Draft report on the evaluation of the developed software tool Hybrid Designer

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Abstract

Rural areas suffer from high levels of poverty and unemployment, with some 68% of the population there defined as poor. People in rural areas have many needs, and energy (including electricity) is just one of these. The provision of rural services to contribute to rural economic development and improve social equity has been a goal of the post-apartheid government, as poor rural people are often the most impoverished and marginalised South Africans. Off-grid electricity options are increasingly considered, and hybrid systems have been seen as a viable option to adequately meet some rural electricity requirements. Some experience with off-grid systems exists in South Africa, as they have been implemented for applications such as water pumping, domestic usage, tourist facilities, battery charging stations, shops, community centres, schools and clinics. There is a lack of design support for hybrid systems, as in many cases software packages only simulate the hybrid system performance but do not offer help in designing it. Therefore a major goal of this project was to develop a software package that optimises the design of a hybrid system. The produced hybrid system design software is unique in its kind and is one of the most versatile hybrid system optimisation software packages available. The work produced by this project on feasibility analysis, implementation guidelines and policy recommendations explores the framework behind rural off-grid electrification, draws recommendation regarding infrastructure planning and policy development, and assesses feasible implementation scenarios. The computer program can, based on weather and demand data provided by the user, optimise the configuration, sizing and operation strategy for an off-grid remote area power supply system – specifically for hybrid systems. The program makes use of a default component database that holds more than 100 different components of presently available hybrid systems. Users can also add components to the database if they want to. The output can be viewed graphically for every component or overall system performance, or can be exported as a text file and imported into spreadsheets such as Microsoft Excel. The software is unique in its kind and it would be useful to find resources for further evaluation, development and maintenance of the software.

The performance of Hybrid Designer was compared with the software SOLSIM for different basic single source systems and different demand profiles. The behavior of a hybrid system in both programs was compared. The documenting thesis by I. Knoblich is attached to this report. Several interesting points were made. For example, the technical performance of PV and wind turbine generators could be corrected through inserting additionally necessary parameters for wind turbine and PV module operation into the Hybrid Designer model. The results shown by Knoblich have since been corrected for Hybrid Designer. Similarly, the battery model in SOLSIM could be corrected through the comparison. An analysis of the operating strategies employed in SOLSIM and Hybrid Designer showed that the control options available in Hybrid Designer and their optimisation has a beneficial effect on system performance. Evaluation of the outputs of Hybrid Designer with the software tool Hybrid2 were only started: it was made difficult by the difference in the format required to input data and an error found in Hybrid2's costing. Hybrid2 has just recently been updated and will therefore in future be a valuable tool for further evaluations. The work done so far has shown that through the optimisation with Hybrid Designer quite a few system designs are recommended to be hybridised (Kailasanathan 1998). Before the optimisation, in many cases single source systems were preferred to badly designed hybrid systems. In addition, the obtained results from Hybrid Designer were investigated according to the technical and financial quality of the recommendations. Different parameters were varied – such as populations size, complexity of runs, speed, repeatability, stability of runs, and runs with a large number of components in the database. A number of software bugs were identified and fixed during the evaluation process. A list of additional features to put into Hybrid Designer is given in the report by F. Hochmuth in Appendix A. It was said in the report that at population sizes of 250 the software produced good and reliable results. The software works well, with some minor problems still to be resolved, and some additions still to be made. Hybrid Designer can therefore be used to design and simulate hybrid energy systems using genetic algorithms. The system is recommended to be used by trained experts only. While it has been made user-friendly using a Windows 95 interface, the degree of sophistication and the nature of the genetic algorithm make some training for the user

necessary to be able to fully exploit the program's abilities. Alternatively, the users' manual could include an in-depth section about the impact of the various options on the validity and the time required by the run. The system is not supposed to be used with more that one battery type, or more than one panel type.

In summary it can be said that Hybrid Designer is an effective tool in optimising off-grid and hybrid systems for rural electrification but can benefit from further development and resources. It is recommended that the evaluation and utilisation of the developed Hybrid Designer continue, and that data logging programs be established in conjunction with the installation and operation of hybrid systems.

