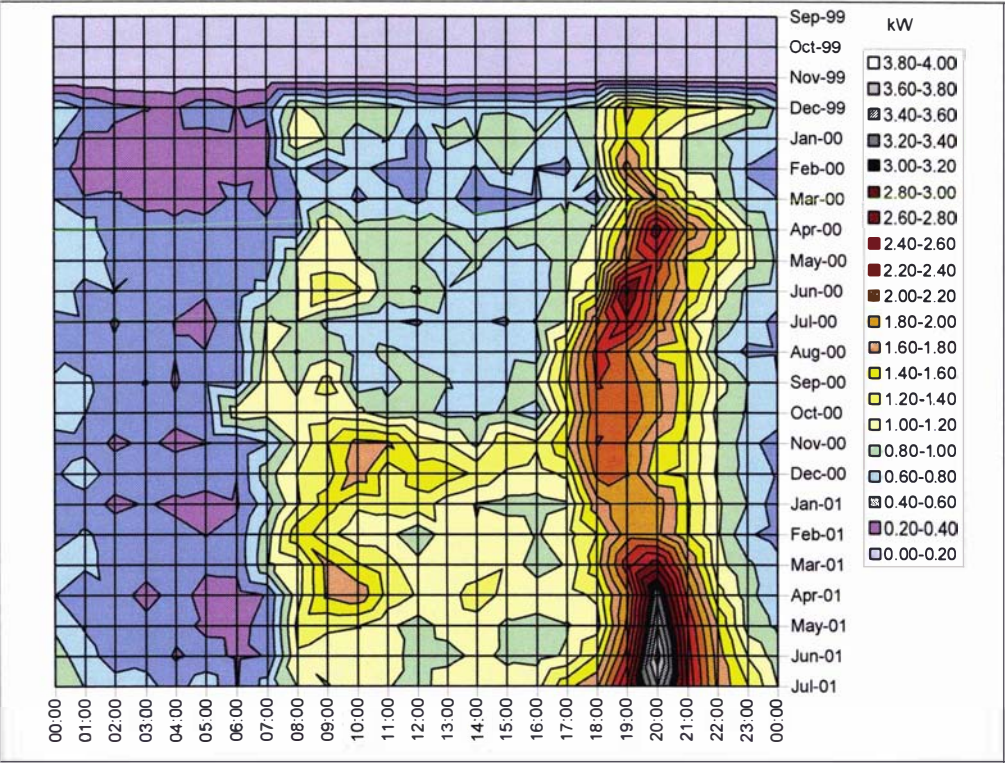


Figure 18.49 The mean monthly – diurnal domestic, water heating and workshop load profile over the duration of the monitoring for Site 4.

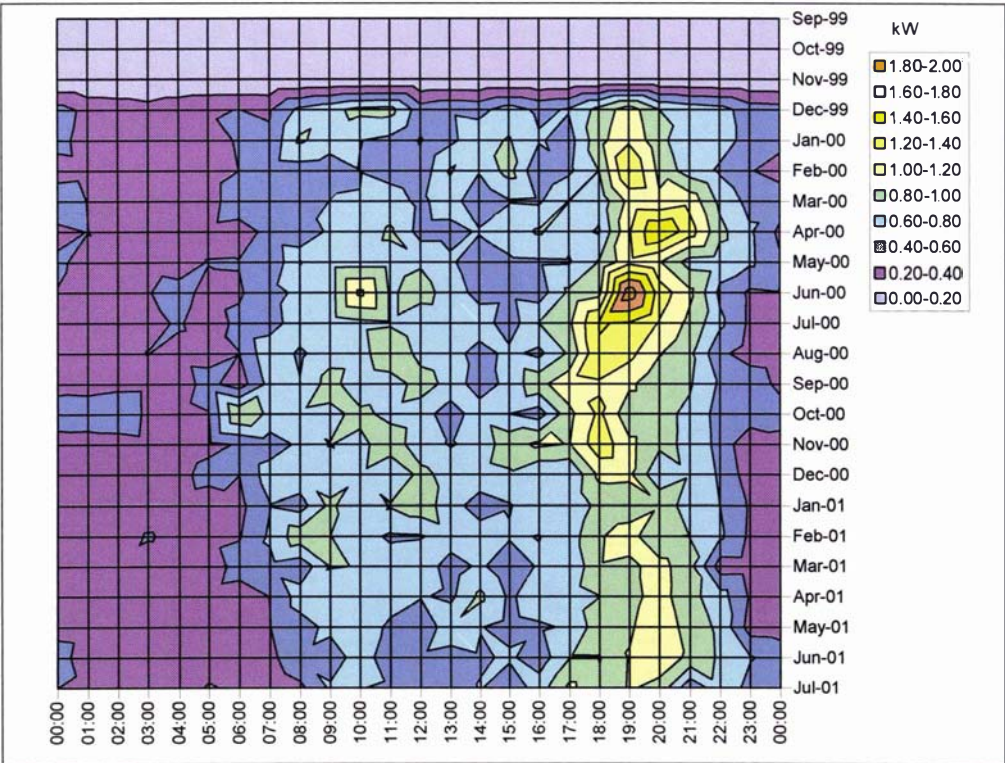


Figure 18.50 The standard deviation of the mean monthly – diurnal domestic, water heating, and workshop load profile over the duration of the monitoring for Site 4.

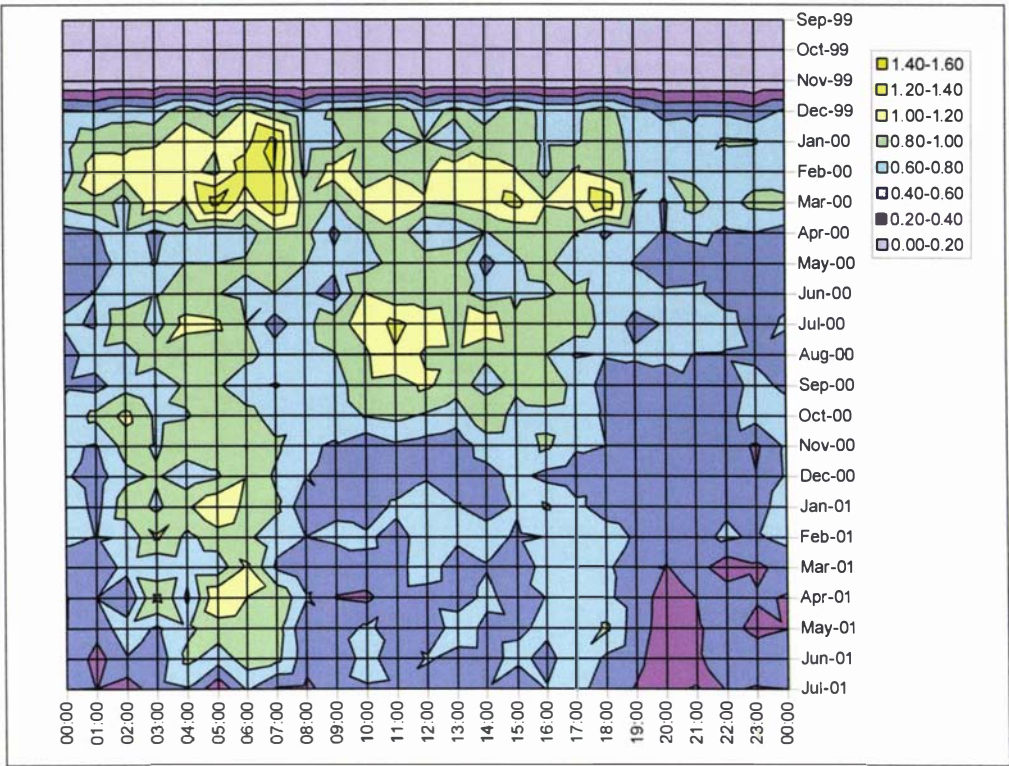


Figure 18.51 The coefficient of variation of the monthly – diurnal domestic, water heating, and workshop load profile over the duration of the monitoring for Site 4.

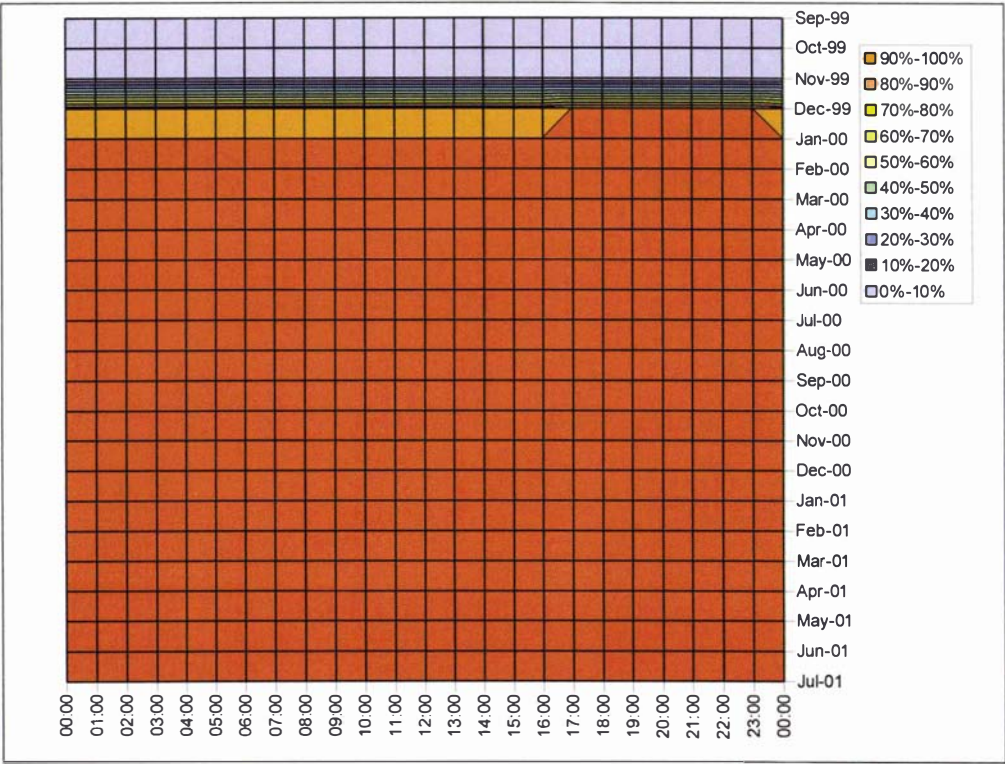


Figure 18.52 The data solidity of the monthly – diurnal domestic, water heating, and workshop load profile over the duration of the monitoring for Site 4.

Site 4 Domestic Load Profile Only

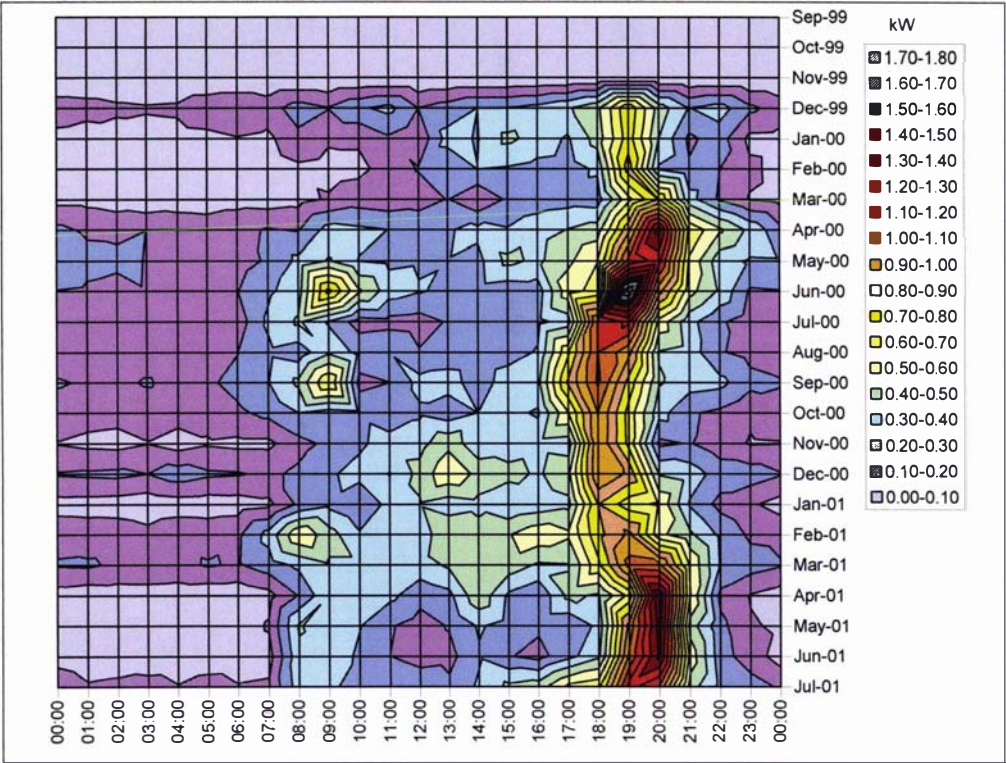


Figure 18.53 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 4.

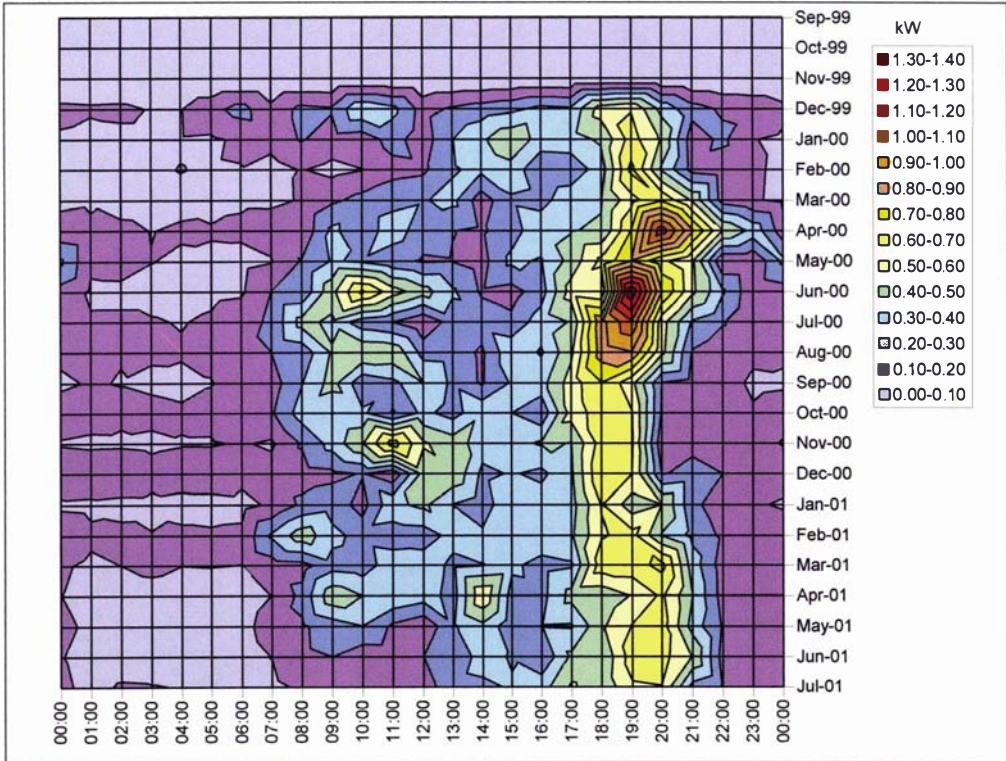


Figure 18.54 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 4.

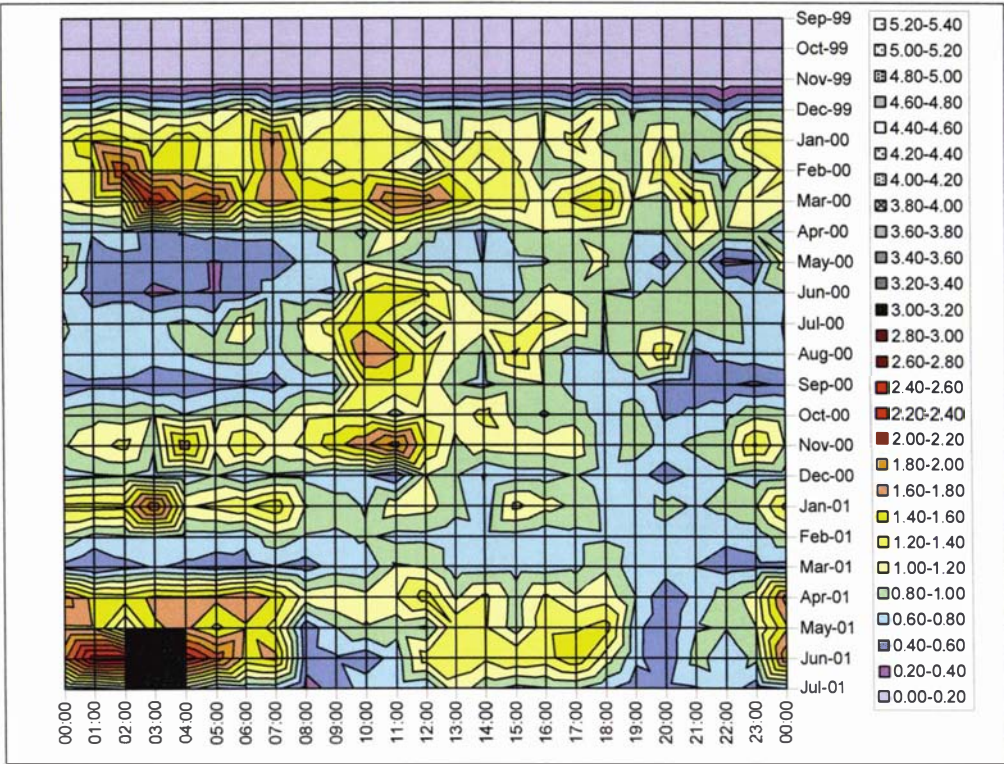


Figure 18.55 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 4.

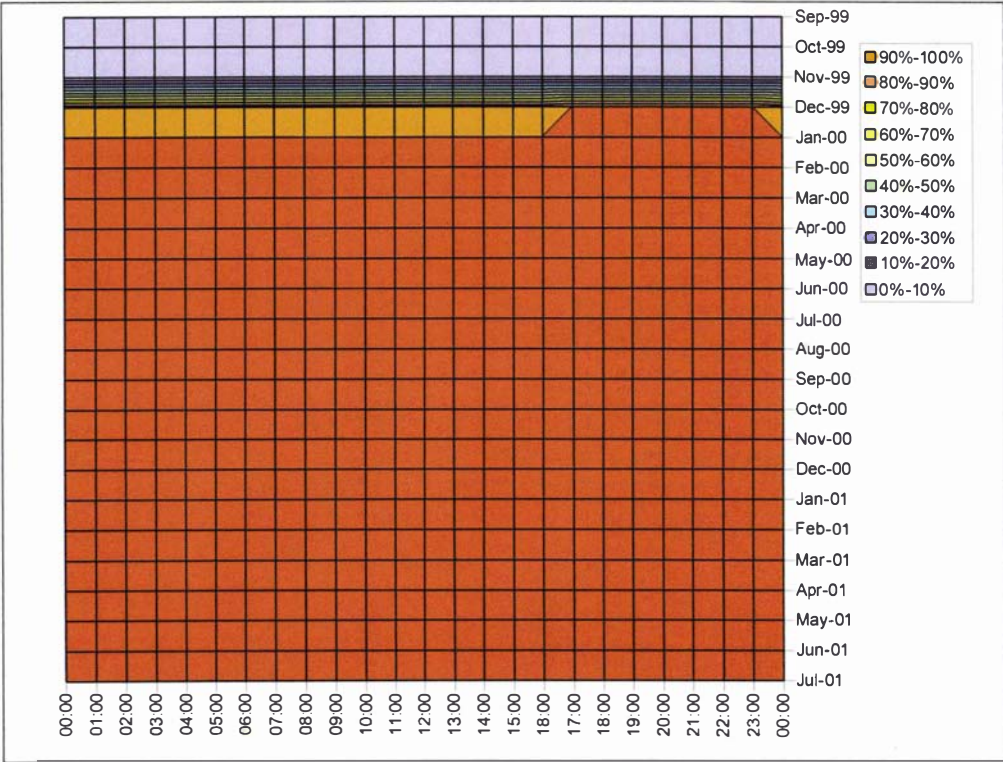


Figure 18.56 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 4.

Site 4 Water Heating Load Profile Only

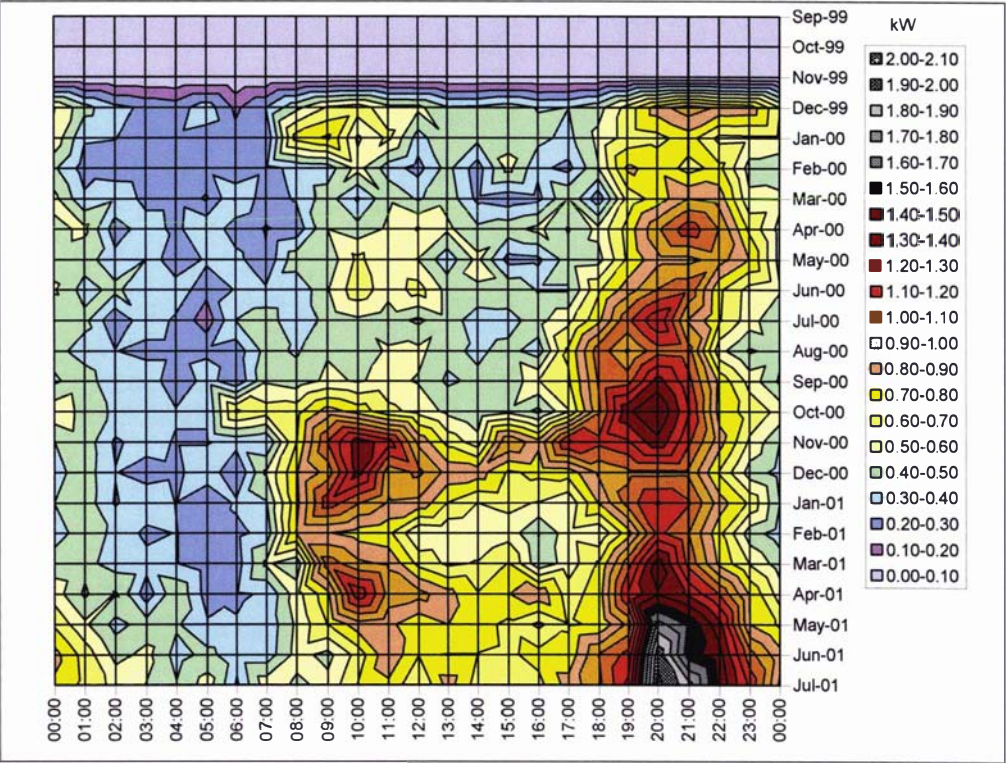


Figure 18.57 The mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 4.

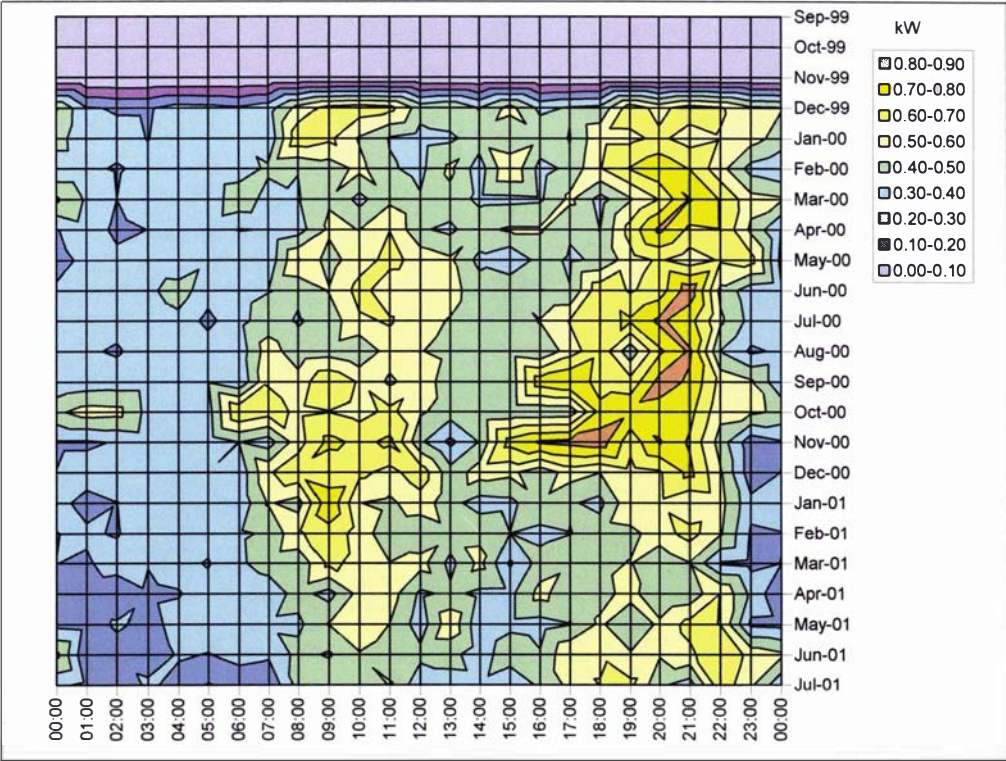


Figure 18.58 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 4.

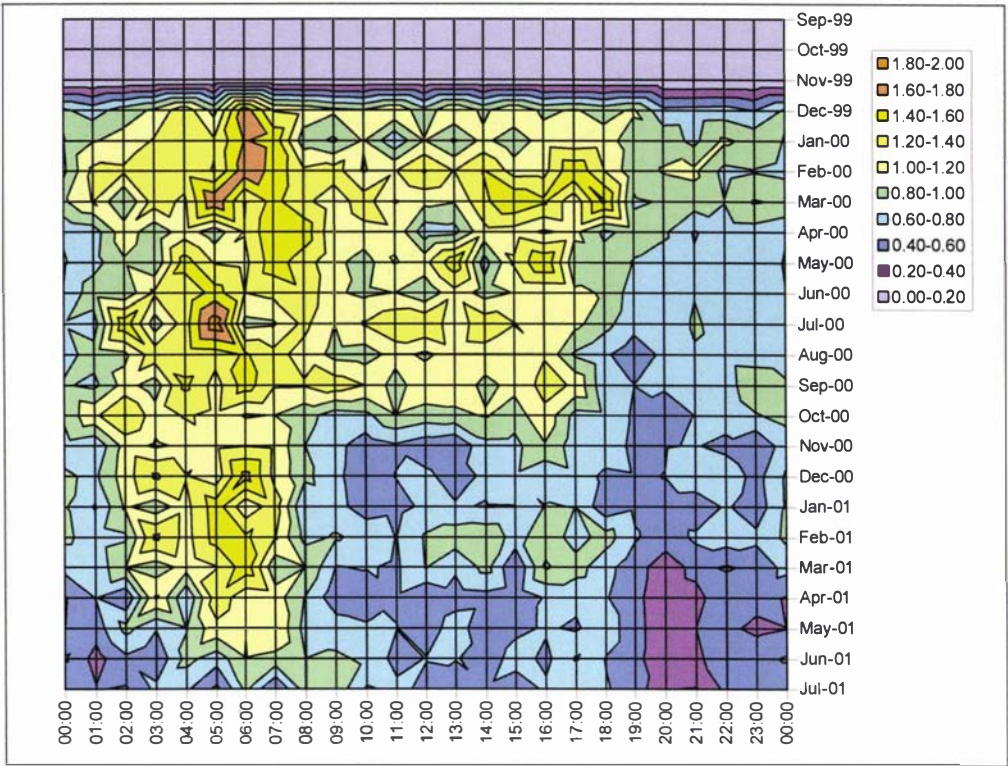


Figure 18.59 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 4.

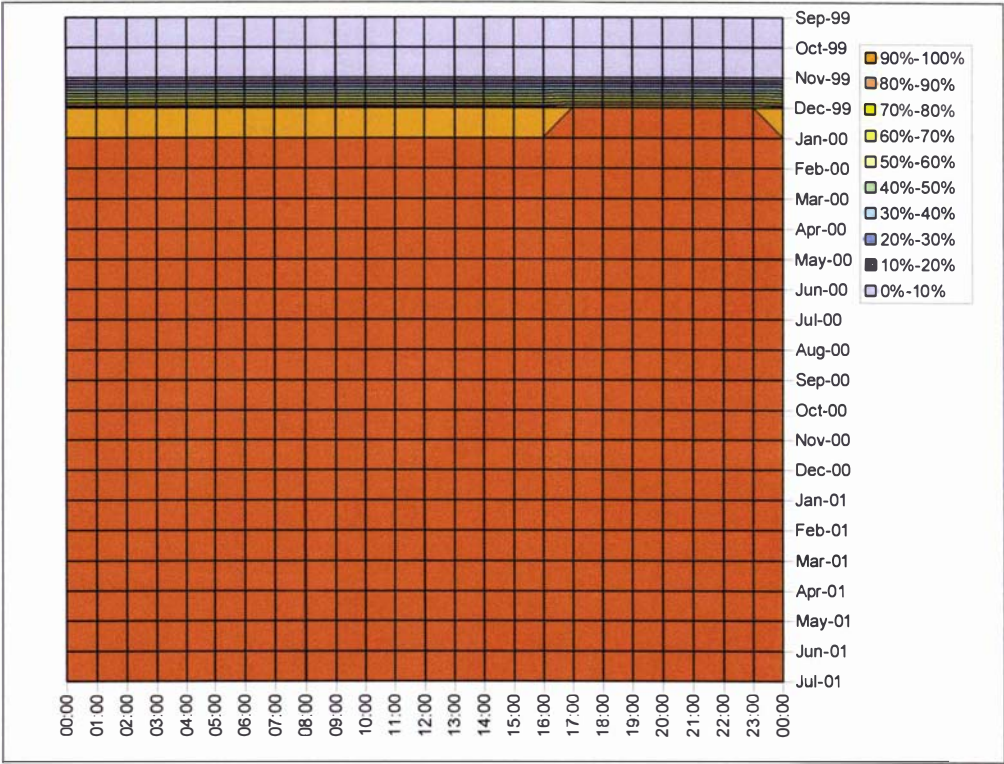


Figure 18.60 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 4.

Site 4 Workshop Load Profile Only

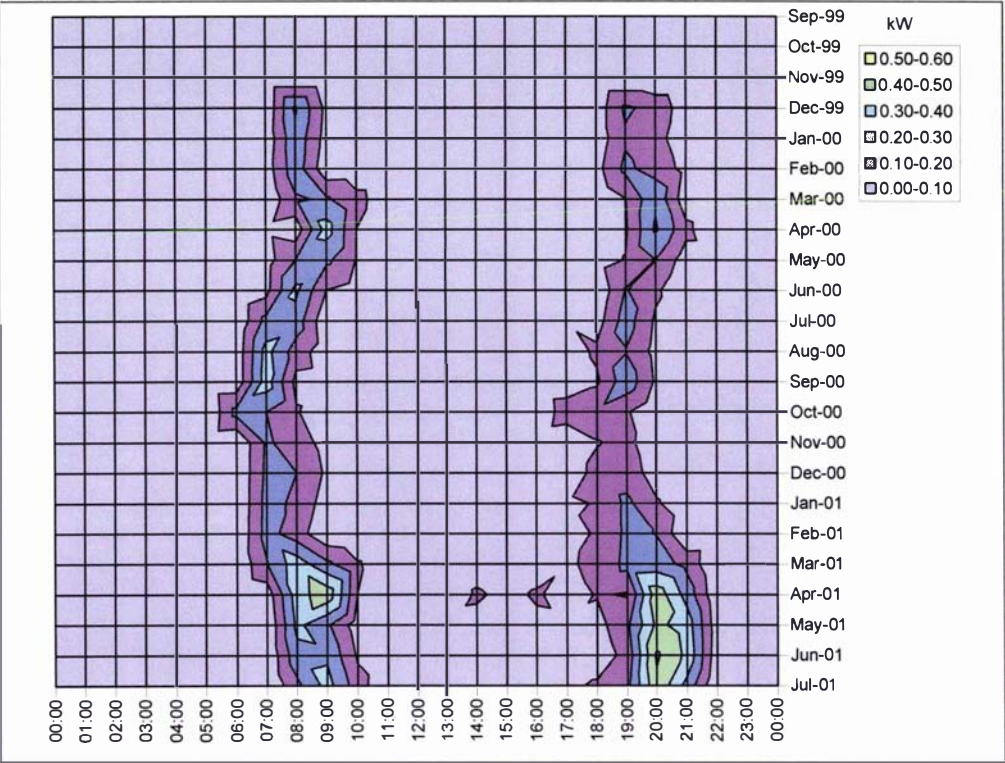


Figure 18.61 The mean monthly – diurnal workshop load profile over the duration of the monitoring for Site 4.

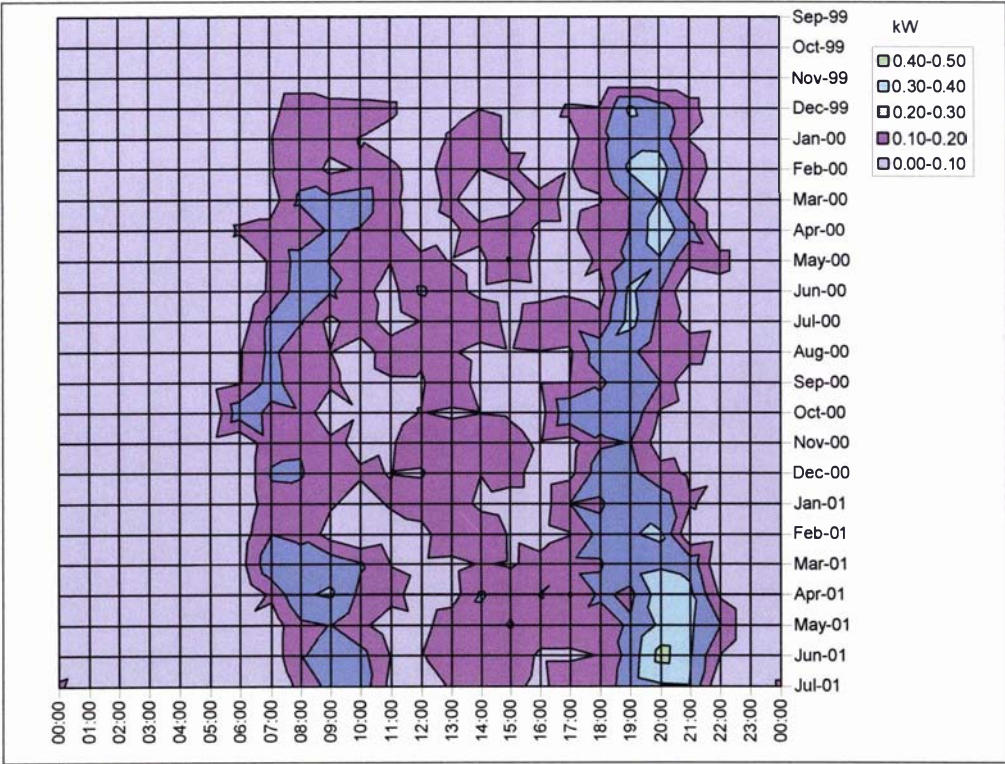


Figure 18.62 The standard deviation of the mean monthly – diurnal workshop load profile over the duration of the monitoring for Site 4.

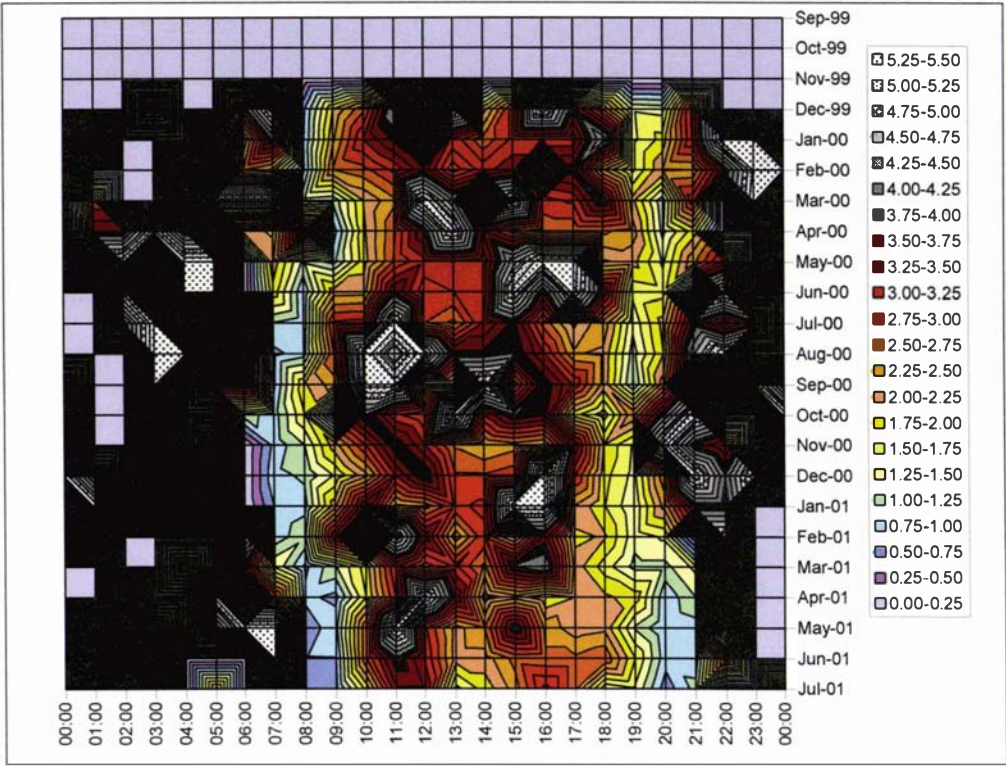


Figure 18.63 The coefficient of variation of the monthly – diurnal workshop load profile over the duration of the monitoring for Site 4.

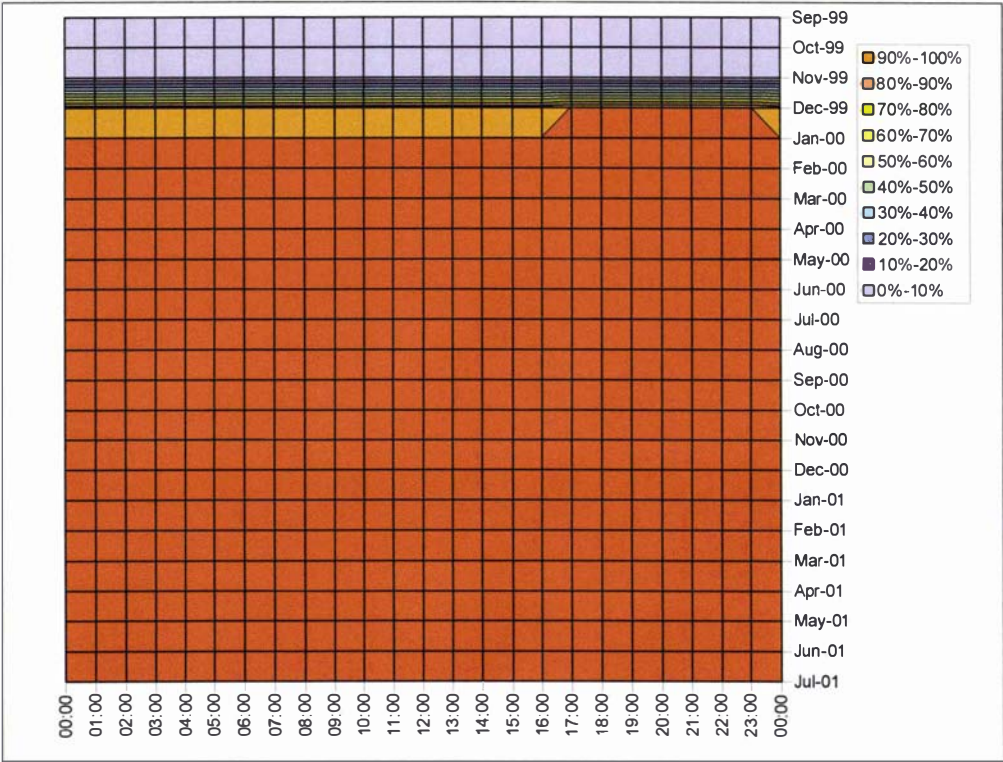


Figure 18.64 The data solidity of the monthly – diurnal workshop load profile over the duration of the monitoring for Site 4.

18.2.5 Site 5 – Electricity Load Profiles

Site 5 Domestic and Water Heating Load Profiles

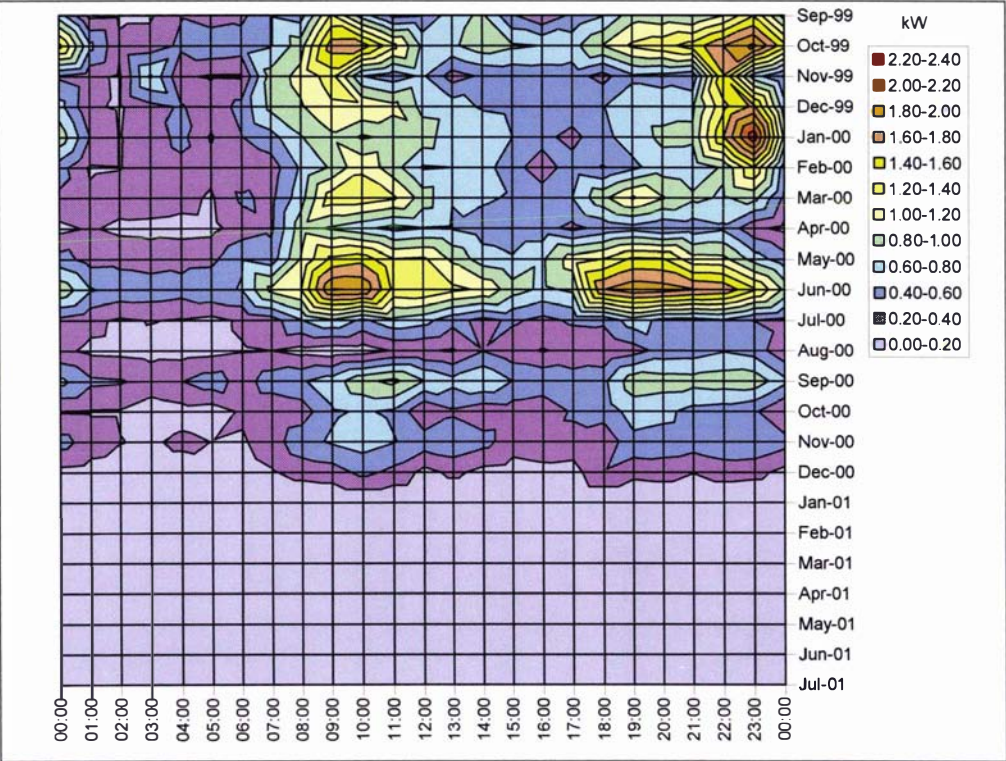


Figure 18.65 The mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 5.

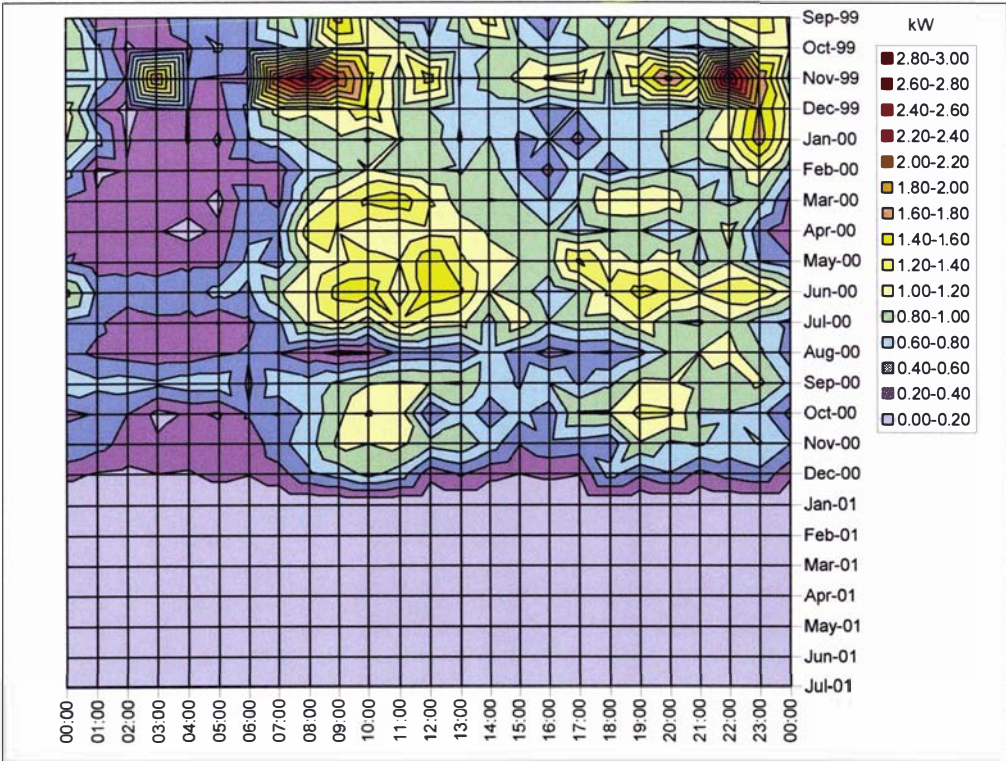


Figure 18.66 The standard deviation of the mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 5.

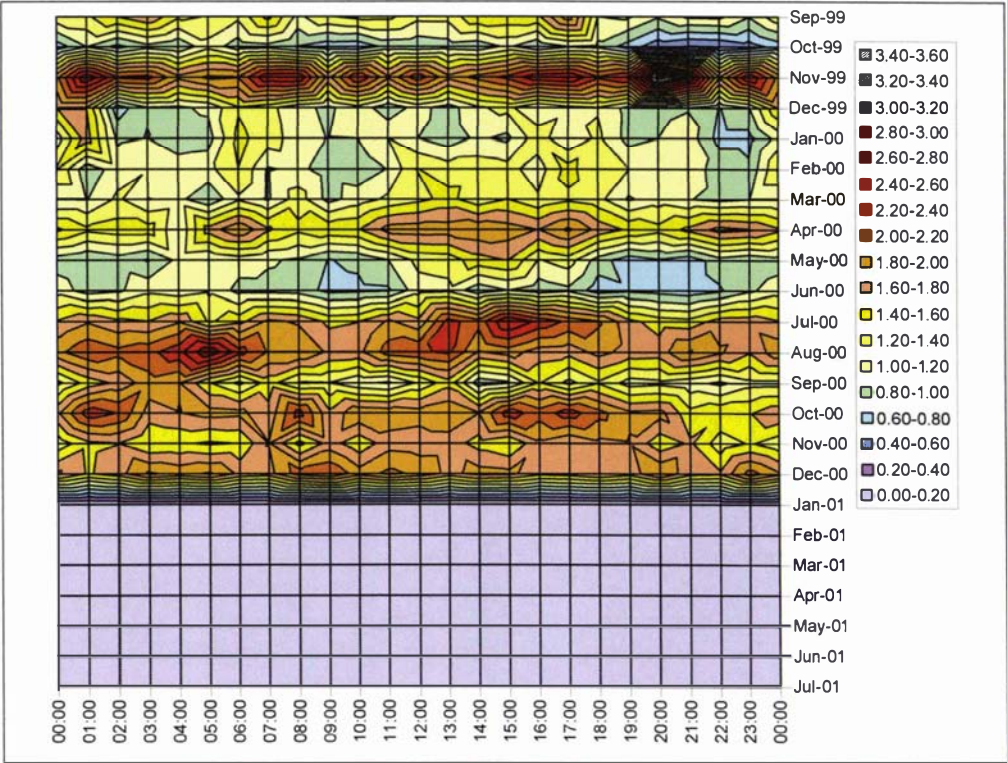


Figure 18.67 The coefficient of variation of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 5.

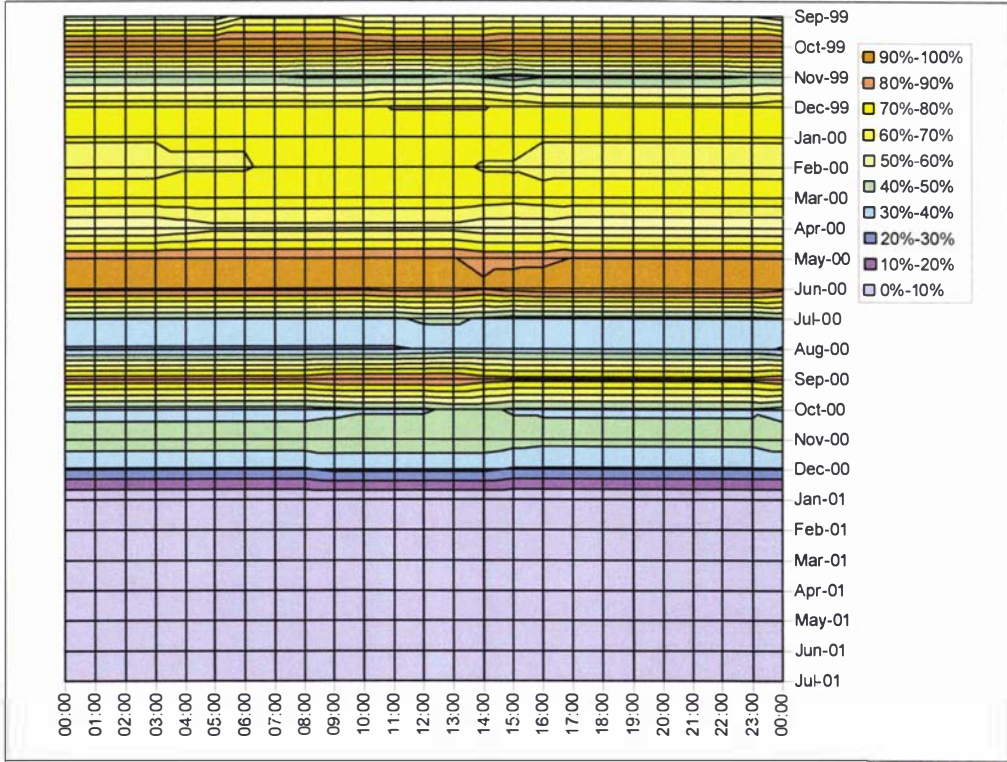


Figure 18.68 The data solidity of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 5.

Site 5 Domestic Load Profile Only

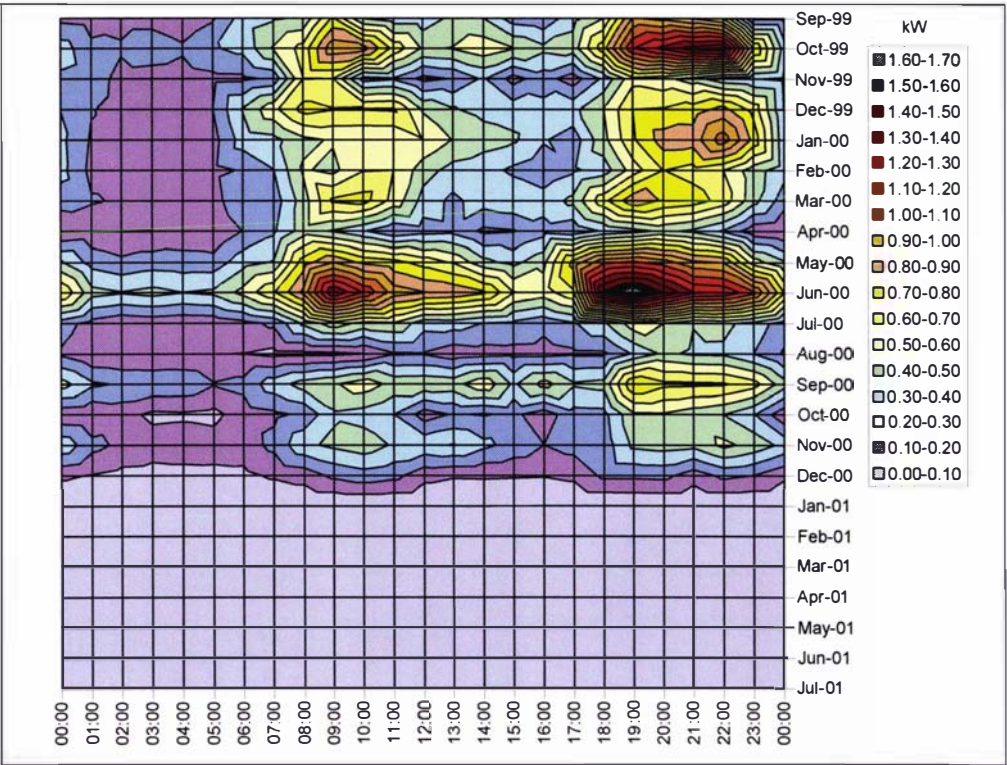


Figure 18.69 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 5.

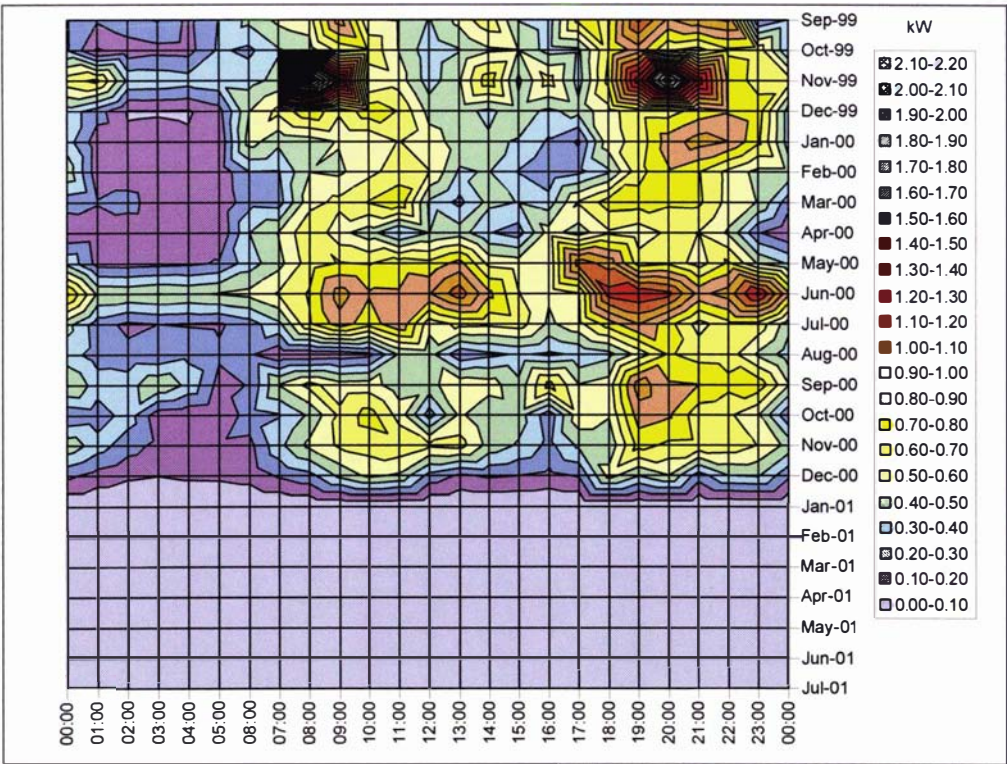


Figure 18.70 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 5.