Contents

1 Introduction

1.1 Where are hybrid systems used?

The majority of rural people do not have access to electricity and other important services such as water and education, and there is a lack of job opportunities. There is a need to support rural SMMEs and other educational, health and empowerment requirements and to provide necessary infrastructure. Electricity seems to have in some instances a minor role to play in stimulating rural productive activities, but its provision has in many cases contributed to growth in retail activities, in the amount and quality of some produced outputs, and to the required infrastructure in general. It is estimated that in 1999 one million rural South African households will still be unelectrified, due to the high costs of grid extensions to very remote communities with low actual electricity consumption. Off-grid electricity options are increasingly considered, and hybrid systems have been seen as a viable option to adequately meet some rural electricity requirements.

Some experience with off-grid systems exists in South Africa as they have been implemented for applications such as water pumping, domestic usage, tourist facilities, battery charging stations, shops, community centres, schools and clinics. However, experience with hybrid systems, which are a combination of different types of electricity generating energy sources, is limited world-wide, in terms of design, configuration and control. This is partly because their implementation experience is limited so far, which has also contributed to there being minimal and insufficiently detailed evaluation of data measured from such systems. There is a lack of design support for hybrid systems as, in many cases, software packages only simulate the hybrid system performance without offering help in designing it. Therefore a major goal of the project was to develop a software package that optimises the design of a hybrid system. The produced hybrid system design software is unique in its kind and is one of the most versatile hybrid system optimisation software packages available. The work produced by this project on feasibility analysis, implementation guidelines and policy recommendations explores the framework behind rural off-grid electrification, draws recommendation regarding infrastructure planning and policy development, and assesses feasible implementation scenarios.

The computer program can, based on weather and demand data provided by the user, optimise the configuration, sizing and operation strategy for an off-grid remote area power supply system, and specifically for hybrid systems. The program makes use of a default component database that holds more than 100 presently available different components of hybrid systems. Users can also add components to the database if they want to. The output can be viewed graphically for every component or overall system performance, or can be exported as a text file and imported into spreadsheets such as Microsoft Excel. The software is unique, and it would be useful to find resources for running training courses and for maintaining it.

The evaluation of the developed software tool presented in this report has been part of the greater project initiative, which focused on the appropriateness of hybrid system technology to service needs and to support economic development. Hybrid systems remain to be tested in the field, and will only be successful if used in a larger package addressing integrated and sustainable infrastructure requirements for social equity and economic development.

1.2 Challenges when designing hybrid systems

The use of hybrid off-grid electricity depends on the comparative costs, affordability, quality of service, and accessibility of other locally available energy options, as well as user acceptance of a system technology – that is, the user perceptions of how 'good' and reliable the electricity generating technology is.

Hybrid system design is often discussed in terms of minimising life cycle costs while meeting a given demand reliably. Life cycle costs (LCCs) are the sum of the equipment costs and discounted operation costs arising during the project until the end of the project horizon. LCCs in operating a hybrid system to meet a given demand reliably can be lower than in a single-source system if renewable energy sources, their complementarity and the component capacities are utilised to a better extent. If designed with this intent, a hybrid system has the potential to improve the load factors of generators and conversion elements, as well as to improve the exploitation of the available renewable energy sources. This leads to savings in maintenance requirements and component replacement costs.

In single-source systems, over-sizing the electricity generating sources to meet demand reliably, as in adverse weather conditions and for high demand peaks, increases initial costs substantially. High wear and tear, often associated with low load factors, and adjusting the supply to rapidly changing and peaky demand levels in single source systems increase operating costs, adding to the overall life cycle costs. On the other hand it should be considered that, even if a hybrid system can become less intensive on LCCs and maintenance wear of its components, when properly sized, it could in some cases need more costly control equipment and balance of system components.

Many practical hybrid system designs and implementations are often based on progressive experience, including trial and error. Monitoring studies frequently report unanticipated problems, such as premature battery degradation, requiring design corrections after installation. This can be costly, especially for remote applications in a developing country. Two problem areas repeatedly mentioned have been (a) the sizing of system components, and (b) control, particularly in more complex systems [Bezerra et al–91], but also in simpler PV/diesel hybrid systems [Dijk et al-91a], and even after prior simulation studies [Dijk et al-91b].