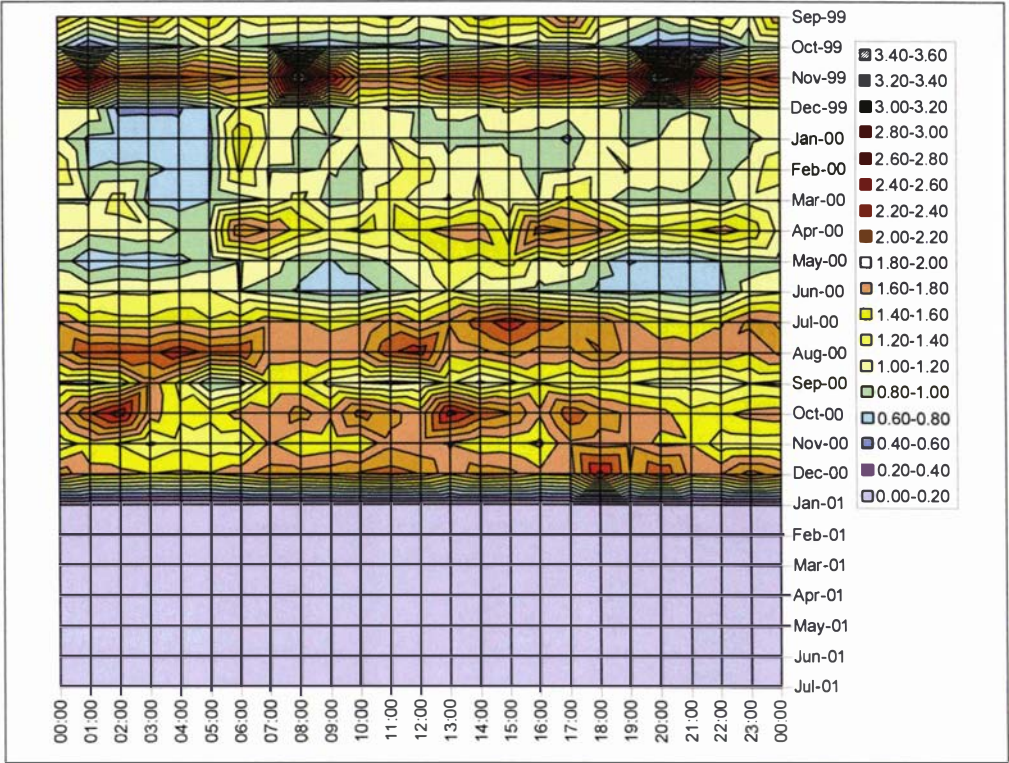


Figure 18.71 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 5.

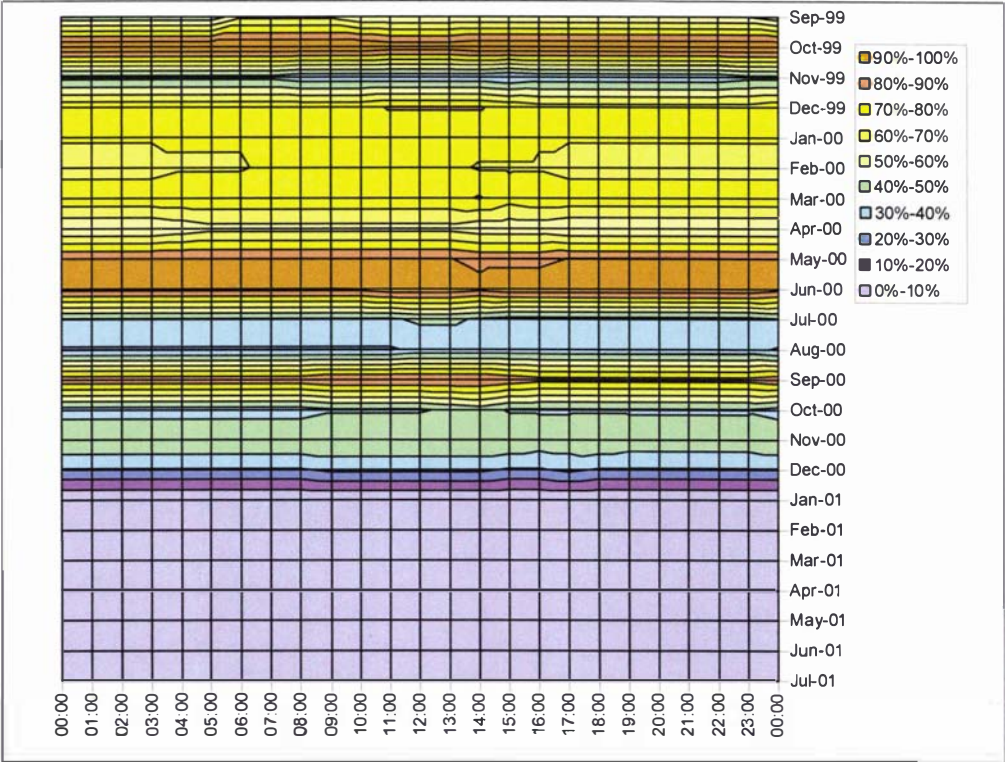


Figure 18.72 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 5.

Site 5 Water Heating Load Profile Only

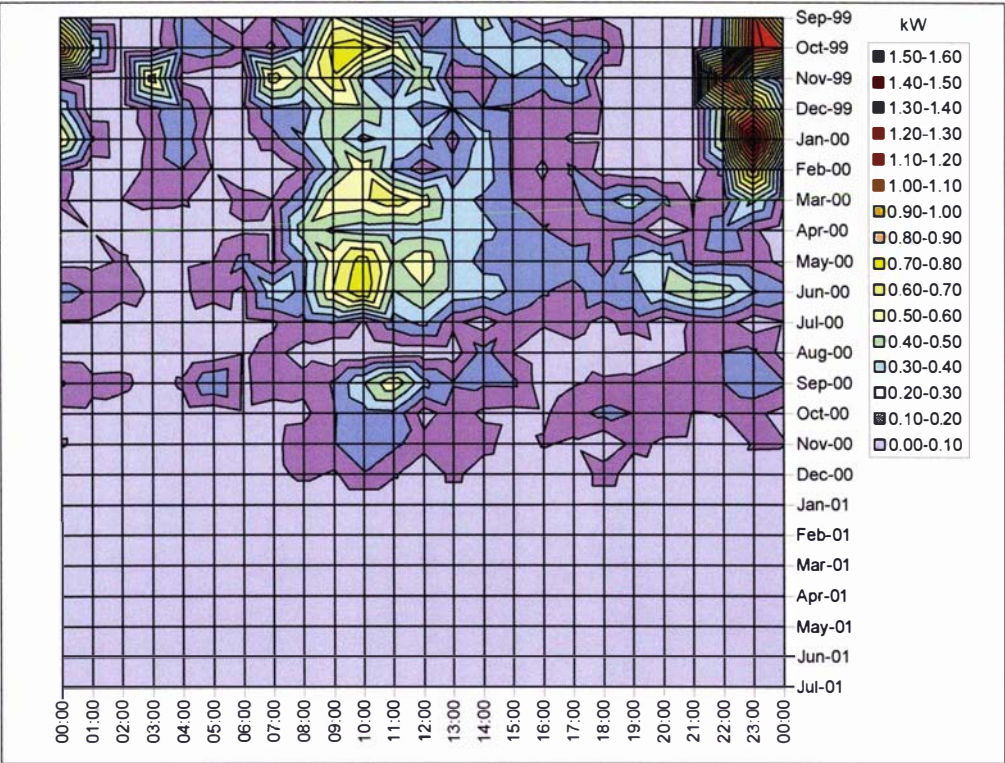


Figure 18.73 The mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 5.

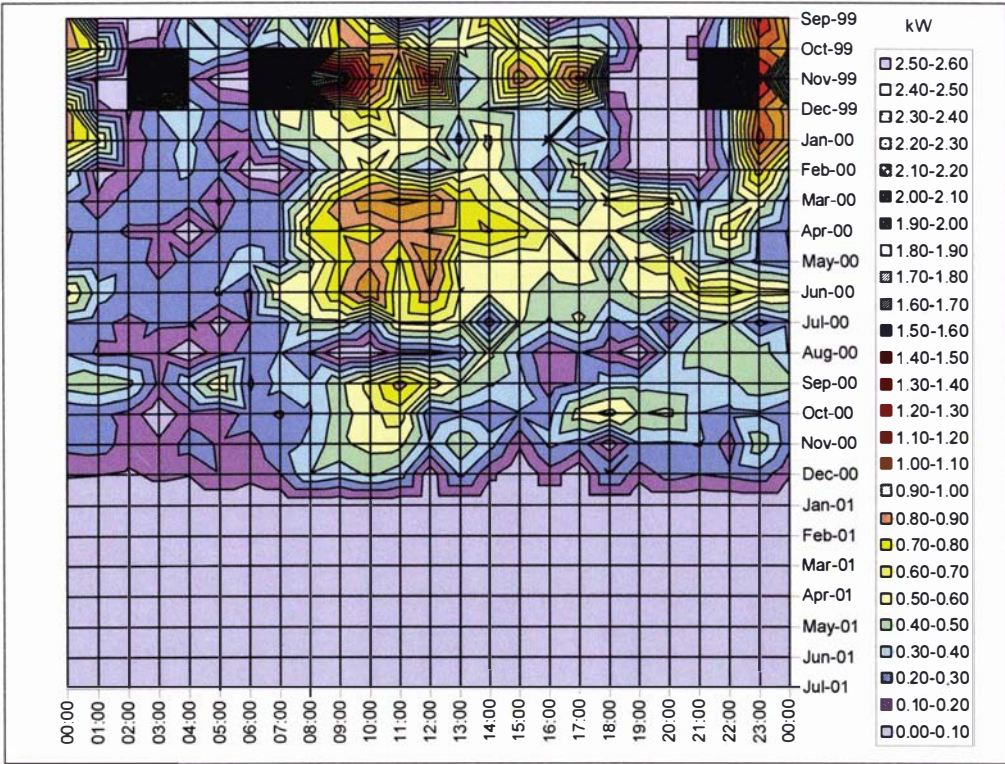


Figure 18.74 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 5.

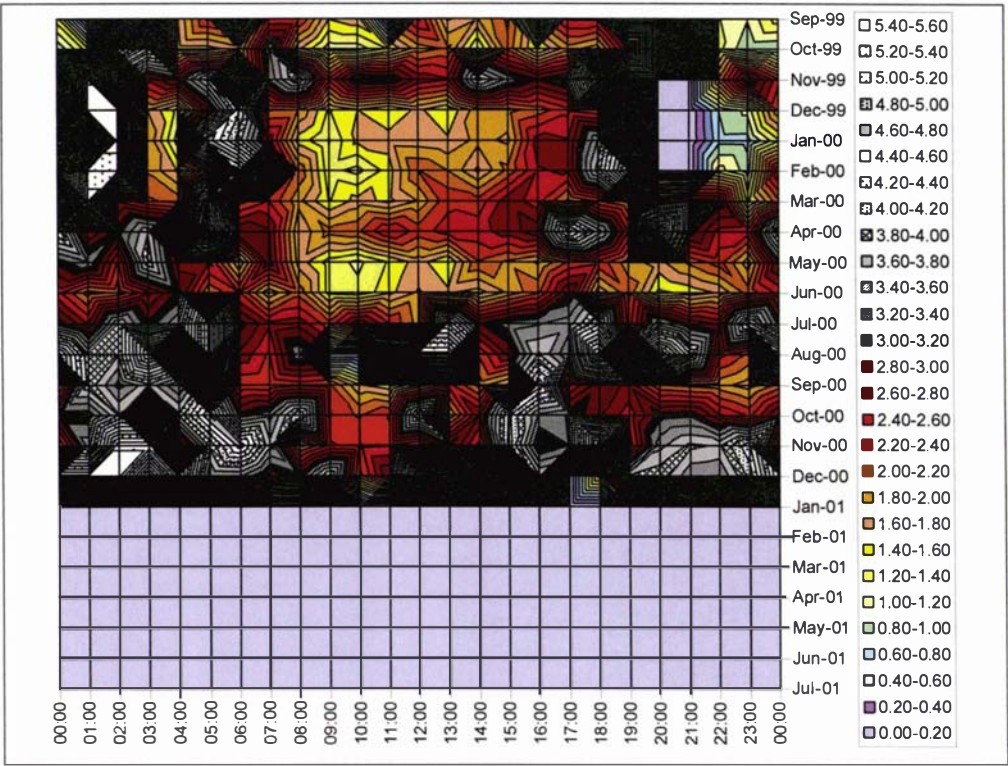


Figure 18.75 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 5.

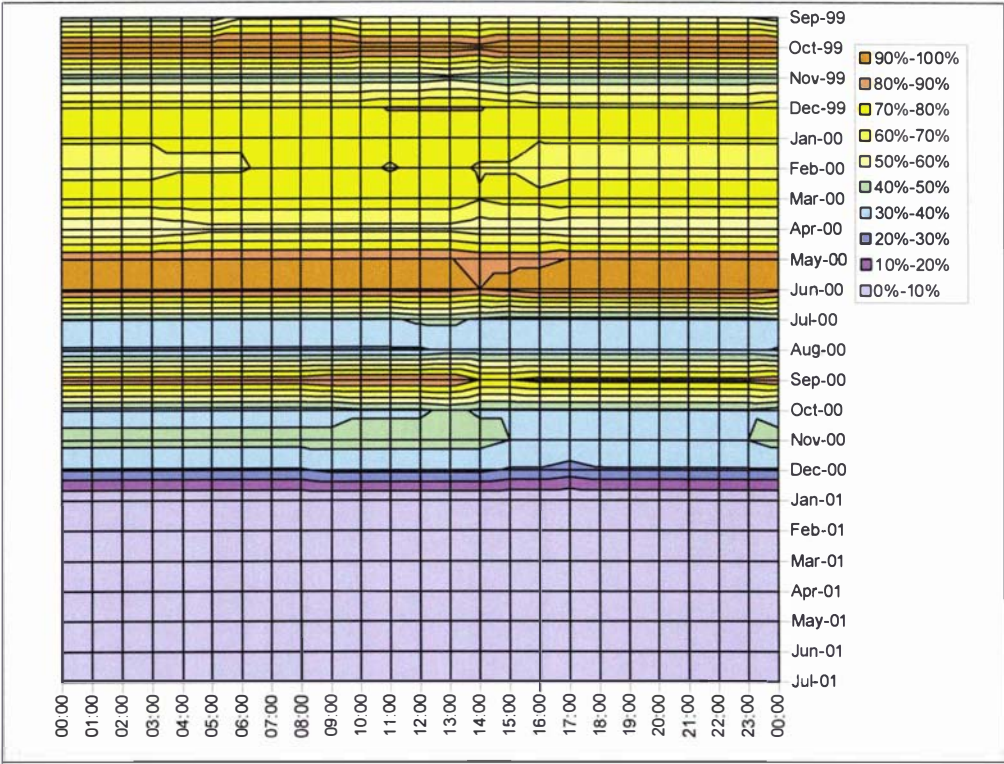


Figure 18.76 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 5.

18.2.6 Site 6 – Electricity Load Profiles

Site 6 Domestic and Water Heating Load Profiles

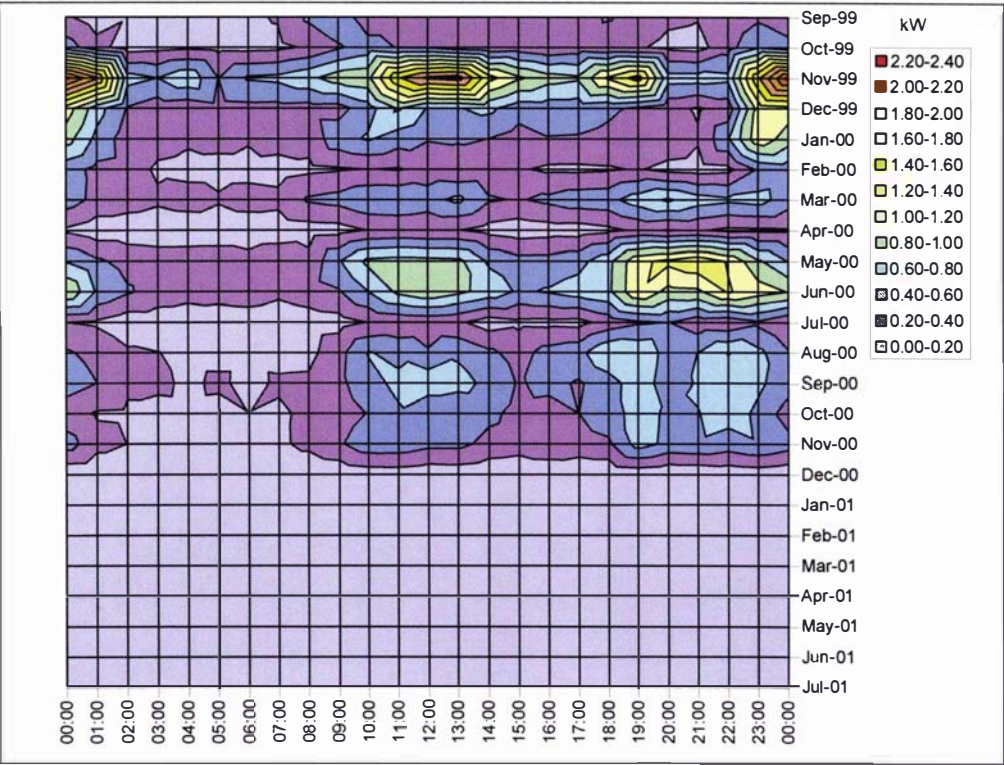


Figure 18.77 The mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 6.

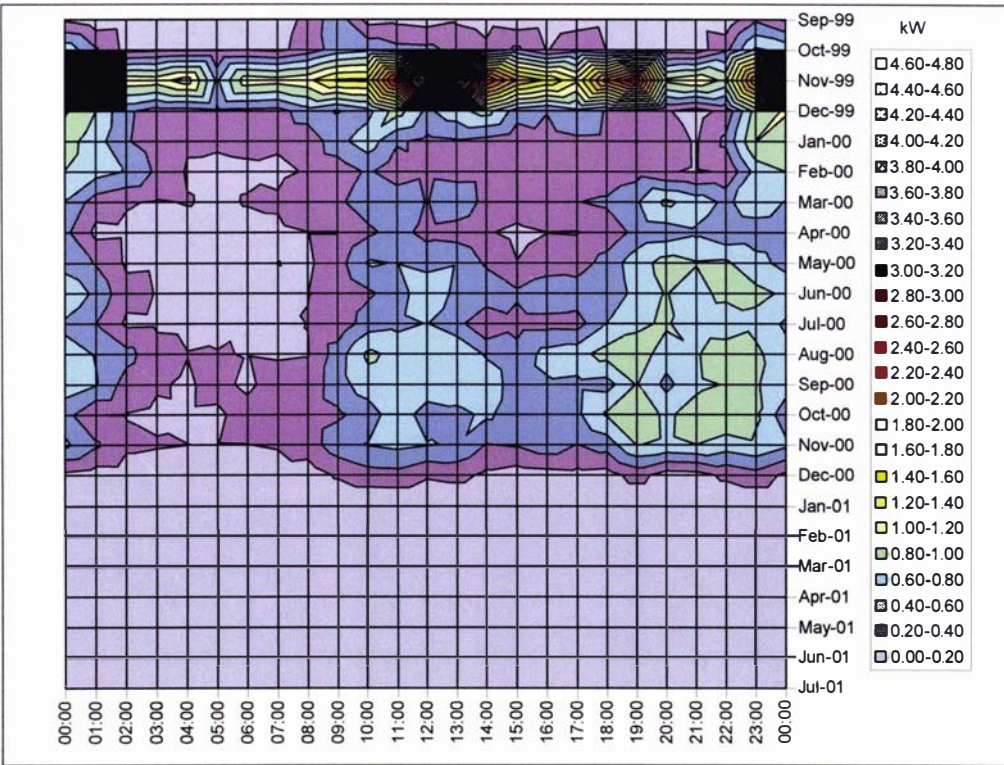


Figure 18.78 The standard deviation of the mean monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 6.

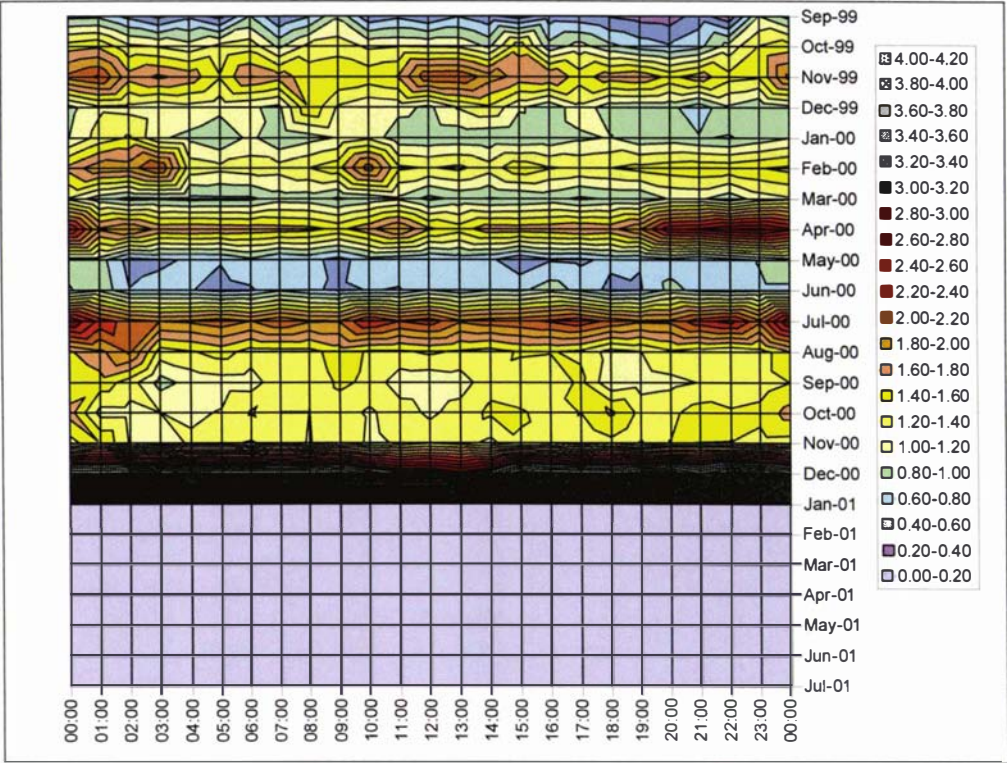


Figure 18.79 The coefficient of variation of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 6.

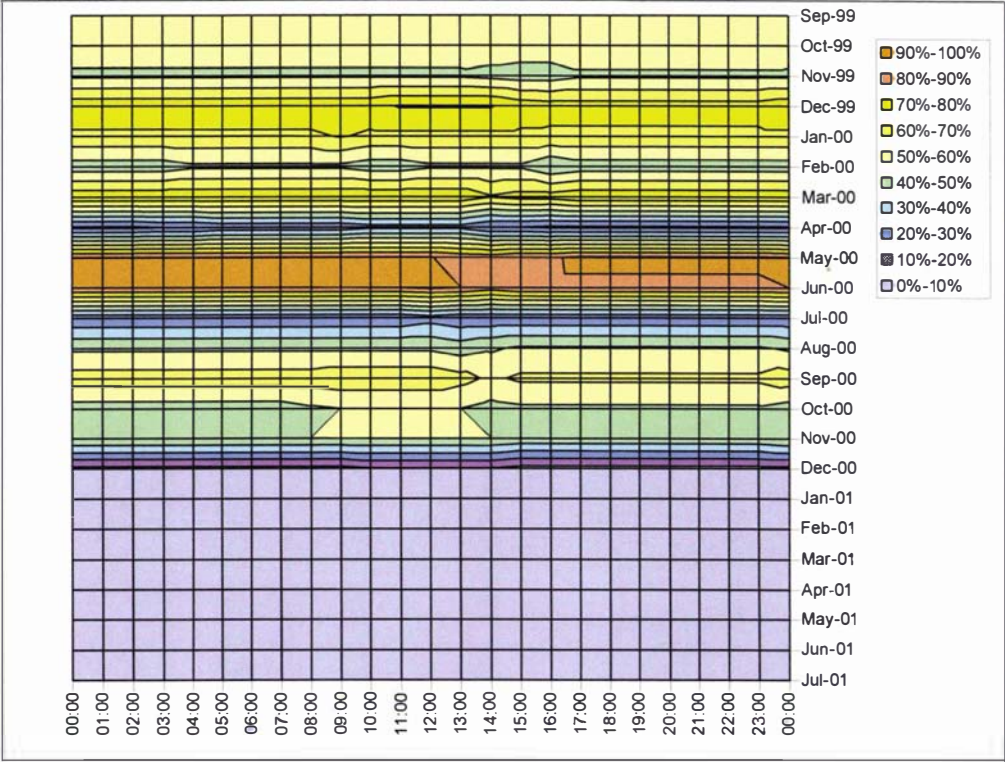


Figure 18.80 The data solidity of the monthly – diurnal domestic and water heating load profile over the duration of the monitoring for Site 6.

Site 6 Domestic Load Profile Only

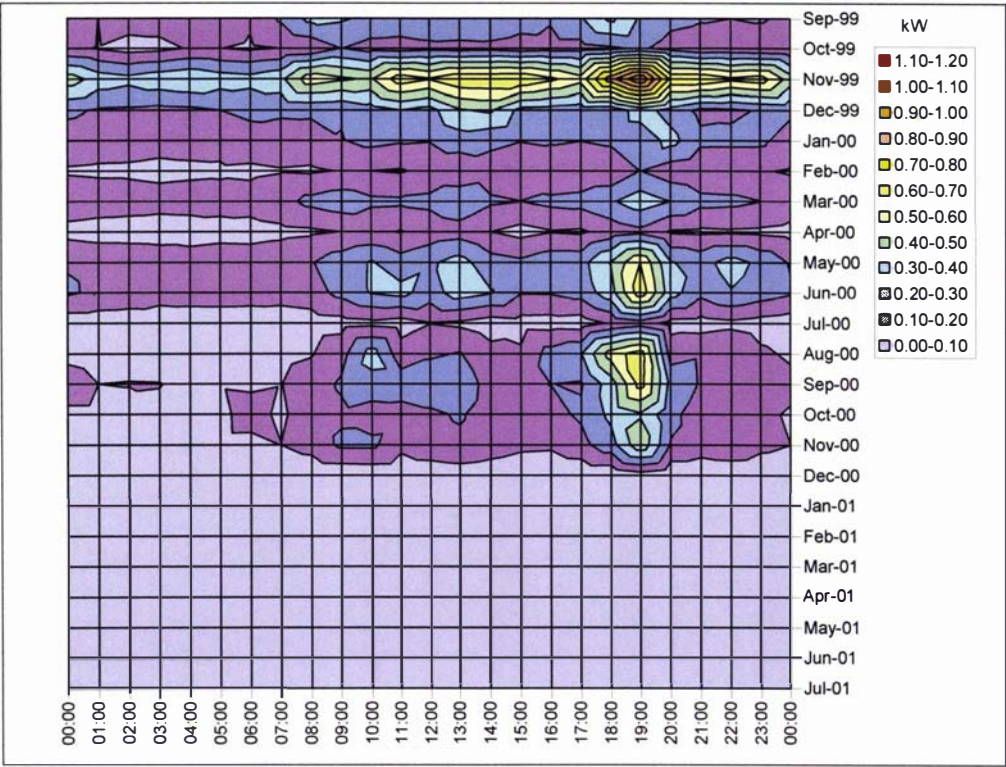


Figure 18.81 The mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 6.

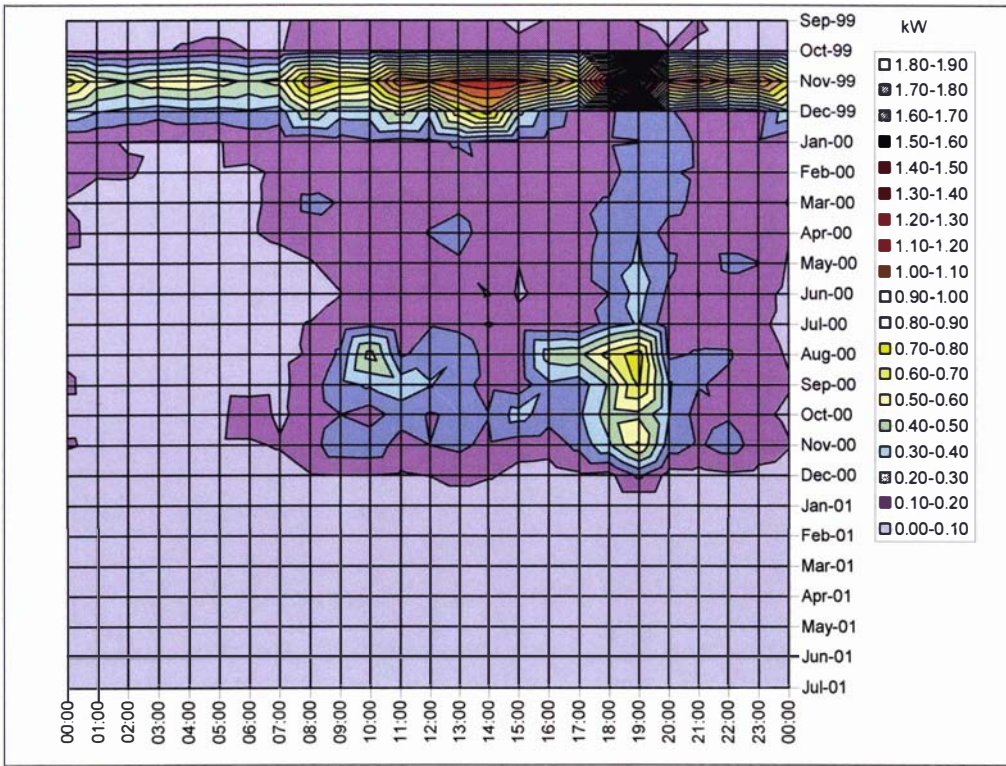


Figure 18.82 The standard deviation of the mean monthly – diurnal domestic load profile over the duration of the monitoring for Site 6.

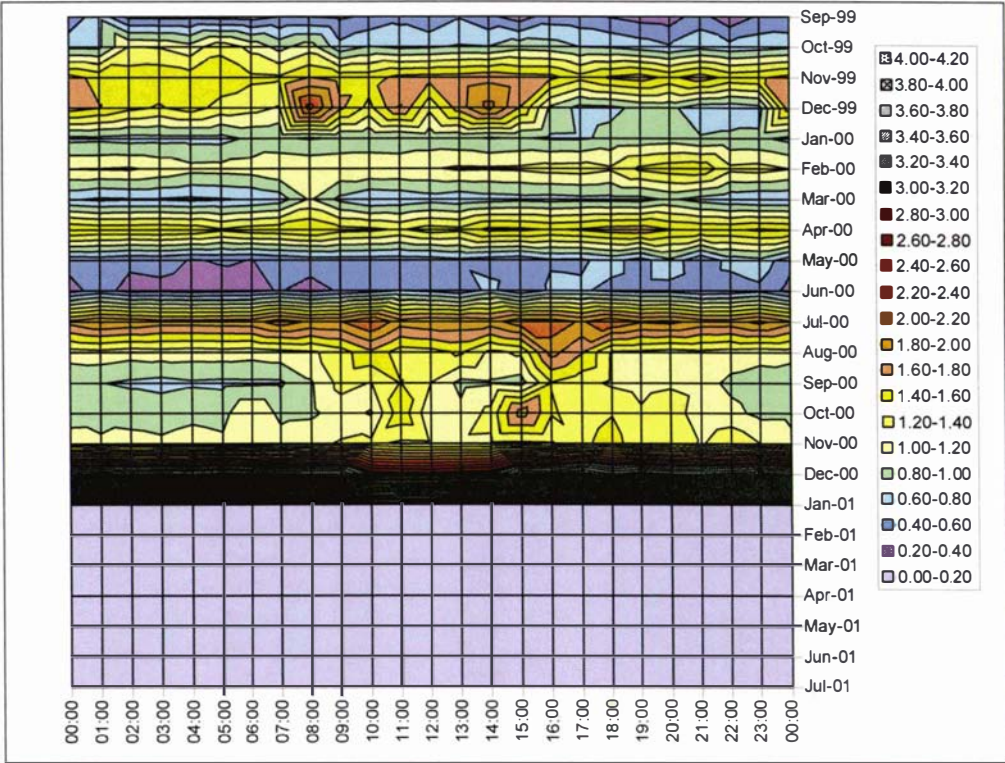


Figure 18.83 The coefficient of variation of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 6.

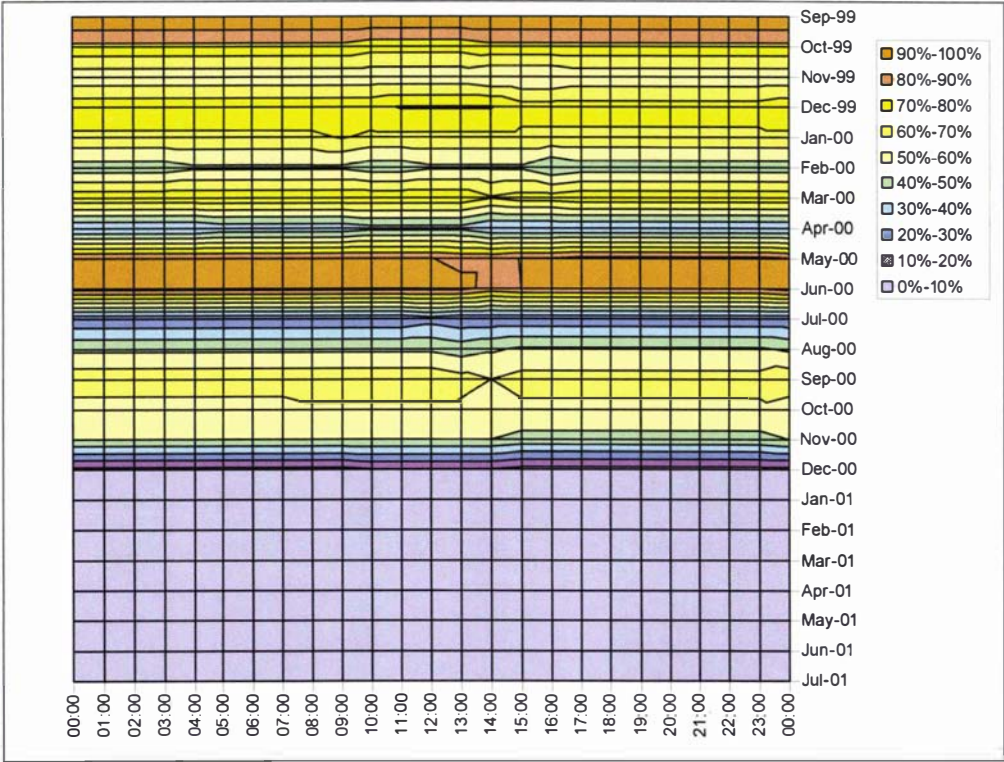


Figure 18.84 The data solidity of the monthly – diurnal domestic load profile over the duration of the monitoring for Site 6.

Site 6 Water Heating Load Profile Only

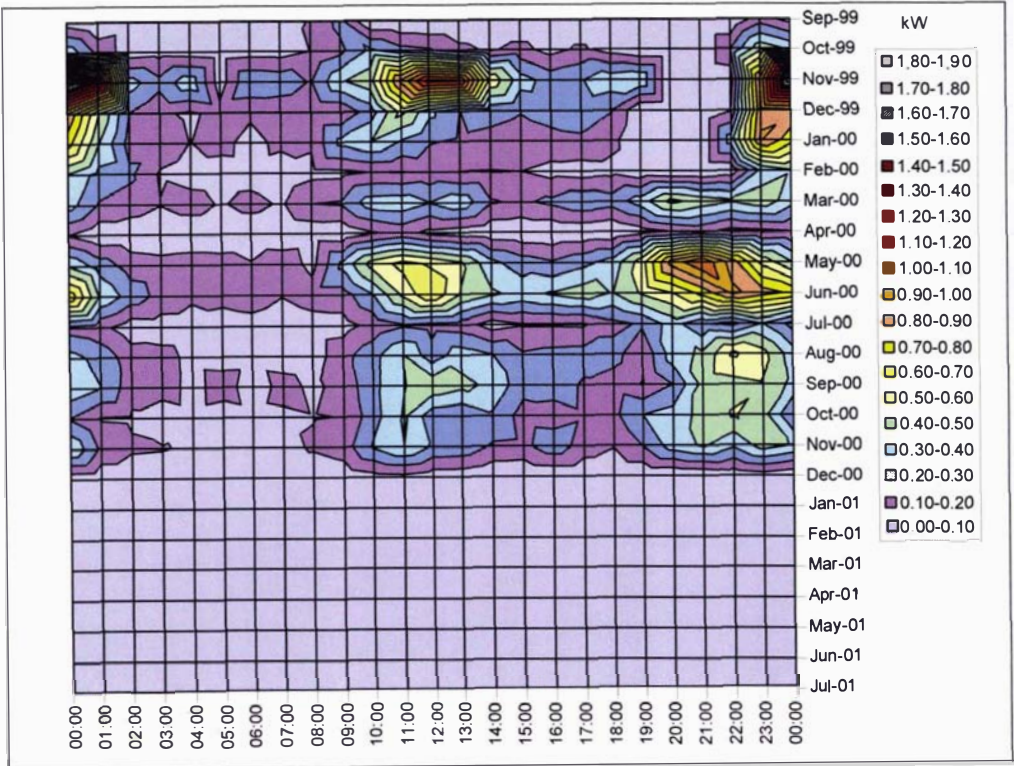


Figure 18.85 The mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 6.

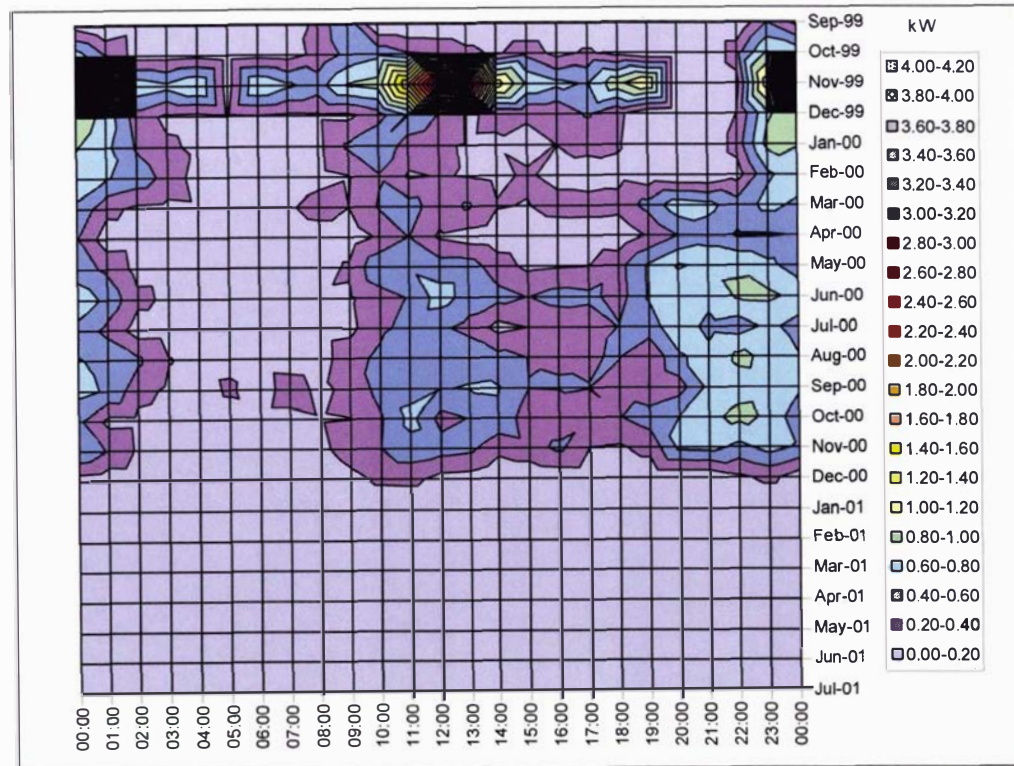


Figure 18.86 The standard deviation of the mean monthly – diurnal water heating load profile over the duration of the monitoring for Site 6.

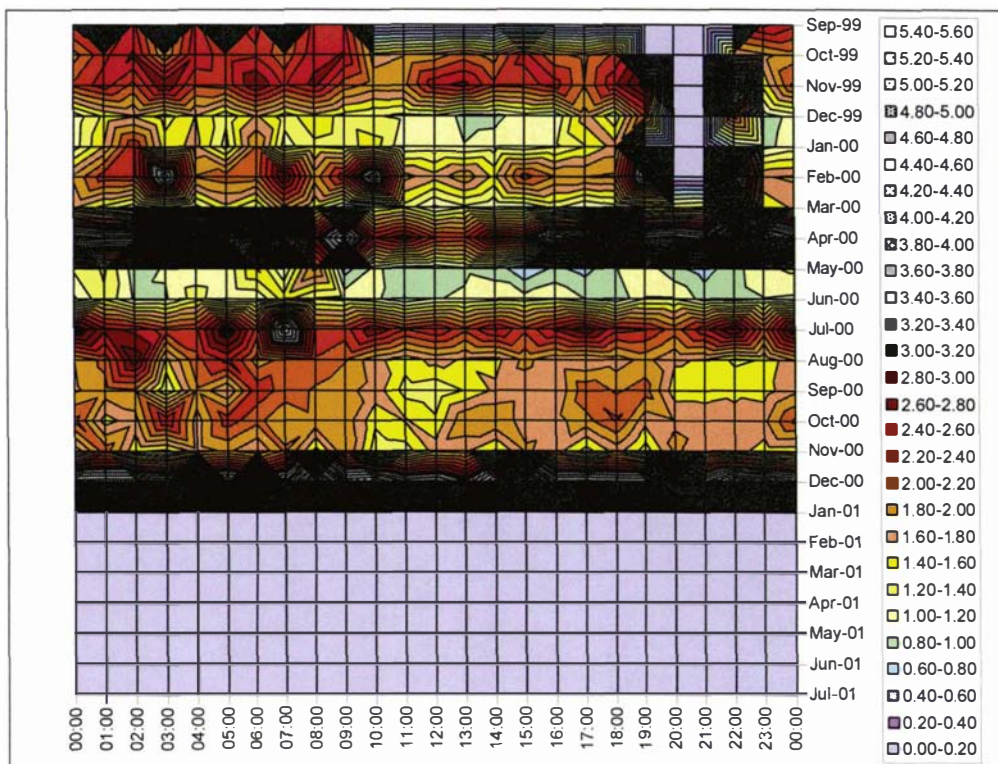


Figure 18.87 The coefficient of variation of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 6.

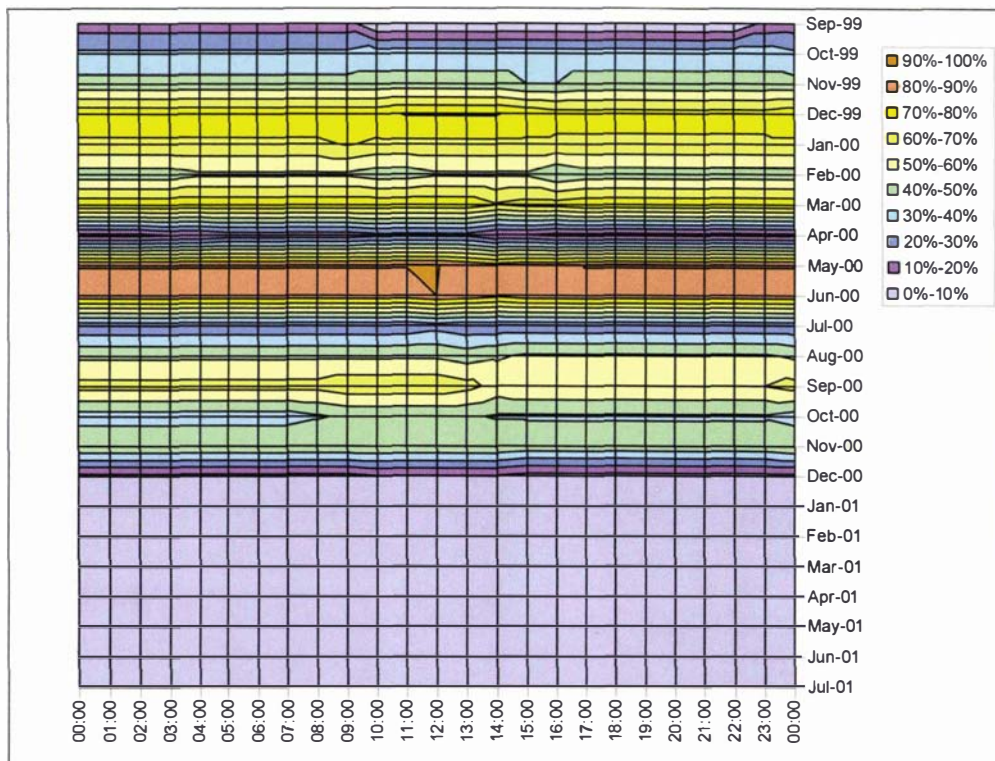


Figure 18.88 The data solidity of the monthly – diurnal water heating load profile over the duration of the monitoring for Site 6.

18.2.7 Site 7 – Electricity Load Profiles

Site 7 Shearing Shed and Freezer Shed Load Profiles

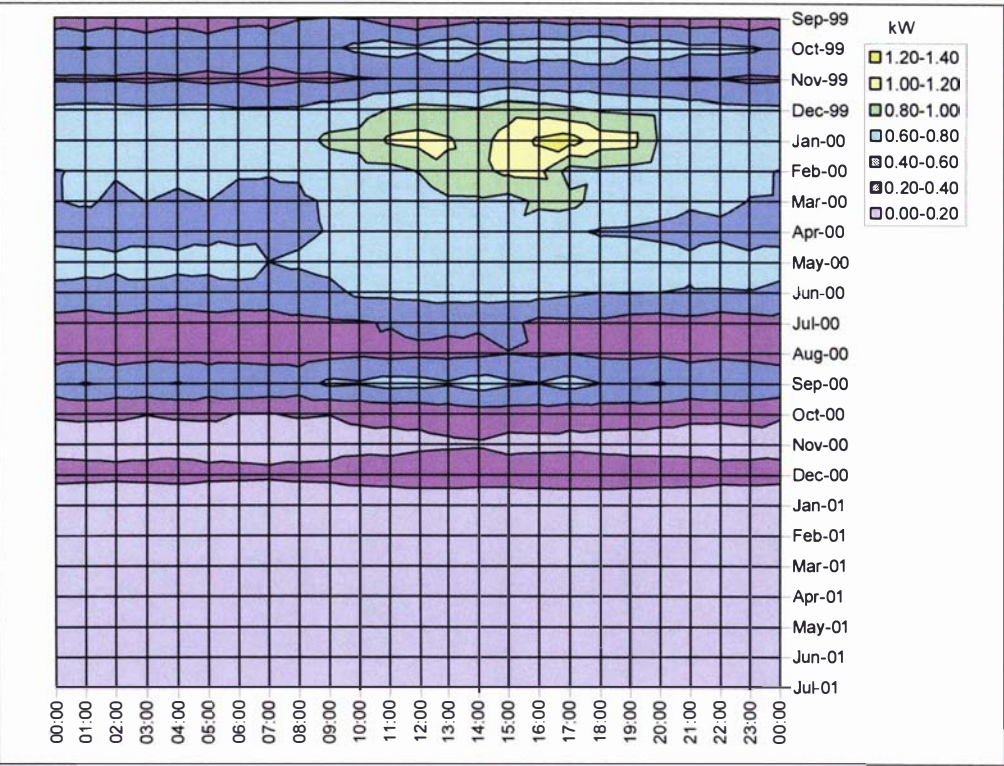


Figure 18.89 The mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 7.

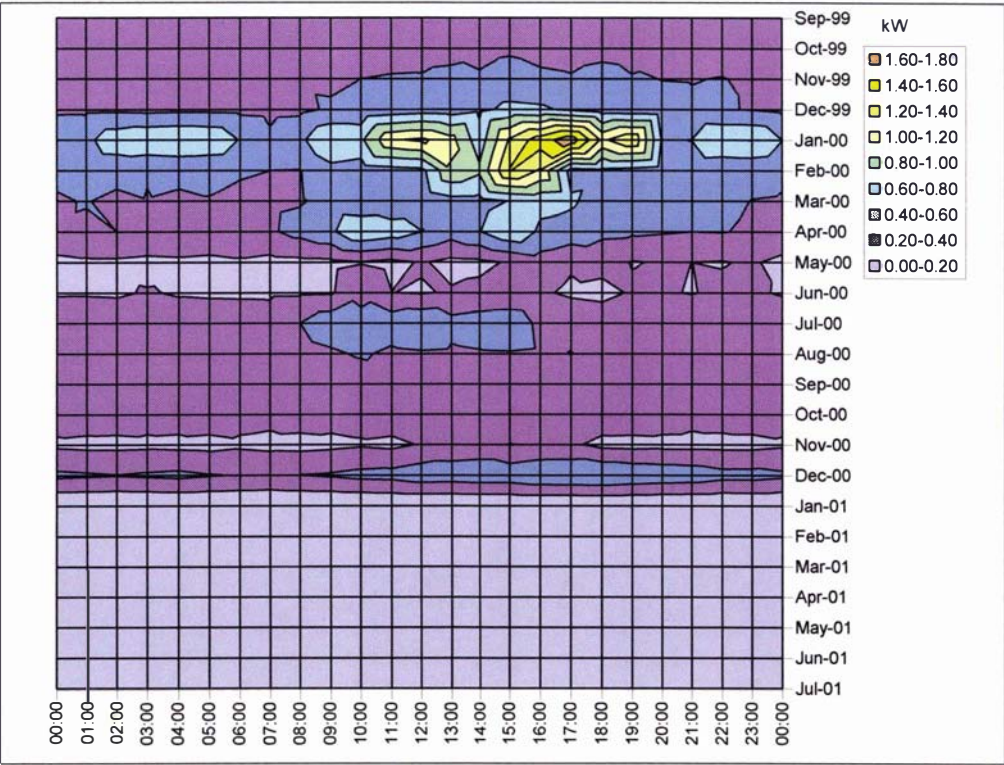


Figure 18.90 The standard deviation of the mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 7.

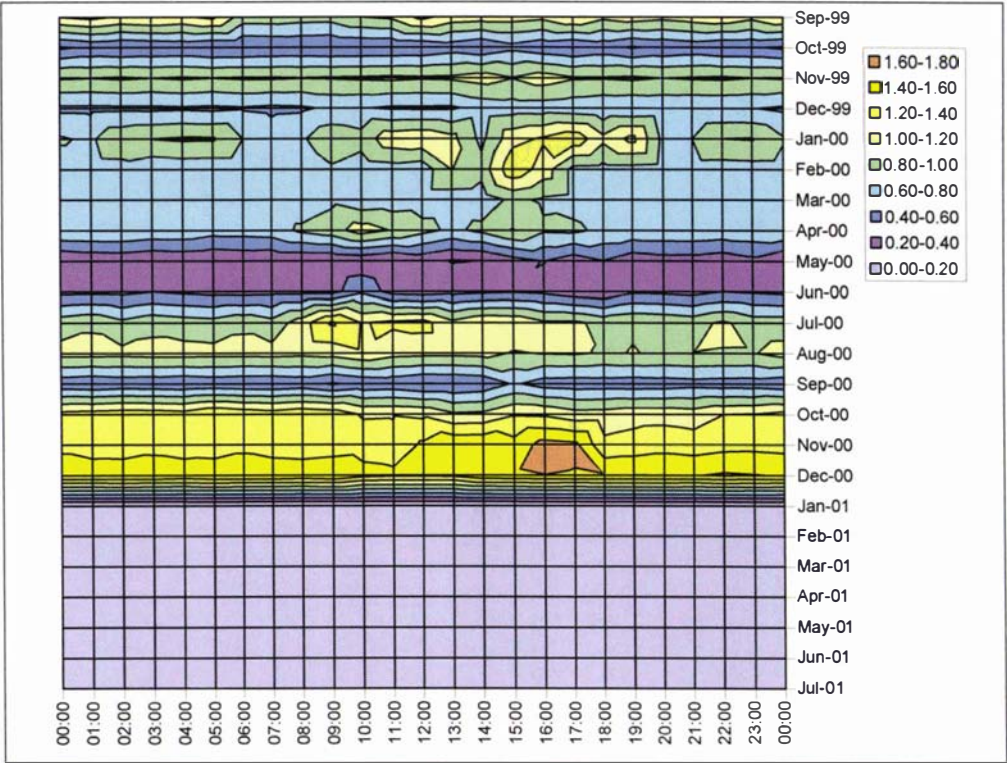


Figure 18.91 The coefficient of variation of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 7.

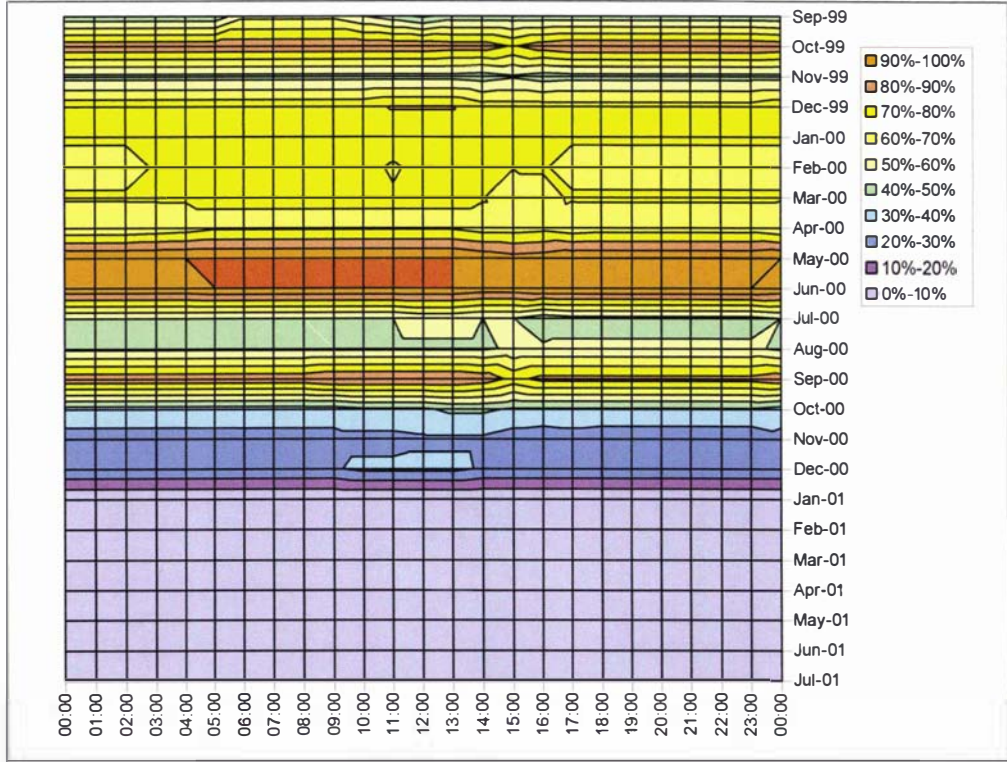


Figure 18.92 The data solidity of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 7.

Site 7 Shearing Shed Load Profile Only

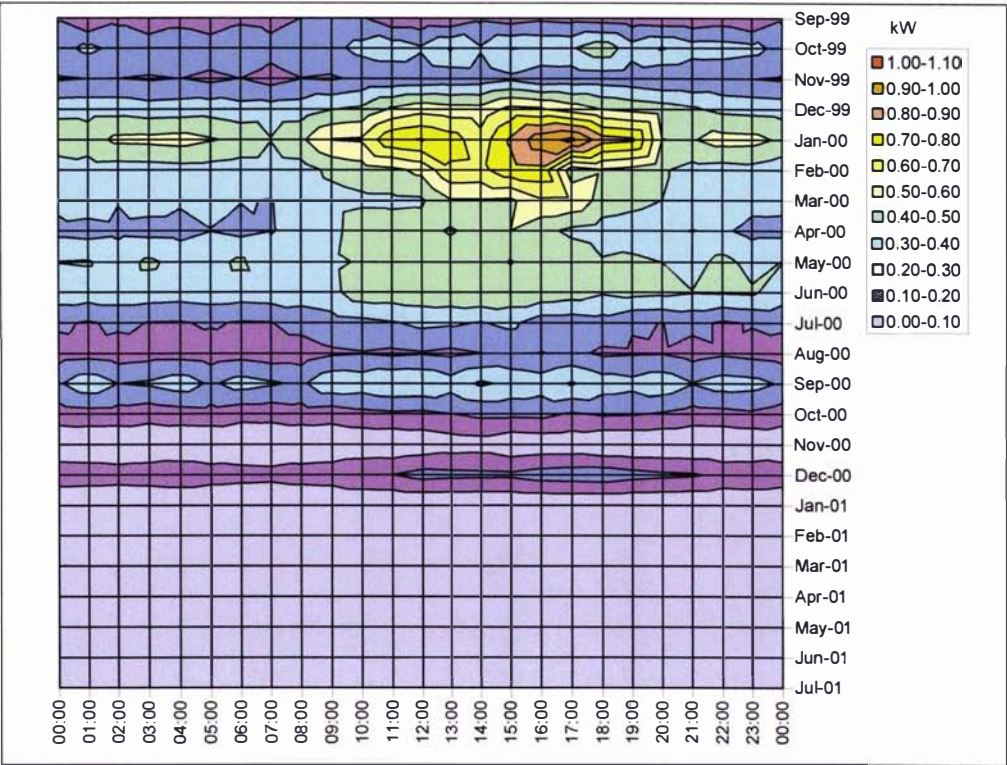


Figure 18.93 The mean monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 7.

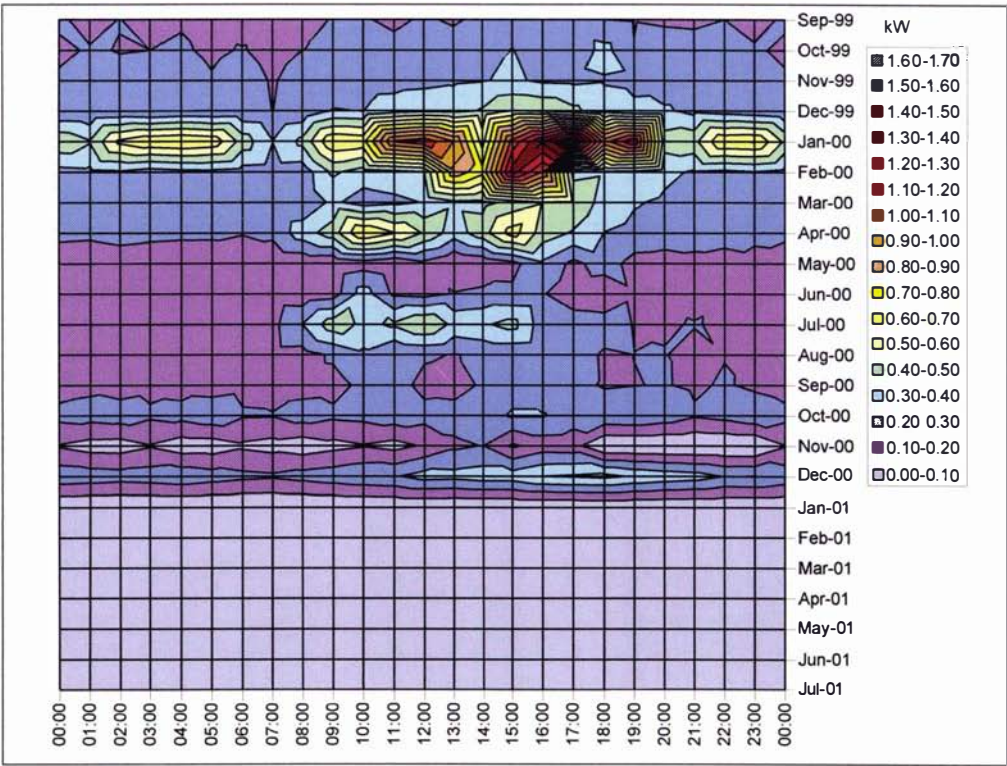


Figure 18.94 The standard deviation of the mean monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 7.

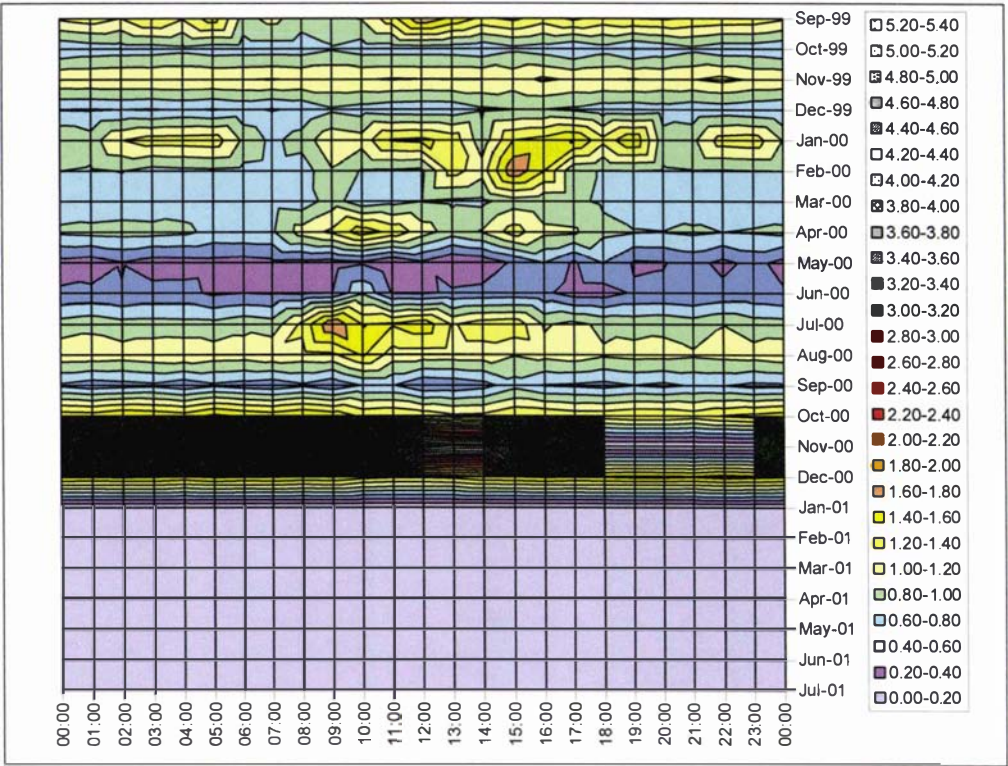


Figure 18.95 The coefficient of variation of the monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 7.

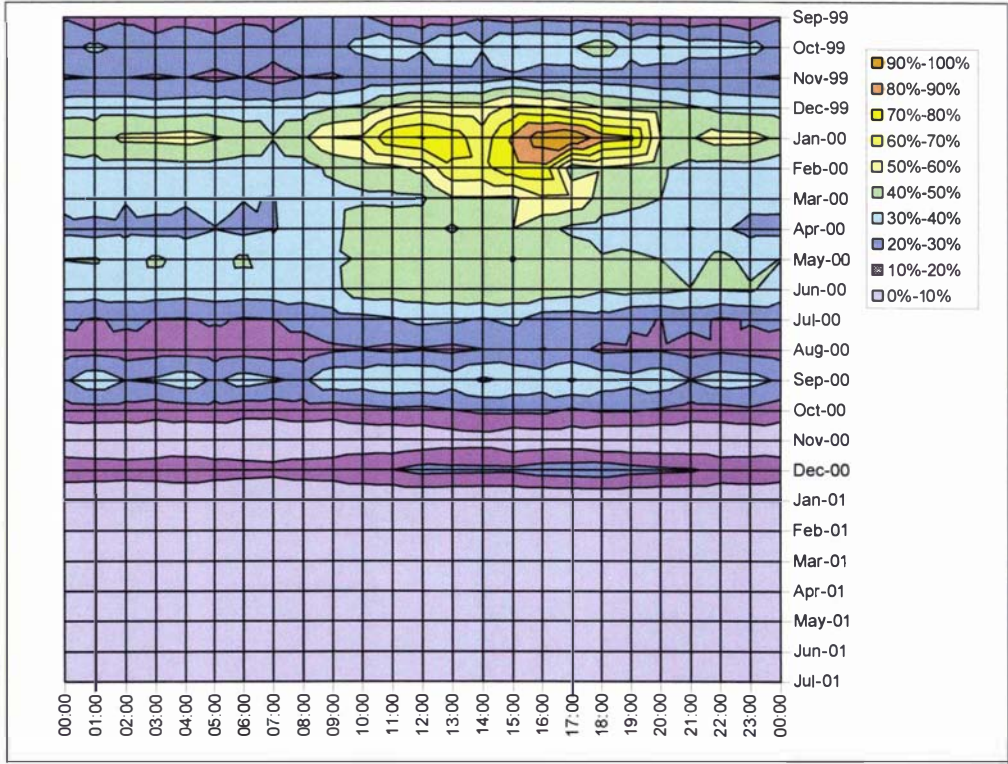


Figure 18.96 The data solidity of the monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 7.

Site 7 Freezer Shed Load Profile Only

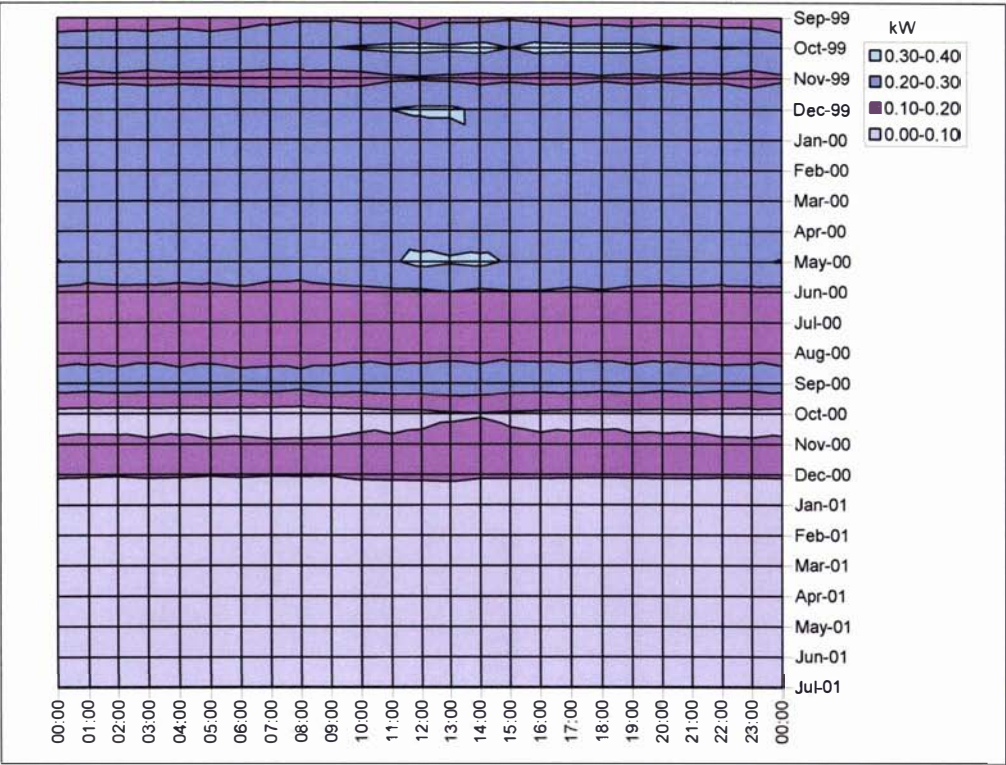


Figure 18.97 The mean monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 7.

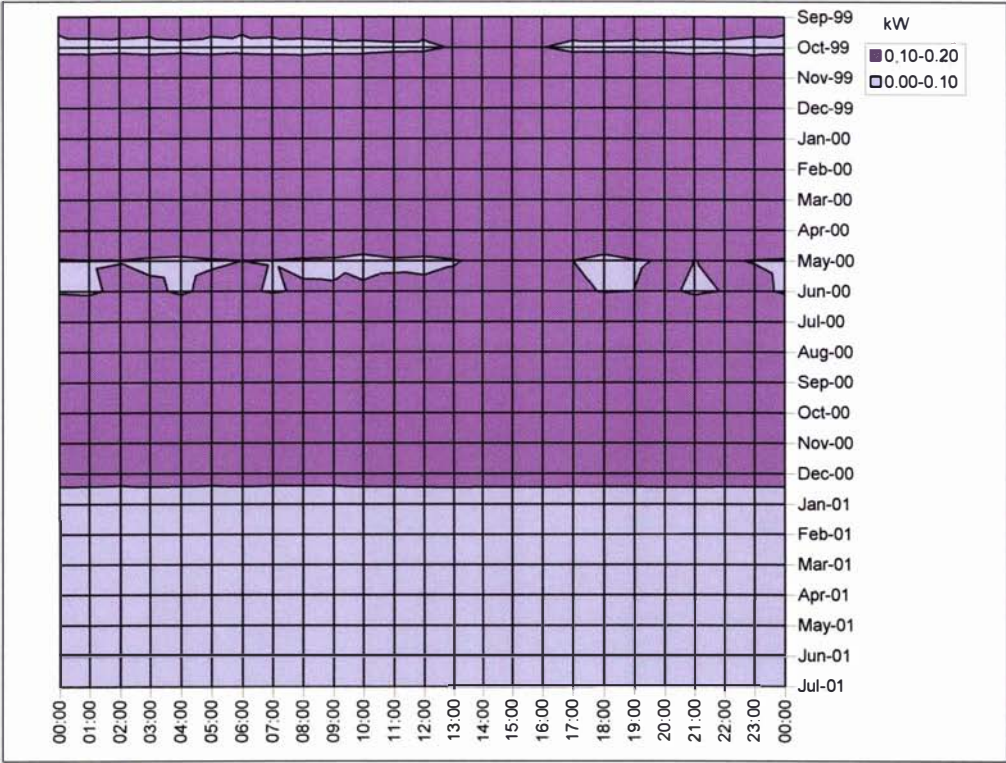


Figure 18.98 The standard deviation of the mean monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 7.

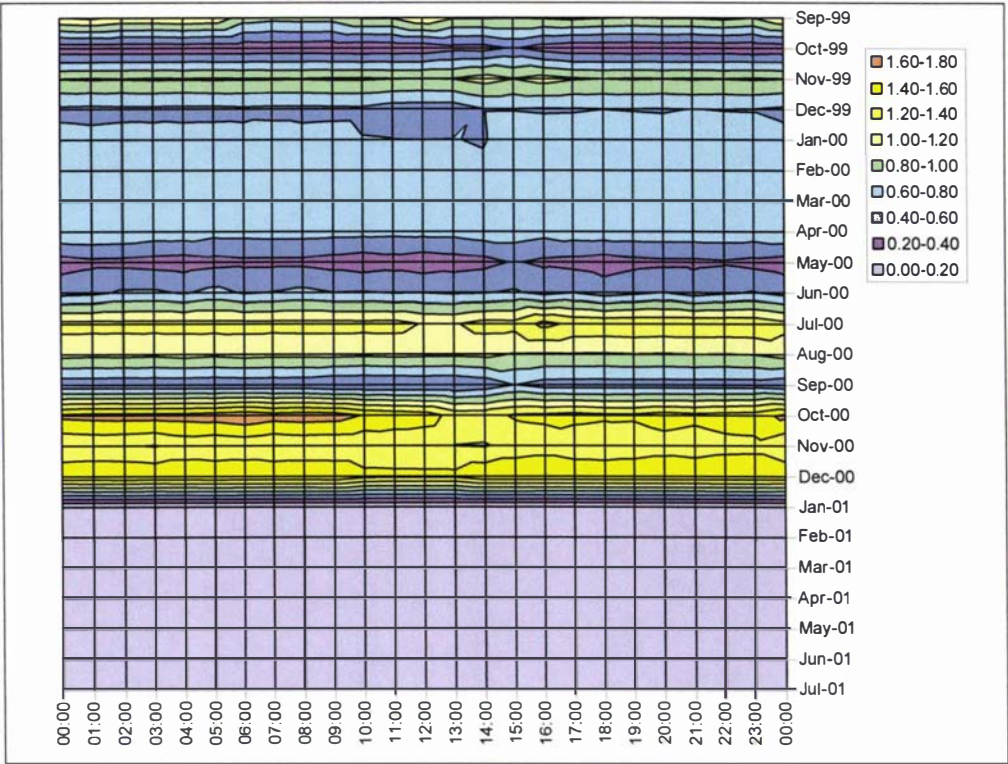


Figure 18.99 The coefficient of variation of the monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 7.

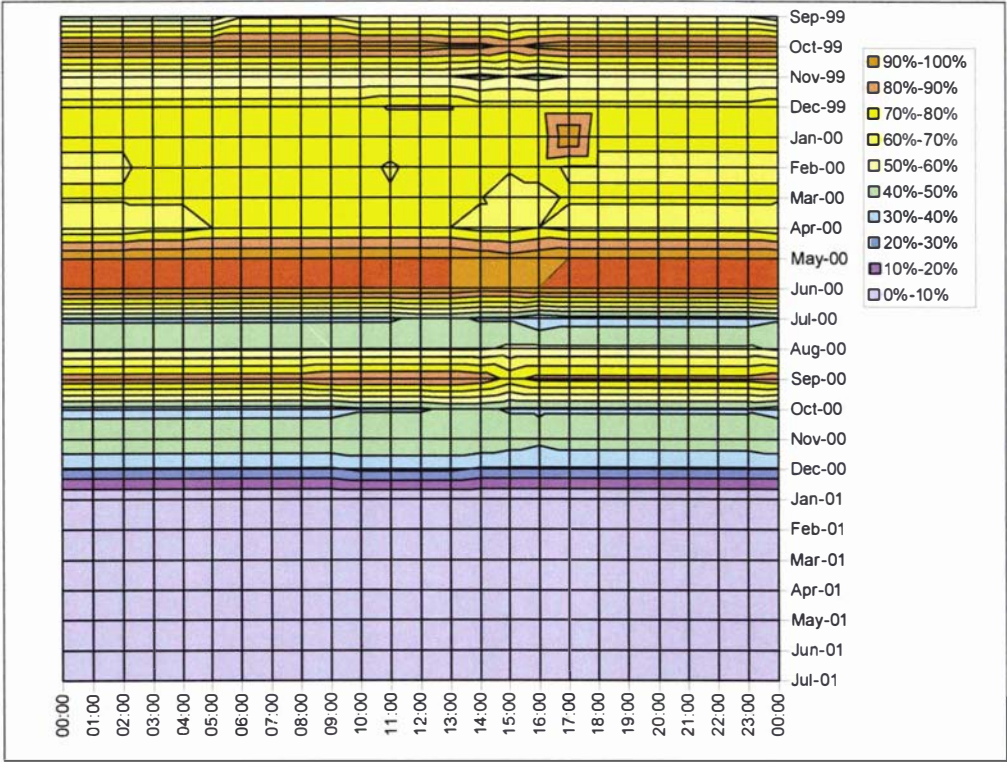


Figure 18.100 The data solidity of the monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 7.

18.2.8 Site 8 – Electricity Load Profiles

Site 8 Shearing Shed and Freezer Shed Load Profiles

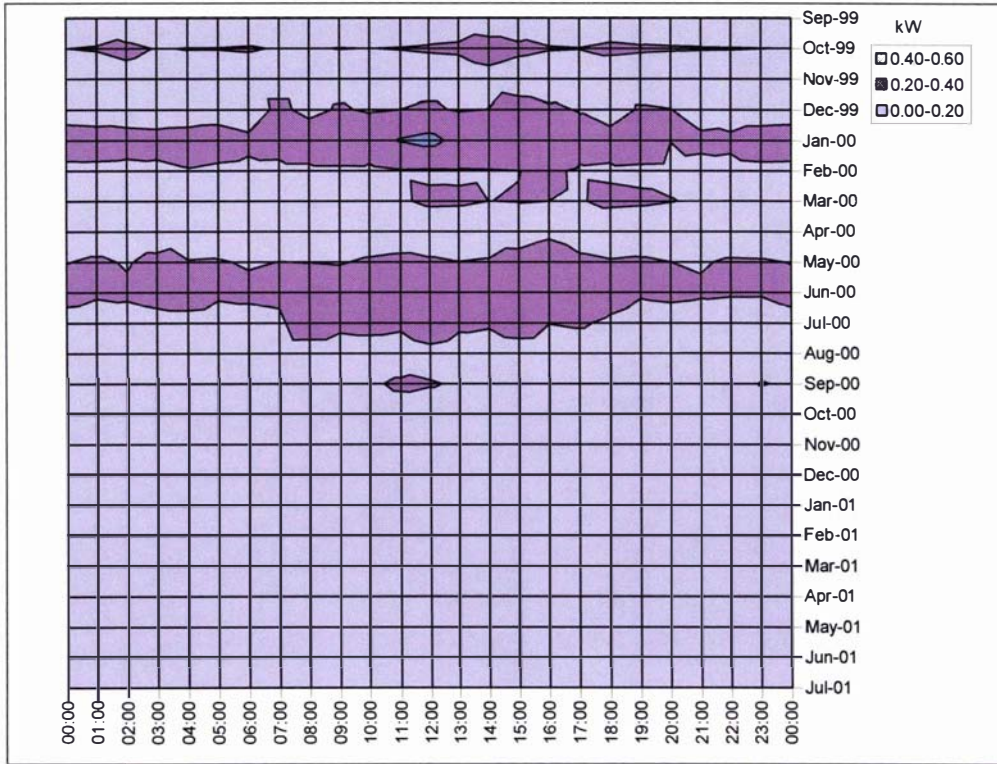


Figure 18.101 The mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 8.

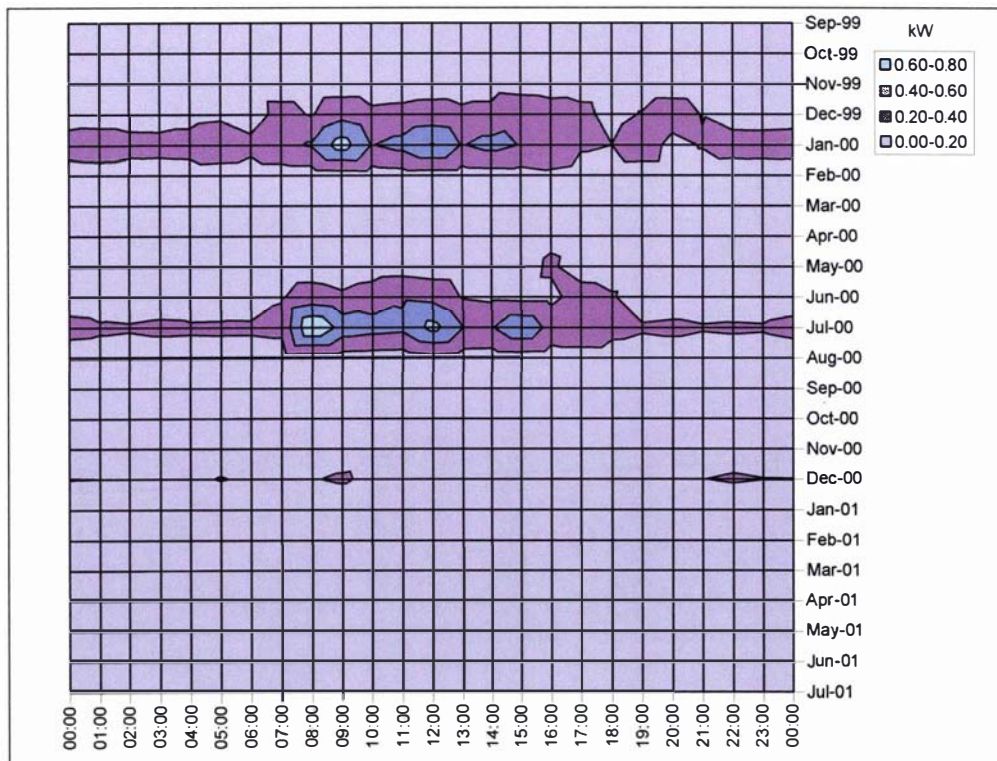


Figure 18.102 The standard deviation of the mean monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 8.

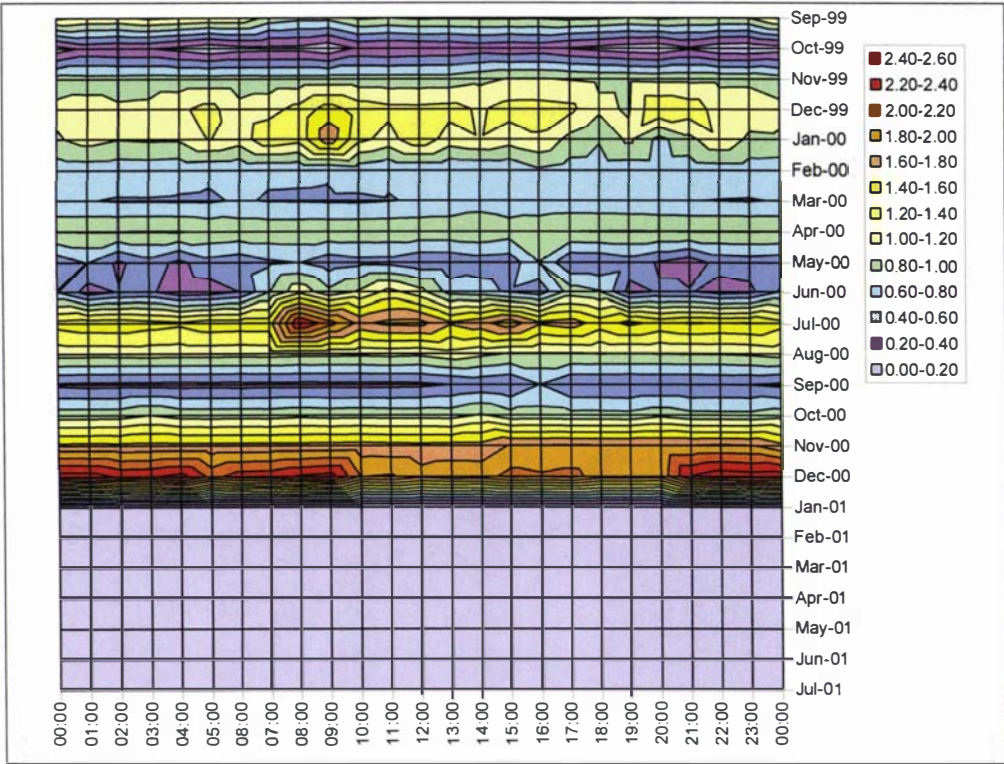


Figure 18.103 The coefficient of variation of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 8.

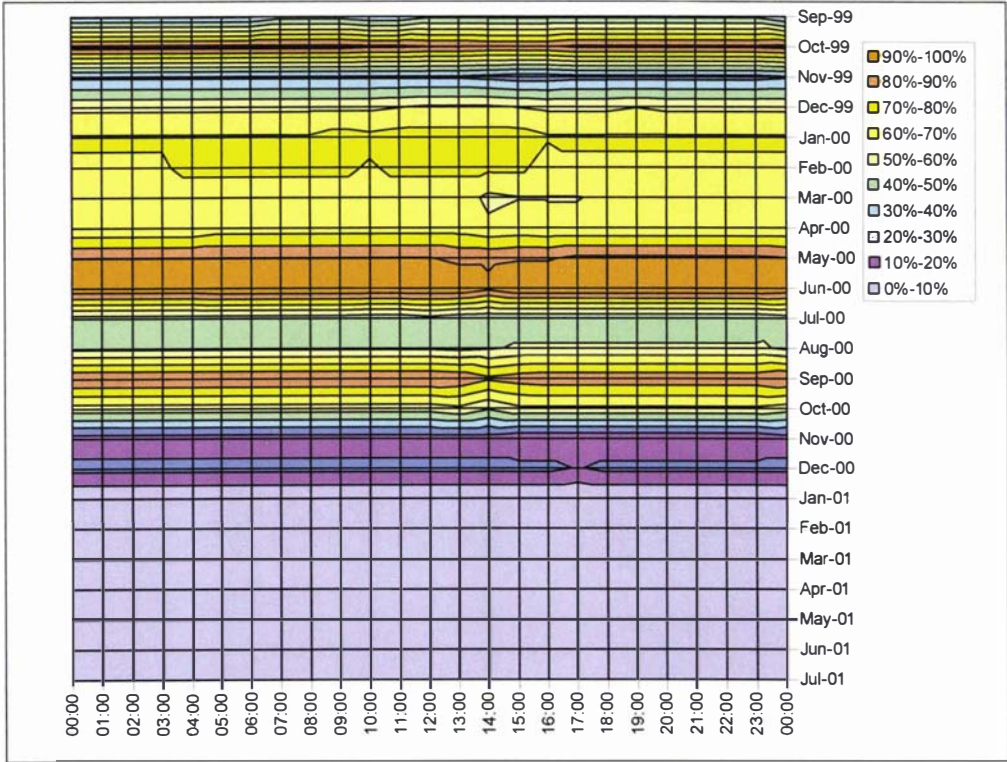


Figure 18.104 The data solidity of the monthly – diurnal shearing shed and freezer shed load profile over the duration of the monitoring for Site 8.

Site 8 Shearing Shed Load Profile Only

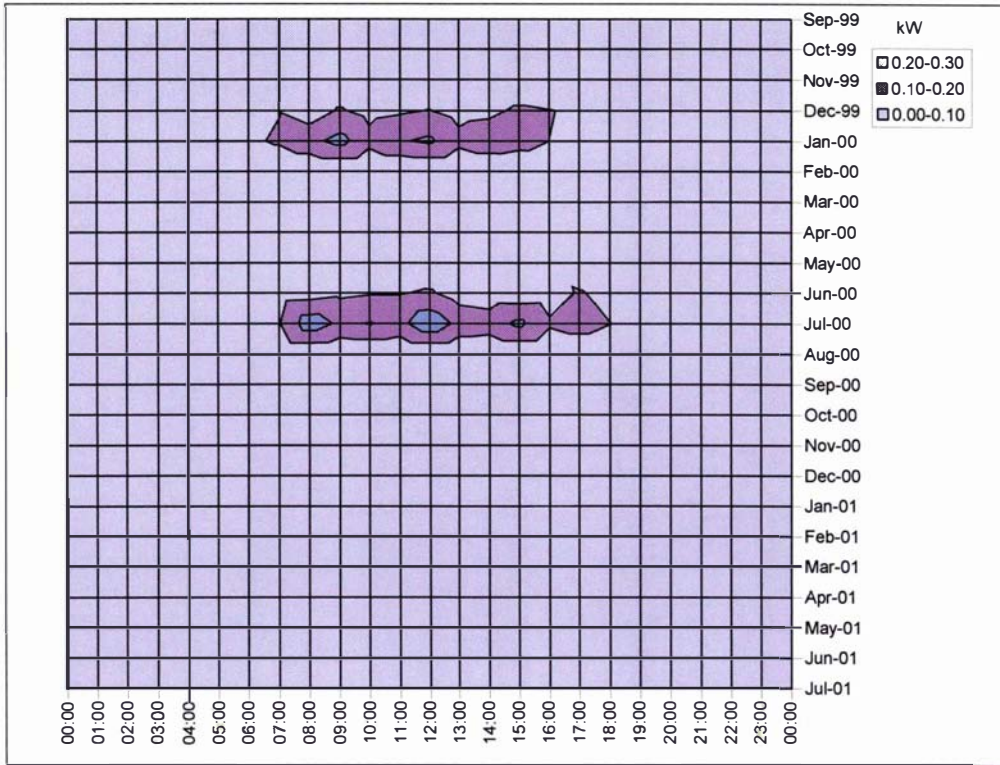


Figure 18.105 The mean monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 8.

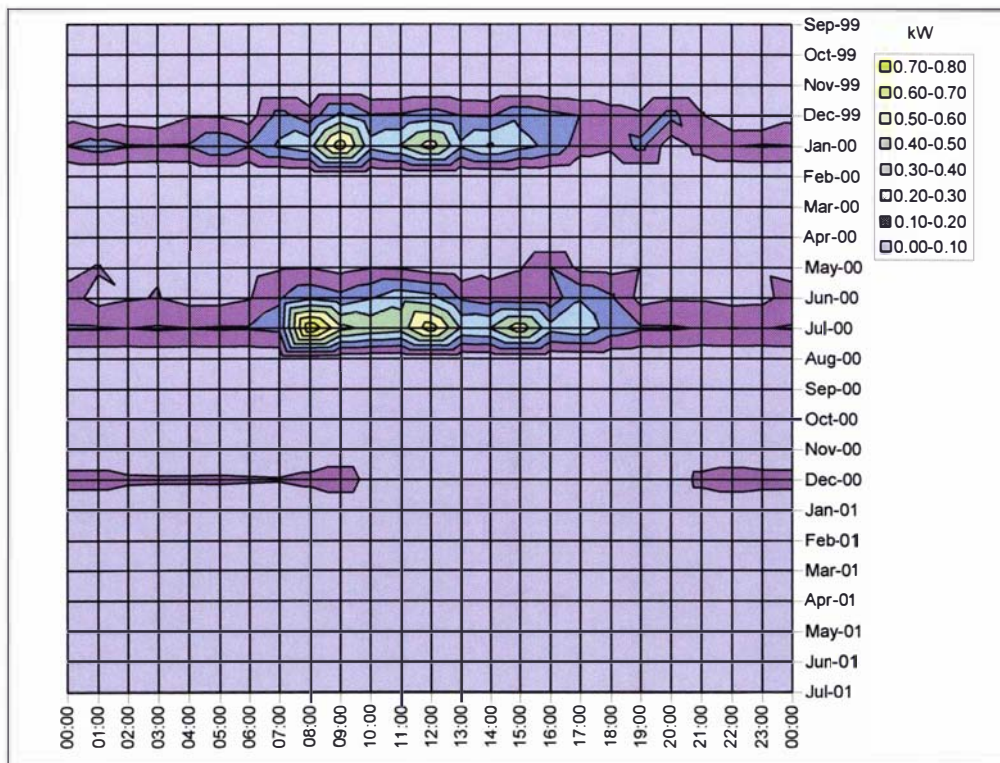


Figure 18.106 The standard deviation of the mean monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 8.

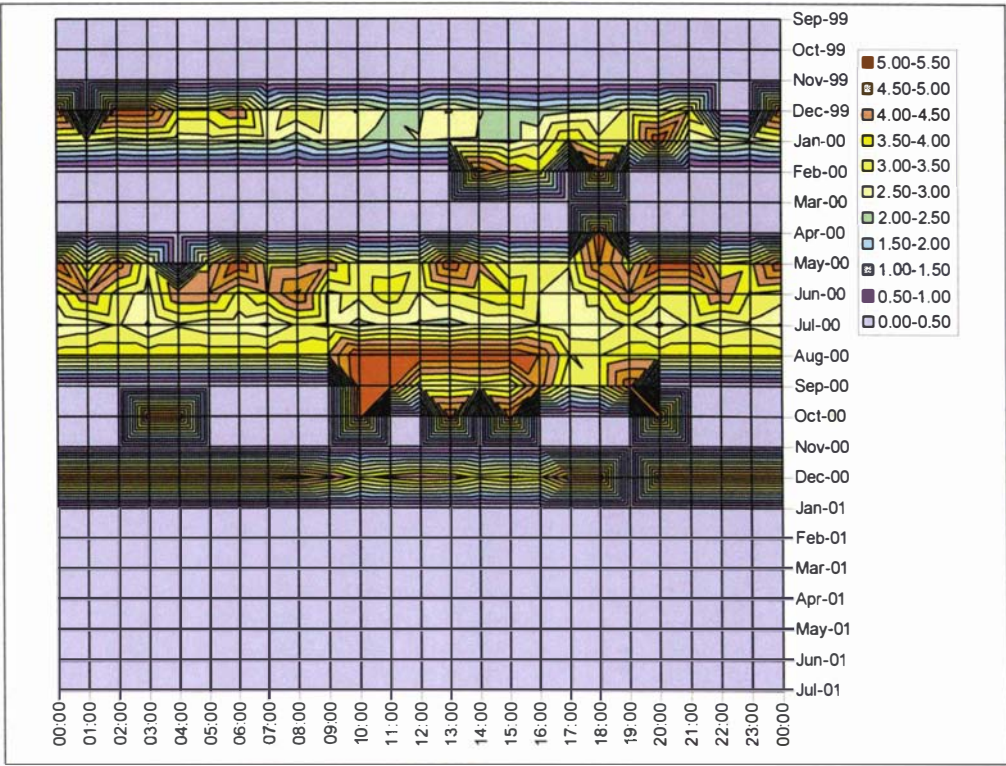


Figure 18.107 The coefficient of variation of the monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 8. Be aware of the scale change to 0.50 kWh.

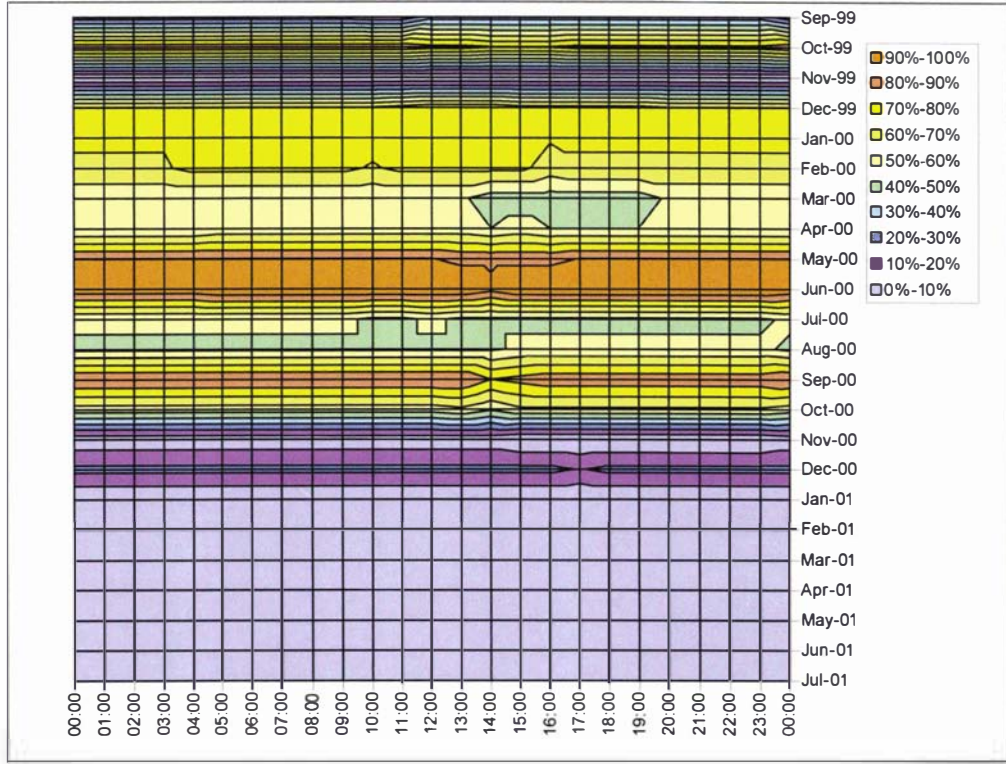


Figure 18.108 The data solidity of the monthly – diurnal shearing shed load profile over the duration of the monitoring for Site 8.

Site 8 Freezer Shed Load Profile Only

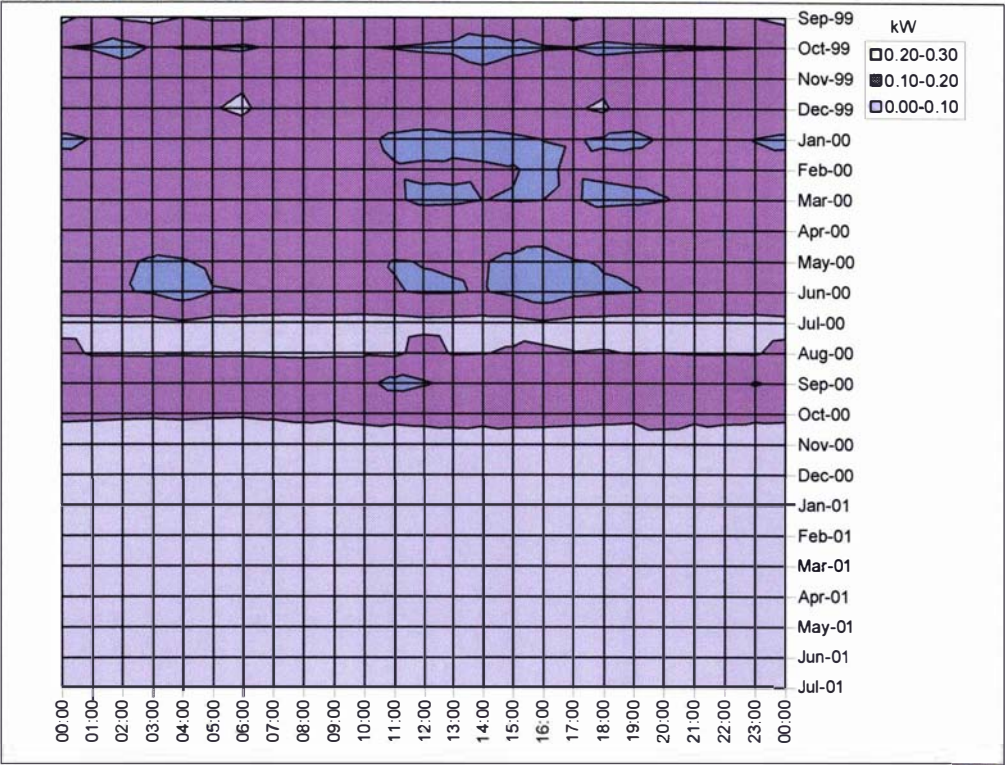


Figure 18.109 The mean monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 8.

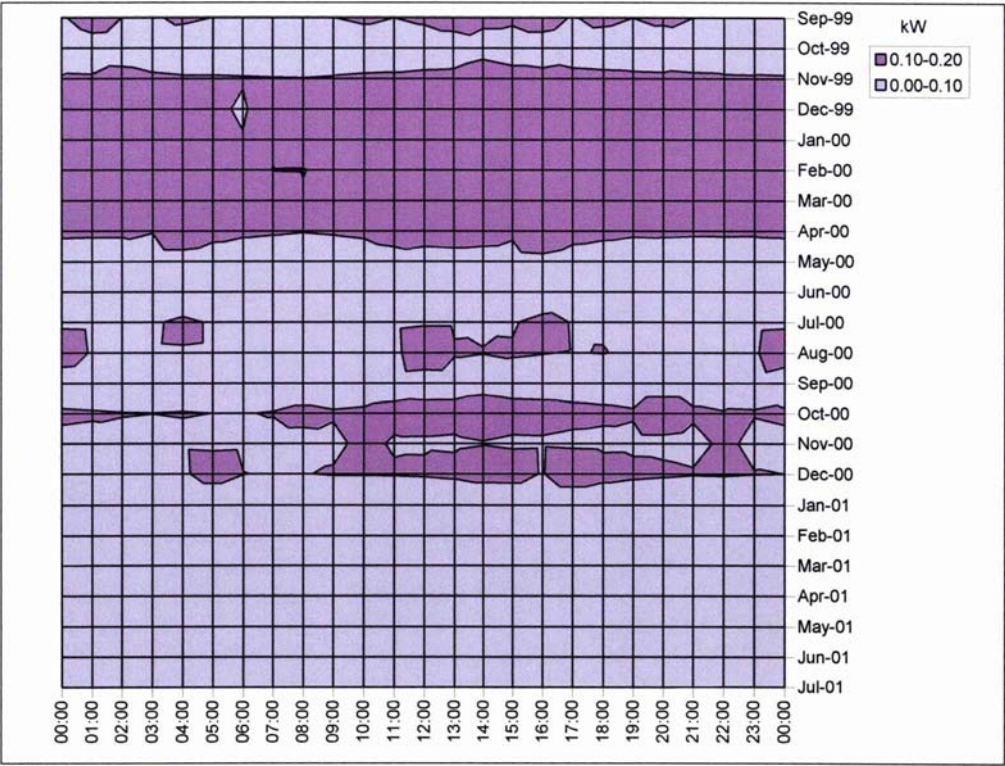


Figure 18.110 The standard deviation of the mean monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 8.

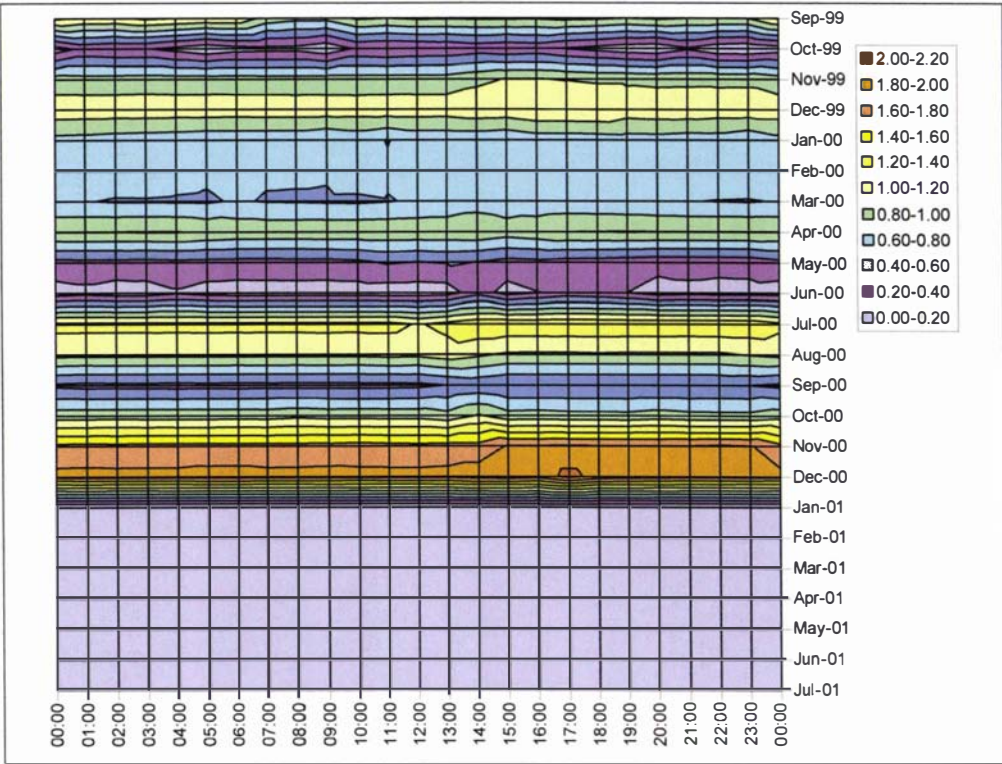


Figure 18.111 The coefficient of variation of the monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 8.

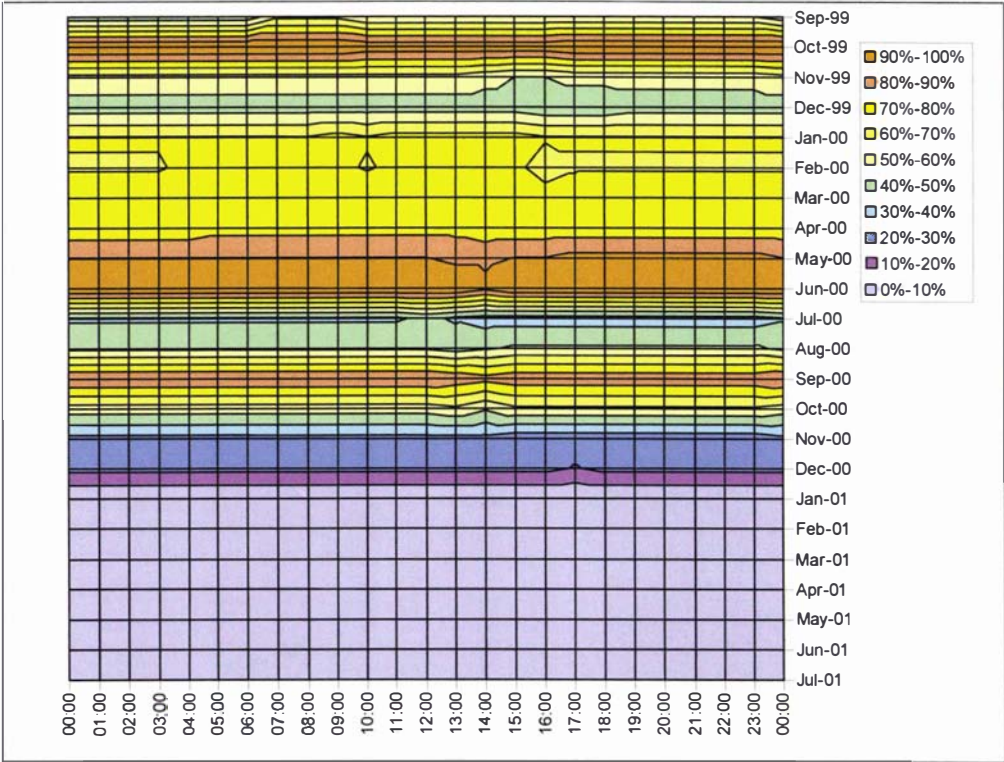


Figure 18.112 The data solidity of the monthly – diurnal freezer shed load profile over the duration of the monitoring for Site 8.

18.2.9 Metering Problems

Data was lost from some sites through various reasons including meter installation problems, ongoing meter malfunction or maintenance problems, power outages, corrupt files on transfer from the meter to the computer, and missed down-load times leading to data overwriting (Table 18.1).

Table 18.1 A detailed listing of the monitored load and duration, meter type, and any metering problems.

Site	Load type	Monitored duration	Meter type	Meter problems
1	Domestic	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Water heating			
2	Domestic	Apr-00 – Jul-01	Seaward MD-300.	A 'data read' error in the meter in the period prior to April 2000, and again in June 2000 lead to a loss of data in these periods.
	Water heating			
3	Domestic	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Water heating	Jan-00 – Oct-00	Seaward MD-300.	A 'data read' error in the meter in the period up to January 2000, and again in the period after October 2000 led to data loss.
4	Domestic	Dec-99 – Jul-01	Seaward MD-300.	No problems.
	Water heating			
	Workshop			
5	Domestic	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Water heating			
6	Domestic	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Water heating			
7	Freezer shed	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Shearing shed			
8	Freezer shed	Sep-99 – Dec-00	Siemens S2A-100.	Data overwriting due to missed download times after seven days, or data loss from memory due to power outages, otherwise, no problems.
	Shearing shed			
9	Shearing shed	No monitoring	Seaward MD-300	An electronic error in the meter in the early period of monitoring was unable to be fixed. Meter was uninstalled and as no replacement meter was available, this site was not monitored.

18.3 Short-Term Duration Analysis – Electricity Loads

This section should be reading conjunction with section 6.3.3. Certain modelling parameters were required for modelling of load profiles in HOMER. This section details the analysis undertaken to assess the duration before these modelling parameters became apparent in the monitored data. The parameters of daily load profiles, hourly and daily 'noise', and the annual daily mean load were discussed fully in Chapter 6. This section includes the daily and hourly statistics of the monitored duration (section 18.3.1), a cumulative daily mean electricity load analysis (section 18.3.2), and an hourly cumulative mean electricity load analysis (section 18.3.3).

18.3.1 Daily and Hourly Load Statistics

An analysis of the daily descriptive statistics provides a statistical picture of all of the daily loads (kWh/d) (Table 18.2). The data will be of use when estimating the mean daily load (kWh/d), and the daily 'noise' value in HOMER modelling of electricity loads.

Table 18.2 The descriptive statistics for the daily electricity load data for the duration of the monitoring.

Site	Load type	Mean (kWh/d)	Standard Error	Median (kWh/d)	Standard Deviation (kWh/d)	Sample Variance	Range	Minimum (kWh/d)	Maximum (kWh/d)	Count (days)	Confidence Level (95.0%)
1	dom	11.34	0.1260	11.39	2.15	4.62	19.24	2.85	22.09	291	0.25
	wh	7.27	0.1428	7.01	3.09	9.55	18.17	0	18.17	468	0.28
2	dom	10.67	0.2055	10.24	4.14	17.15	29.10	0.46	29.56	406	0.40
	wh	12.46	0.1636	12.54	3.30	10.87	23.23	0	23.23	406	0.32
3	dom	19.62	0.5986	17.25	9.23	85.27	64.91	0	64.91	238	1.18
	wh	19.97	0.5460	20.70	9.01	81.10	47.84	1.84	49.68	272	1.07
4	dom	7.32	0.1274	7.13	3.09	9.56	18.17	0.69	18.86	589	0.25
	wh	14.27	0.1898	14.26	4.61	21.23	23.00	3.91	26.91	589	0.37
	ws	1.41	0.0326	1.38	0.79	0.63	4.37	0	4.37	589	0.06
5	dom	15.61	0.4468	14.50	7.58	57.50	56.17	4.23	60.40	288	0.88
	wh	7.65	0.3011	6.51	4.80	23.03	38.51	1.69	40.20	254	0.59
6	dom	7.86	0.4979	6.82	7.68	59.00	51.40	2.70	54.10	238	0.98
	wh	10.87	0.6223	9.81	8.78	77.07	74.90	0	74.90	199	1.23
7	fs	7.52	0.1262	8.08	2.08	4.35	7.74	2.23	9.97	273	0.25
	ss	12.02	0.3447	10.87	5.47	29.94	67.33	5.90	73.23	252	0.68
8	fs	5.26	0.0664	5.18	1.09	1.19	8.06	0	8.06	269	0.13
	ss	1.16	0.2356	0.00	3.60	12.93	27.16	0	27.16	233	0.46
KEY: "dom" is the domestic load, "wh" is the water heating load, "fs" is the freezer shed load, and "ss" is the shearing shed load.											

The descriptive hourly statistics for the duration of the monitoring (Table 18.3) will be useful when estimating the level of 'noise' variation to use in HOMER modelling of electricity load profiles. The large maximums for the water heating loads of Sites 2, 3, 5, and 6 were recorded in November 1999 probably resulted from the suspected voltage anomalies previously noted in the load profiles.

Table 18.3 The descriptive statistics for the hourly electricity loads for the duration of the monitoring.

Site	Load type	Mean (kWh)	Standard Error	Median (kWh)	Standard Deviation (kWh)	Sample Variance	Range	Minimum (kWh)	Maximum (kWh)	Count (hours)	Confidence Level (95.0%)
1	dom	0.47	0.0025	0.48	0.22	0.05	2.24	0.05	2.29	7,676	0.005
	wh	0.30	0.0041	0.25	0.43	0.18	2.35	0.00	2.35	11,257	0.008
2	dom	0.45	0.0055	0.23	0.55	0.30	4.26	0.00	4.26	9,787	0.011
	wh	0.52	0.0040	0.46	0.40	0.16	2.30	0.00	2.30	9,787	0.008
3	dom	0.81	0.0084	0.60	0.67	0.46	4.57	0.00	4.57	6,519	0.016
	wh	0.83	0.0125	0.46	1.01	1.02	3.22	0.00	3.22	6,541	0.024
4	dom	0.30	0.0035	0.23	0.41	0.17	4.95	0.00	4.95	14,158	0.007
	wh	0.59	0.0048	0.69	0.57	0.32	3.22	0.00	3.22	14,158	0.009
	ws	0.06	0.0014	0.00	0.16	0.03	2.07	0.00	2.07	14,158	0.003
5	dom	0.65	0.0082	0.34	0.69	0.47	11.80	0.00	11.80	6,948	0.016
	wh	0.32	0.0080	0.00	0.67	0.45	10.90	0.00	10.90	6,949	0.016
6	dom	0.33	0.0050	0.22	0.40	0.16	6.40	0.00	6.40	6,503	0.010
	wh	0.45	0.0106	0.27	0.79	0.62	16.20	0.00	16.20	5,585	0.021
7	fs	0.31	0.0011	0.34	0.09	0.01	0.42	0.04	0.46	7,344	0.002
	ss	0.50	0.0045	0.45	0.37	0.14	7.68	0.06	7.74	7,051	0.009
8	fs	0.22	0.0007	0.21	0.06	0.00	0.55	0.00	0.55	6,767	0.001
	ss	0.04	0.0025	0.00	0.20	0.04	3.04	0.00	3.04	6,331	0.005
KEY: "dom" is the domestic load, "wh" is the water heating load, "fs" is the freezer shed load, and "ss" is the shearing shed load.											

18.3.2 Cumulative Annual Mean Electricity Loads Analysis

The cumulative annual daily mean load of all the sites was analysed (Figure 18.113 and Figure 18.115) and this provided data for the analysis of the duration before the annual daily mean load settled and became apparent.

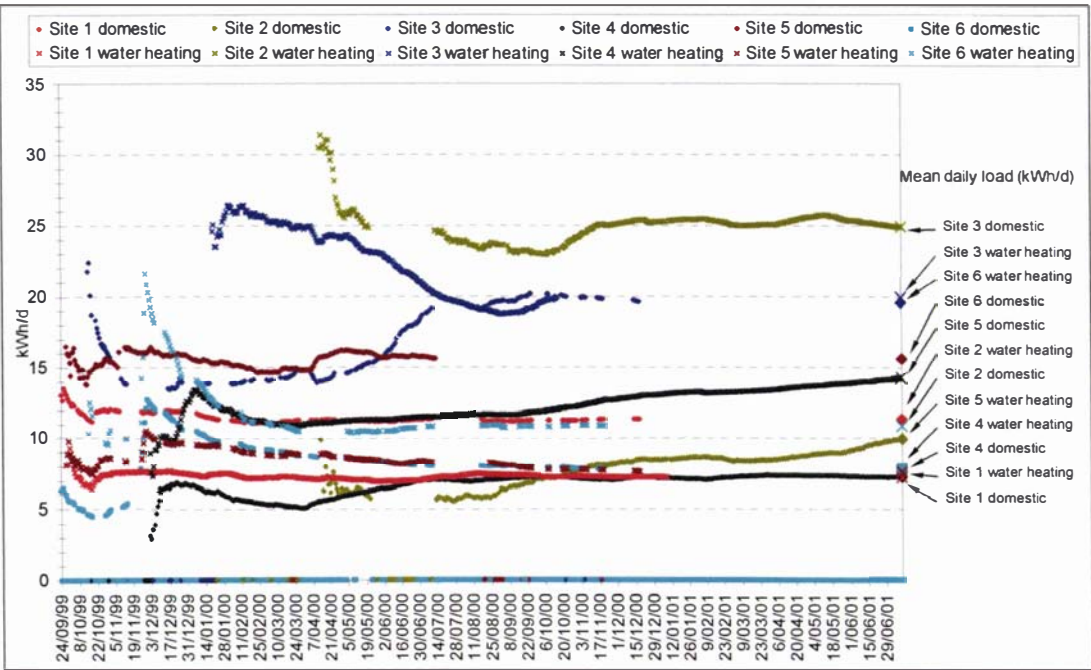


Figure 18.113 Cumulative daily mean electricity loads for the domestic and water heating loads for complete weeks only.

The daily mean values are indicated on the right hand axis for each of the load sites.

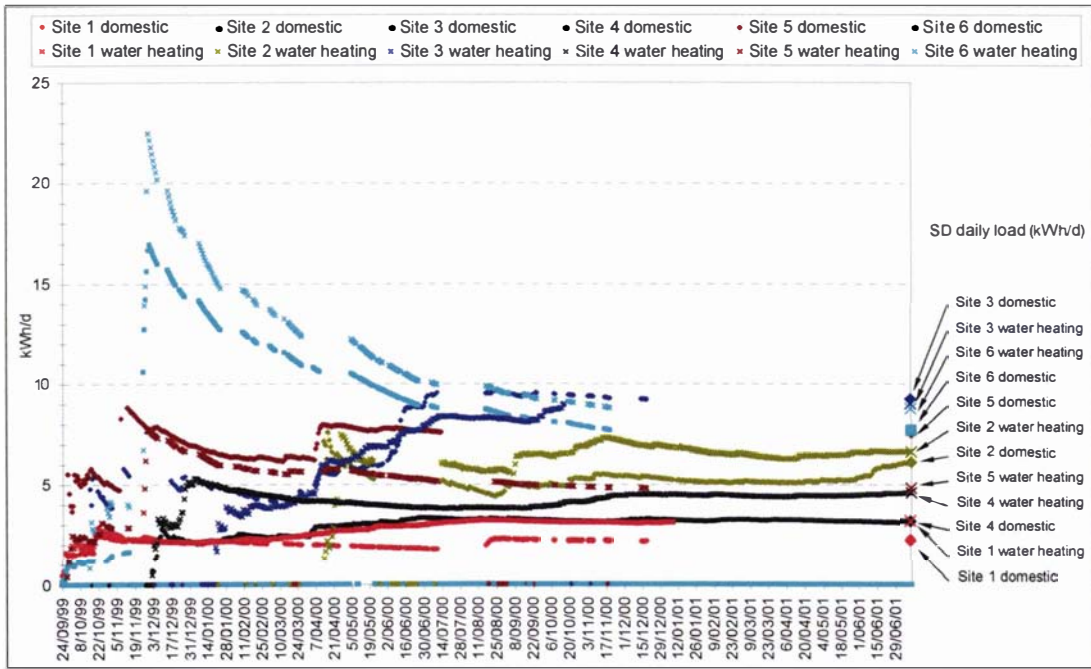


Figure 18.114 Cumulative daily standard deviation of the electricity loads for the domestic and water heating loads for complete weeks only. The overall daily standard deviation values are indicated on the right hand axis for each of the load sites.

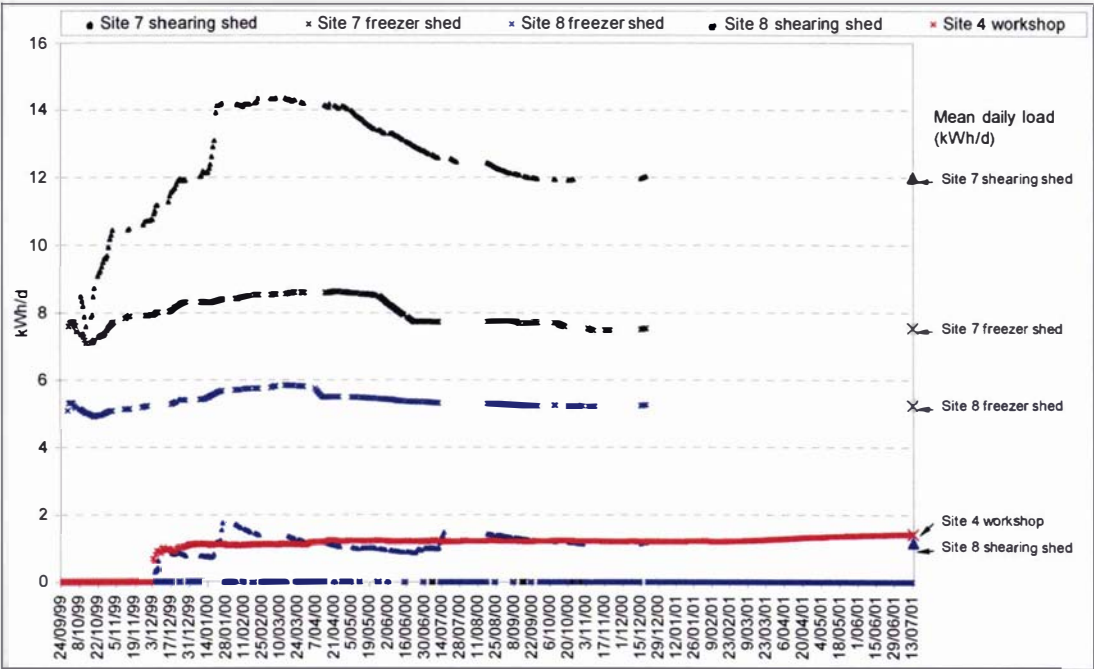


Figure 18.115 Cumulative daily mean electricity loads for the farm loads for complete weeks only. The daily mean values are indicated on the right hand axis for each of the load sites.

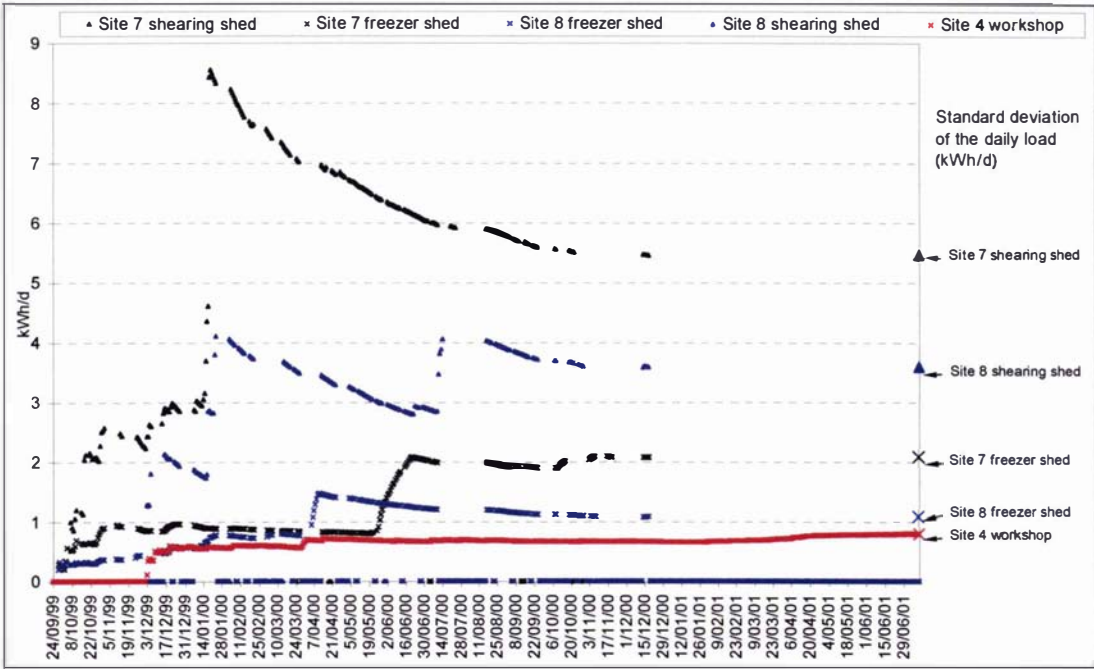


Figure 18.116 Cumulative daily standard deviation of the electricity loads for the farm loads for complete weeks only. The overall daily standard deviation values are indicated on the right hand axis for each of the load sites.

18.3.3 Cumulative Hourly Electricity Load Standard Deviation Analysis

The cumulative hourly mean load of all the sites was analysed (Figure 18.117 and Figure 18.118) and this provided data for the analysis of the duration before the hourly standard deviation mean load settled and became apparent.

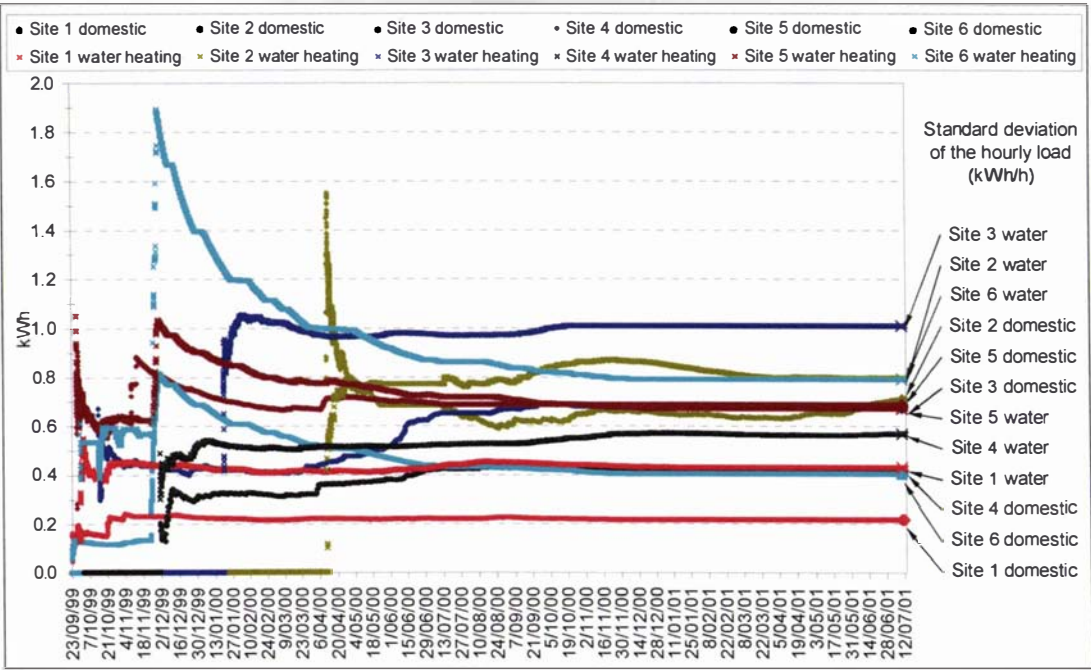


Figure 18.117 Cumulative standard deviation for the hourly domestic and water heating electricity loads for the Totara Valley community.

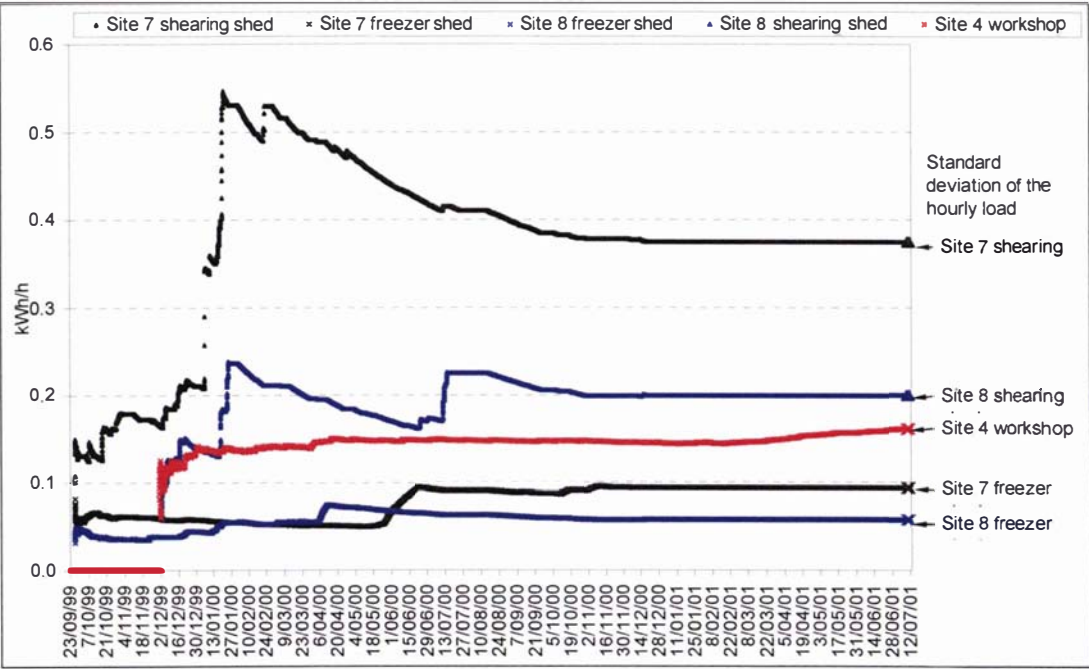


Figure 18.118 Cumulative standard deviation for the hourly shearing sheds, freezer sheds and workshop electricity loads for the Totara Valley community.

Appendix G

19 Renewable Energy Resource Data

This section documents material supplementary to Chapter 7, the renewable energy resources of Totara Valley. Details concerning the assessment of the Totara Valley hydro resource at three points over three different times are given in Table 19.1 to Table 19.7. These include the estimated cross sectional area of the stream at the point of assessment, the correction factor used in order to compensate for flow distortions due to the roughness of the streambed, and the estimated stream flow velocity. The flow rate is then given as calculated using the above factors.

19.1 Hydrological Resource Data

Three locations with micro-hydro energy potential were identified in the Totara Stream and monitored as part of this research. The 'velocity – area' method was used to assess the flow rate of the stream. This method requires a five to 10 metre long relatively straight section of stream of uniform shape, free of in-stream obstacles or large areas of eddy flow, and ideally should have a relatively even cross sectional flow rate.

The velocity area method required an estimate of stream flow velocity and to do this, multiple floats were timed over a set length of stream and the velocity calculated in metres per second. The number of timed runs was dictated by the variation in times as the monitoring progressed so if there was little difference (i.e. all floats came through the 'finish line' in a cluster) then a lower number of timed runs were undertaken. If there was a large apparent difference between time runs, (i.e. the floats came through the 'finish line' as a long string of times) then a larger number of timed runs were undertaken.

19.1.1 Hydro Site 1 – Farm 1

Three assessments were made of this section of stream with the third assessment in August in order to assess the 'normal' winter flow rate. The stream flow calculation parameters shown in Table 19.1 are from a 7.5-metre section of stream approximately 2100 mm wide with a uniform shape and pebble bottom of small smooth stones. The equivalent of thirty-two timed runs of oranges as floats were used to derive an average velocity.

The results shown in Table 19.2 are from a 7-metre section of stream approximately 2400 mm wide with a uniform shape and pebble bottom of small smooth stones. In total, twenty-two timed runs were used to derive an average velocity.

The results shown in Table 19.3 are from a 10-metre section of stream approximately 1800 mm wide with a uniform shape and pebble bottom of small smooth stones. In total, thirty-five timed runs were used to derive an average velocity.

Table 19.1 The calculated flow rate of Totara Stream at Hydro Site 1 – January 2000.

Estimated mean cross-sectional area	0.254 m ²
Correction factor used	0.65
Estimated mean stream flow velocity	0.30 m/s
Estimated flow rate	0.0496 m ³ /s
	50 l/s

Table 19.2 The calculated flow rate of Totara Stream at Hydro Site 1 – March 2000.

Estimated mean cross-sectional area	0.287 m ²
Correction factor used	0.65
Estimated mean stream flow velocity	0.24 m/s
Estimated flow rate	0.0455 m ³ /s
	46 l/s

Table 19.3 The calculated flow rate of Totara Stream at Hydro Site 1 – August 2000.

Estimated mean cross-sectional area	0.361 m ²
Correction factor used	0.65
Estimated mean stream flow velocity	0.830 m/s
Estimated flow rate	0.1949 m ³ /s
	195 l/s

19.1.2 Hydro Site 2 – Farm 3

The stream flow calculation parameters shown in Table 19.4 are from an 8-metre section of stream approximately 2700 mm wide with a uniform shape and pebble bottom of small smooth stones and sand. In total, thirty-nine timed runs were used to derive an average velocity.

The results in Table 19.5 are from a 5.5-metre section of stream approximately 2400 mm wide with a uniform shape and pebble bottom of small smooth stones and sand. In total, twenty-two timed runs were used to derive an average velocity.

Table 19.4 The calculated flow rate of Totara Stream at Hydro Site 2 – January 2000.

Estimated mean cross-sectional area	0.341 m ²
Correction factor used	0.65
Estimated mean stream flow velocity	0.23 m/s
Estimated flow rate	0.0506 m ³ /s
	51 l/s

Table 19.5 The calculated flow rate of Totara Stream at Hydro Site 2 – March 2000.

Estimated mean cross-sectional area	0.367 m ²
Correction factor used	0.65
Estimated mean stream flow velocity	0.20 m/s
Estimated flow rate	0.0472 m ³ /s
	47 l/s

19.1.3 Hydro Site 3 – Farm 3

The results in Table 19.6 are from an 8-metre section of stream approximately 1200 mm wide with a uniform shape and pebble bottom of small smooth stones and sand. In total, twenty timed runs were used to derive an average velocity.

The results in

Table 19.7 are from a 7.5-metre section of stream approximately 1200 mm wide with a uniform shape and pebble bottom of small smooth stones and sand. In total, twenty timed runs were used to derive an average velocity.

Table 19.6 The calculated flow rate of Totara Stream at Hydro Site 3 – January 2000.

Estimated mean cross-sectional area	0.140 m ²
Correction factor used	0.70
Estimated mean stream flow velocity	0.53 m/s
Estimated flow rate	0.0518 m ³ /s
	52 l/s

Table 19.7 The calculated flow rate of Totara Stream at Hydro Site 3 – March 2000.

Estimated mean cross-sectional area	0.140 m ²
Correction factor used	0.70
Estimated mean stream flow velocity	0.50 m/s
Estimated flow rate	0.0485 m ³ /s
	49 l/s

19.2 Ambient Air Temperature

The mean monthly diurnal temperature, standard deviation, and coefficient of variation of the temperature profile of Totara Valley is given in Figure 19.1 to Figure 19.2 in reference to the potential effect temperature has on household load profiles, solar panel performance, and diurnal landmass heating thus affecting the later afternoon wind-speed increase.

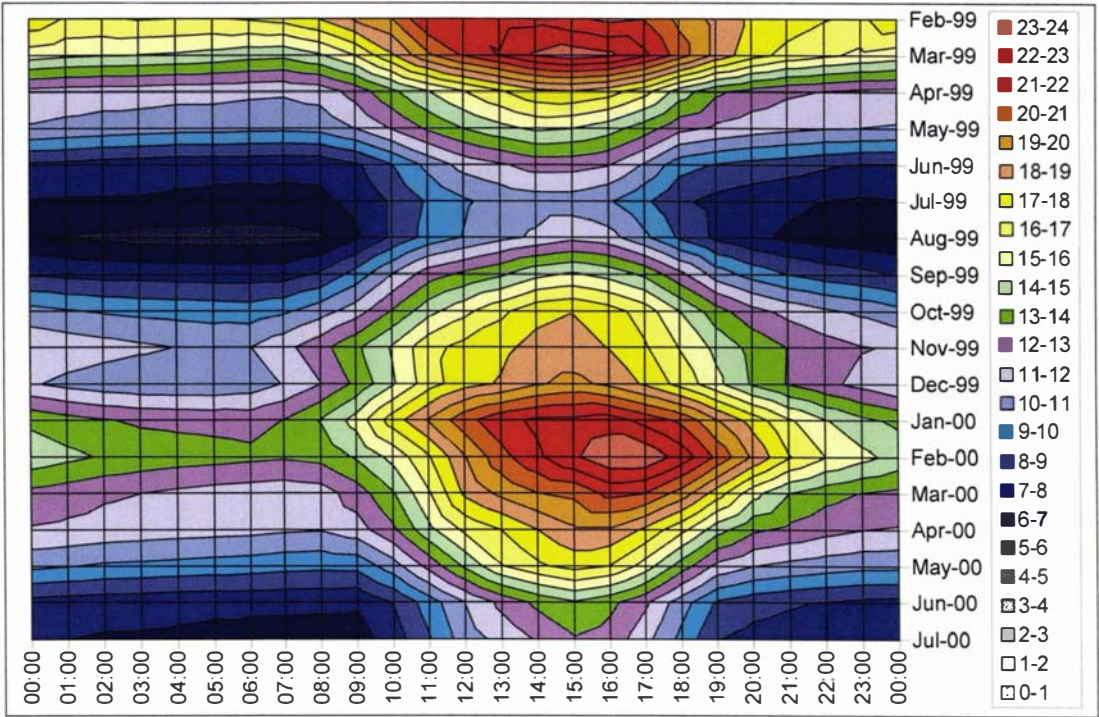


Figure 19.1 Wind Site 1 mean diurnal – monthly temperature profile.

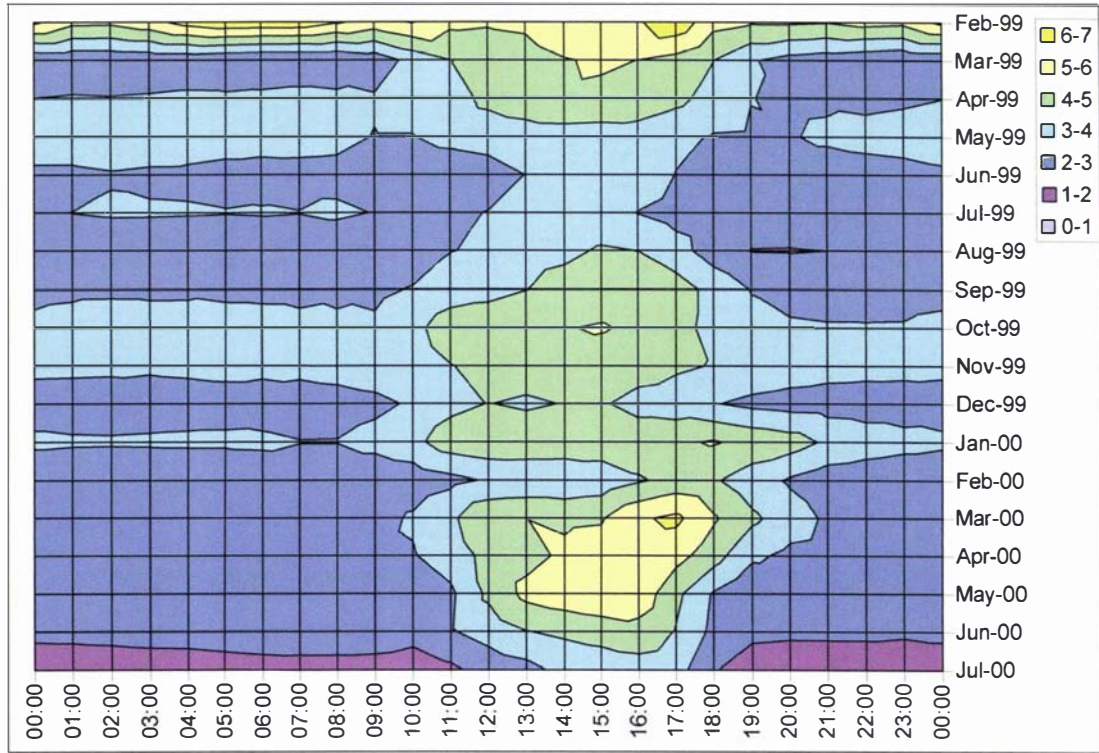


Figure 19.2 Wind Site 1 standard deviation of the diurnal – monthly temperature profile.

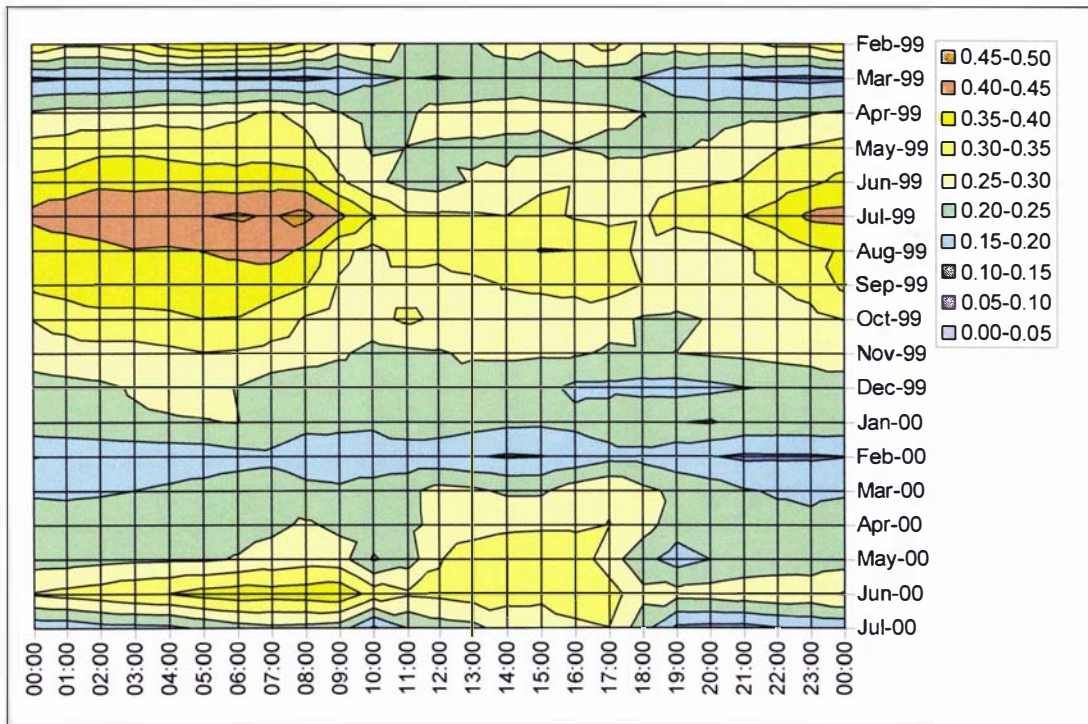


Figure 19.3 Wind Site 1 coefficient of variation of the diurnal – monthly temperature profile.

19.3 Short-term Duration Analysis – Wind Energy Resources

This section should be read with section 7.2.7, and contains:

- an analysis of the Weibull 'k' and 'C' parameters and their plotted distribution curves for Wind Sites 1, 4, and 5,
- an analysis of the diurnal pattern strength factor for all wind sites, and
- an analysis of the hour of peak wind-speed.

19.3.1 Weibull Probability Density Functions

This section should be read in conjunction with the analysis of the stability of the Weibull 'k' and 'C' values for the short-term duration analysis (section 7.2.7). The probability density distribution (p) of a wind-speed (U) is given as Equation 19.1:

Equation 19.1 The probability density distribution of a wind-speed.

$$p(U) = \frac{1}{\sigma^2} U \exp\left(\frac{-U^2}{2\sigma^2}\right)$$

The cumulative probability density distribution (P) calculating the probability of the wind-speed (U) being below a value (v) is given as Equation 19.2:

Equation 19.2 The Rayleigh cumulative probability distribution.

$$\begin{aligned} P(U < v) &= \int_{-\infty}^v p(U) dU \\ &= \frac{1}{\sigma^2} \int_0^v U \exp\left(\frac{-U^2}{2\sigma^2}\right) dU \\ &= 1 - \exp\left(\frac{-v^2}{2\sigma^2}\right) \end{aligned}$$

The probability of the wind-speed (U) exceeding (Q) a value (v) is then given by

Equation 19.3 The Rayleigh cumulative probability of exceedance.

$$Q(> v) = 1 - P(< v) = \exp\left(\frac{-v^2}{2\sigma^2}\right)$$

The Rayleigh distribution of the wind-speeds is given by Equation 19.1, Equation 19.2 and, Equation 19.3. However, a more flexible distribution is the Weibull distribution given by Equation 19.4, and characterised by the 'k' shape factor value (dimensionless), and the scale parameter, 'C' (m/s).

Equation 19.4 The Weibull distribution.

$$Q(> v) = \exp\left(-\left(\frac{v}{C}\right)^k\right)$$

Where :

v = wind speed (m/s)

k = Weibull shape factor (dimensionless)

C = Weibull scale parameter (m/s)

Taking the logarithms of both sides of Equation 19.4 twice we have

$$\ln(-\ln(Q)) = k \ln(v) - k \ln(C)$$

From this, a straight-line graph is plotted from $\ln(-\ln(Q))$ and $\ln(v)$ from which the constants 'k' and 'C' can be determined from the equation of the line ($y = kx + C$).

The Weibull probability density distribution function can be written as Equation 19.5:

Equation 19.5 The Weibull probability density function equation.

$$p(v) = \frac{k}{C} \left(\frac{v}{C}\right)^{k-1} \exp\left(-\left(\frac{v}{C}\right)^k\right)$$

Where :

v = wind speed (m/s)

k = Weibull shape factor (dimensionless)

C = Weibull scale parameter (m/s)

The Weibull 'k' and 'C' parameters have been calculated (Equation 19.5) for 1000 hour incremental durations for Wind Sites 1, 4, and 5 (Figure 19.4, Figure 19.6, and Figure

19.8). From these calculations, the incremental Weibull probability density curves (Equation 19.5) have been produced and plotted (Figure 19.5, Figure 19.7, and Figure 19.9). From these incremental plots of the probability density distribution, an assessment of the relative movements over time of the Weibull 'k' and 'C' can be made.

From Figure 19.4 and Figure 19.5, the movements of the probability density distribution for Wind Site 1 were pronounced in the first 5000 hours. After this duration, the movements were relatively smaller. This can be noted in the large changes in the Weibull 'C' value in Figure 19.4. For Wind Site 4, the movements of the probability density distribution were small (Figure 19.6 and Figure 19.7) in the first 3000 hours before becoming quite pronounced in the final 2000 hours of monitoring. For Wind Site 5, the movements of the probability density distribution were large (Figure 19.8 and Figure 19.9) in the first and last 2000 hours, while the middle duration of monitoring was quite stable for 3000 hours.

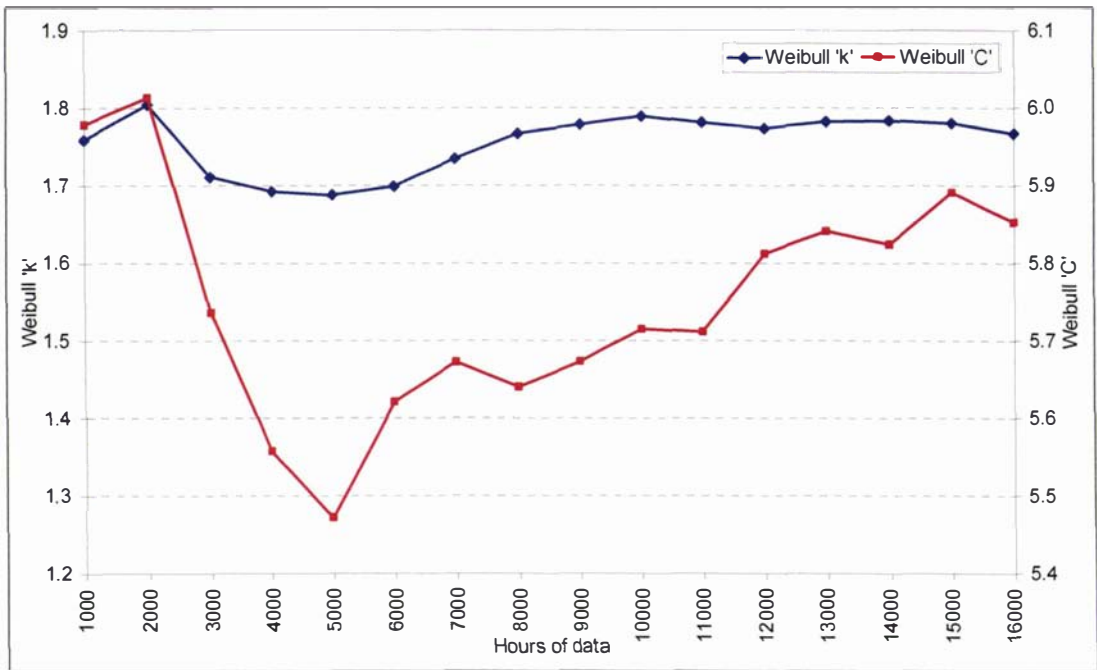


Figure 19.4 The Weibull 'k' and 'C' statistical measures for the Wind Site 1 over the duration of monitoring.

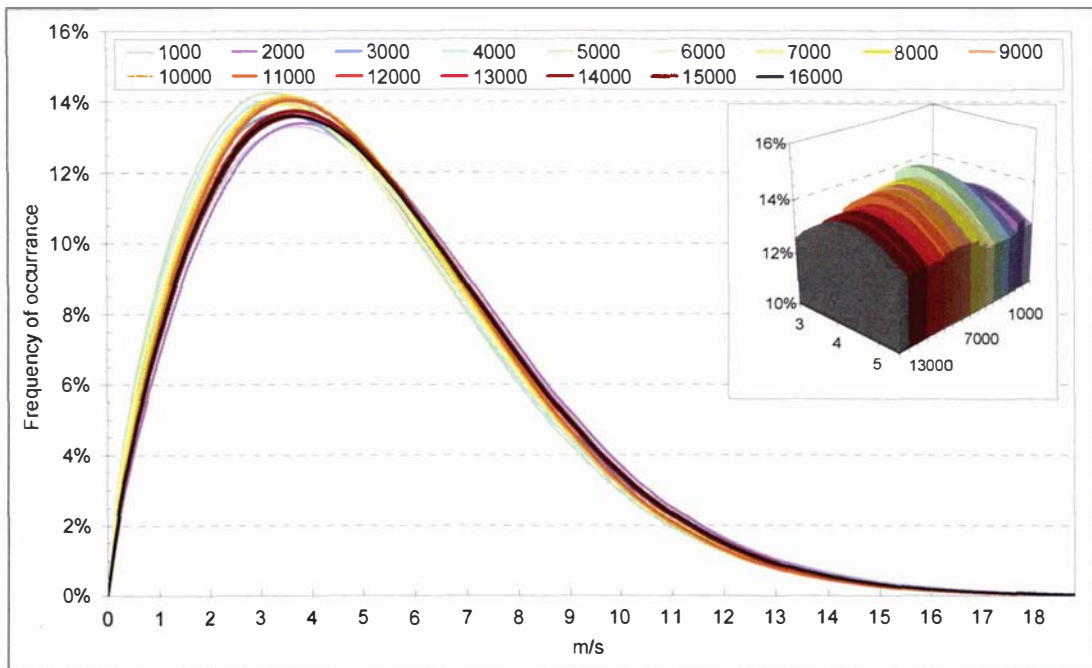


Figure 19.5 The plotted Weibull probability density distribution over the duration of monitoring for Wind Site 1.

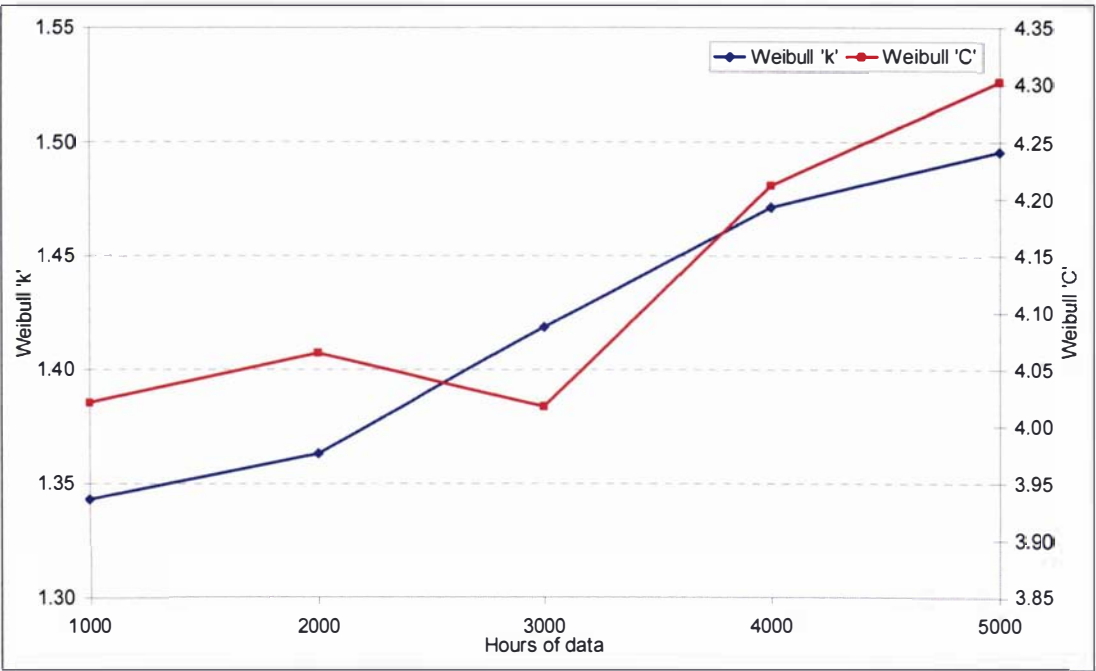


Figure 19.6 The Weibull 'k' and 'C' statistical measures for the Wind Site 4 over the duration of monitoring.

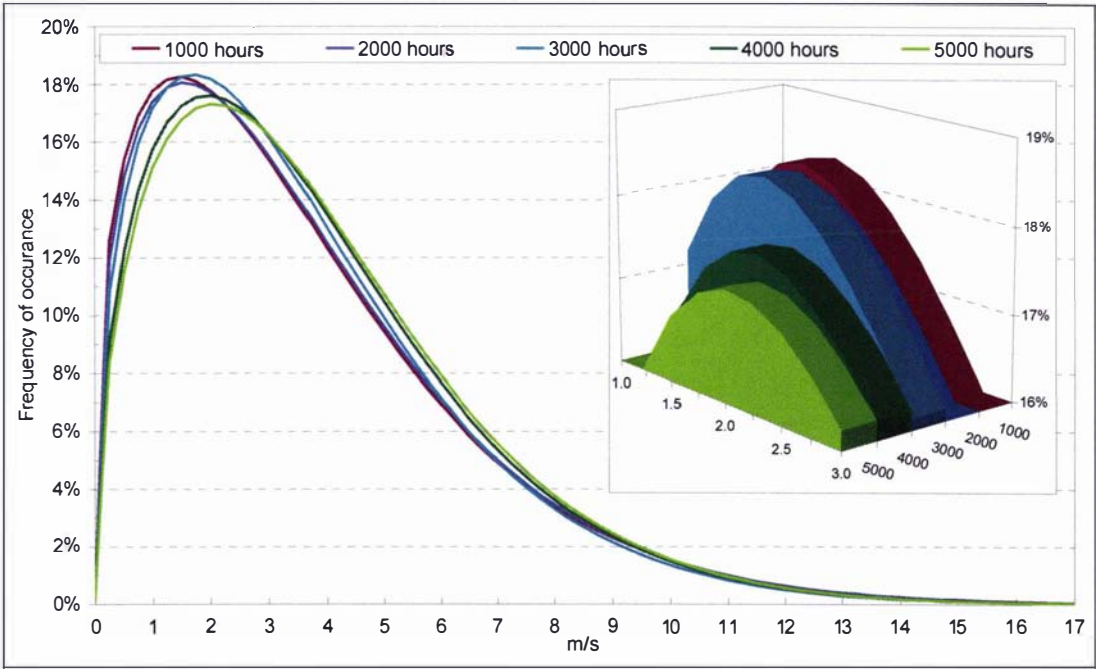


Figure 19.7 The plotted Weibull probability density distribution over the duration of monitoring for Wind Site 4.

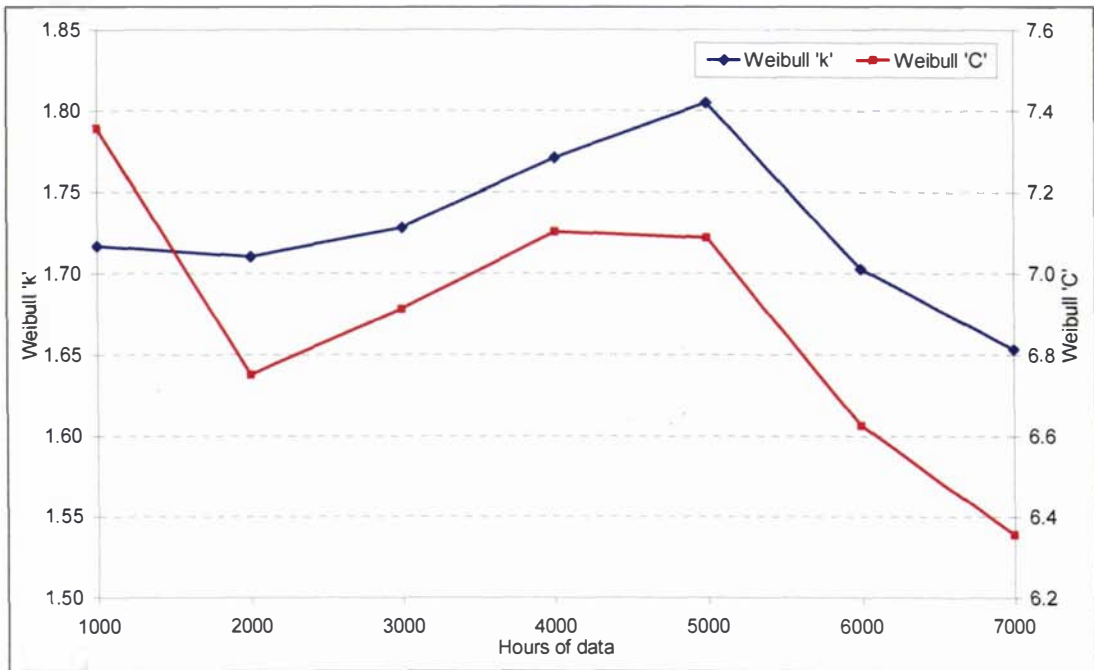


Figure 19.8 The Weibull 'k' and 'C' statistical measures for the Wind Site 5 over the duration of monitoring.

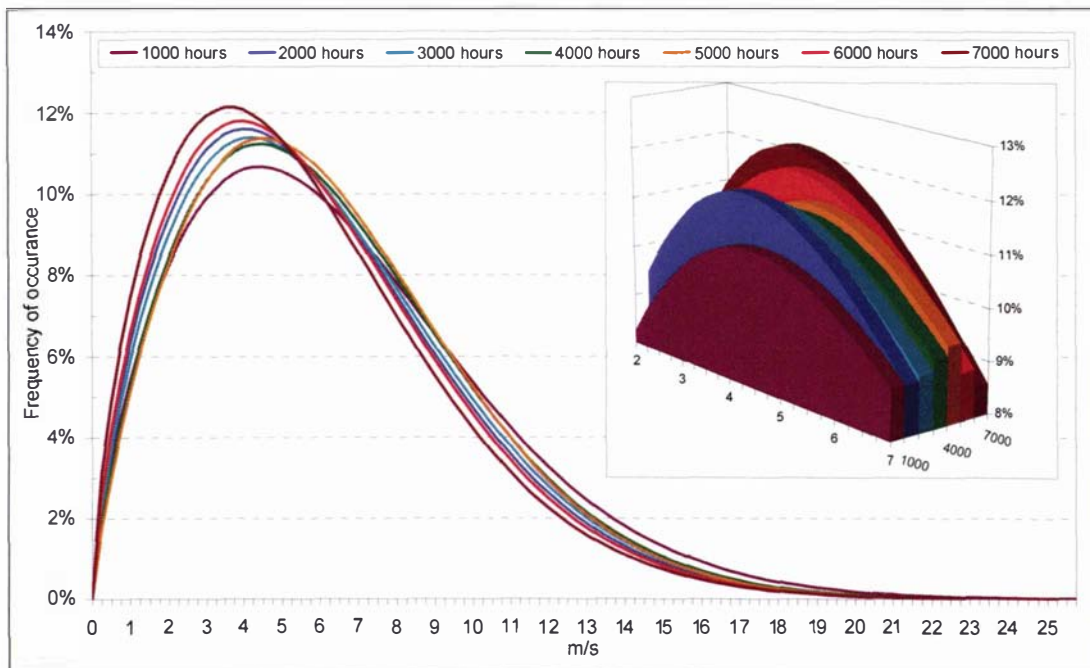


Figure 19.9 The plotted Weibull probability density distribution over the duration of monitoring for Wind Site 5.

19.3.2 Diurnal Pattern Strength Factor

The diurnal pattern strength (DPS) of the five sites varied between months and sites (Figure 19.10). The incremental DPS was calculated to assess the duration before settling.

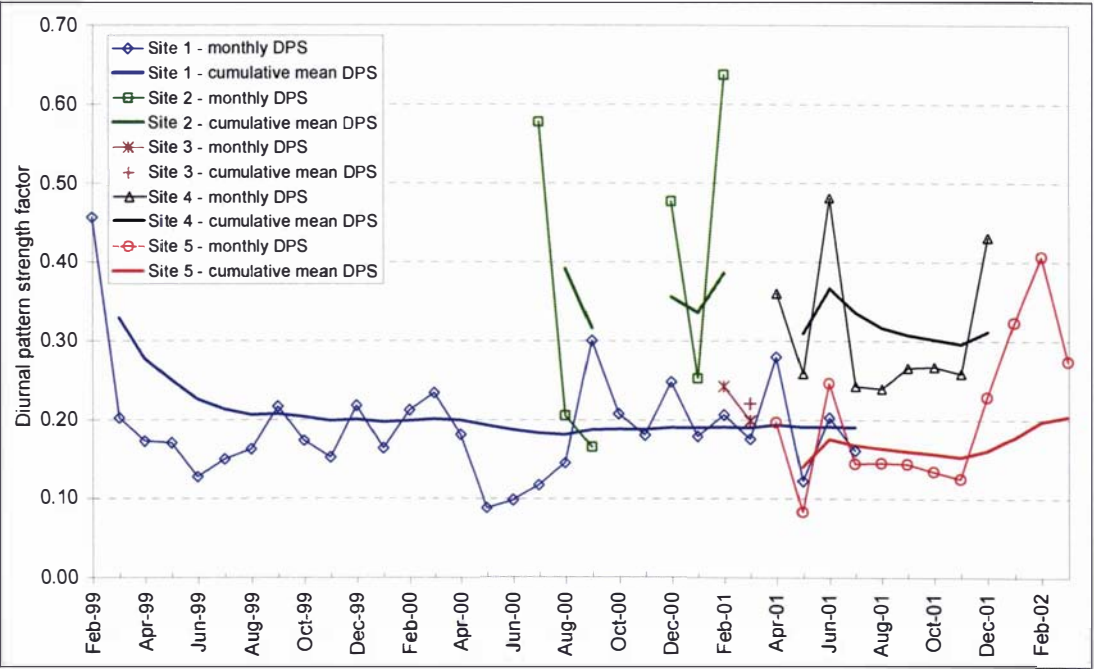


Figure 19.10 The monthly and cumulative mean diurnal pattern strength factor for Wind Sites 1 to 5 over the duration of the monitoring.

19.3.3 Hour of Peak Wind-speed

The hour of peak wind-speed generally occurred between 1200 and 1800 hours for all sites (Figure 19.11), however there was some large variation between months.

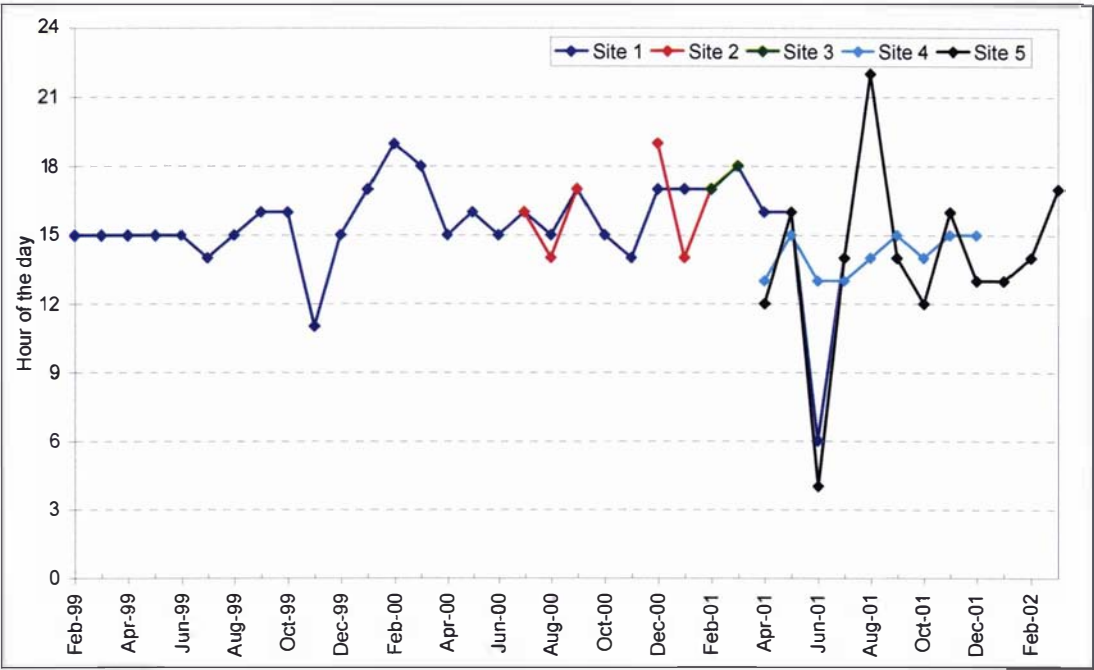


Figure 19.11 The hour of peak wind-speed for Wind Sites 1 to 5 over the duration of the monitoring.

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