1.3 Niche for the DME-supported research

1.3.1 The design optimisation problem

Based on the costs of components, fuel, labour, transport and maintenance, it is desired to evaluate the most cost-effective dimensioning of all components and their operation strategy. Operating the components effectively influences operation costs and therefore overall LCCs. The necessary optimisation of the operation strategy in a hybrid system will focus on efficiency of diesel and battery operation and prolonging component lifetimes. In addition, management of demand, and adjustment to the renewable energy supply, and maximisation of load factors are important and have a significant influence on life cycle costs and sizing. This will also be discussed in this research work when evaluating the case scenarios.

Hybrid systems cover a broad spectrum of applications and design strategies. In some approaches, the renewable generators are sized to meet 90-95% of the load during the year, the storage batteries are sized to supply the peak load demand, and the diesel generator will be used only to recharge the batteries. This minimises generator run-time and fuel use. At the other end of the design spectrum are strategies where the diesel generators are sized to run every day at their most effective load point with power going directly to the load and to the batteries. The energy in the batteries can meet spikes in the power demand and the renewable generators will reduce fuel consumption and engine generator maintenance. As can be seen, between these two different design strategies are many others. It is the task of the design optimisation to recommend a least-cost and reliable design suitable for a given application, with the aim of improving the system performance and lower costs as compared to selecting a rule-of-thumb strategy.

The hybrid system design optimisation problem can be formulated as follows:

> Given an electricity demand profile for a certain location with estimated weather conditions, costs for components, labour, transport and maintenance, find the system made up of one or more electricity generating sources that covers the demand reliably and has lowest overall life cycle costs.

Difficulties in obtaining a demand profile need to be kept in mind in every design process and at every stage. This review, however, deals mainly with the techno-financial aspects of hybrid system design.

This design and operation control problem is non-linear due to non-linear component characteristics and the complexity of the hybrid system component interaction. In the literature, the operation control problem is called the economic power generation problem [Papalexopoulos-93]. An optimal steady state is achieved by adjusting the available controls to minimise an objective cost function subject to specified operating requirements. The difficulty in solving the optimum operation control problem lies mostly in the dimension of the problem [Jansen et al-93].

Simulation programs for this optimisation process are often indispensable because the interaction of different electricity generating sources, storage, conversion elements, switches and the consumer actions requires a computer-based evaluation of a large number of combinations of system configurations, system operation strategies and their associated costs.

1.3.2 Need for a method to size and operate a hybrid systems optimally

To achieve the advantages possible with the use of hybrid systems, appropriate sizing and control of the hybrid system is required. It is necessary to reduce mismatch between generation and demand, while operating diesel generators and conversion elements efficiently and the battery long-lastingly. Thereby the sizing and control setting design are interdependent. In addition, the non-trivial behaviour characteristics of some components make the design task difficult and non-linear.

Because of the complexity of the problem involved and the importance for design engineers to have a method to plan and assess different design possibilities, it is important to have a combined sizing and operation design tool. The intricate problems of prolonging component life times and operating with high capacity and fuel-savingly, while meeting demand and minimising overall life cycle costs, can only be simulated in a well-designed and tested tool.

The challenges which are faced in this context are that the optimisation requires many iterations of the system performance simulations; therefore high accuracy of a hybrid system model is often prohibitive in an optimisation process.

Present approaches have not yet fully resolved the trade-off between optimisation speed and modeling accuracy.

The tool developed in the research work supported by the Department of Minerals and Energy is desired to yield optimal component sizes in terms of those available on the markets, and optimal control settings as part of an operation strategy. Thereby the interdependency between the sizing and control is to be taken into account. The optimisation process needs to yield reliable results with a high probability, while at the same time simulating hybrid system performance with quite an accurate system model. Although there is a clear need for such a tool, its development imposes modeling and computational challenges.

1.3.3 Problem statement for the development of Hybrid Designer

As outlined in the previous sections, there is a need for an integrated optimum design tool that optimises hybrid system designs satisfactorily while incorporating an underlying system model with adequate accuracy. The objectives of this work are to develop a solution to the optimisation problem of hybrid system sizing and operation control, taking into account the interactions between system sizing and operational control settings, yielding an optimal system configuration for given requirements as well as an optimal operation strategy in form of control settings.

Innovative methods for solving this problem incorporate the use of:

- an all-encompassing strategy developed for the optimisation of the system sizing and operation;
- a genetic optimisation algorithm; also implementing a decision-making tool of optimal operating strategies for a set of system components

The work on genetic algorithms suggested the potential in using them as part of the proposed design tool in order to apply optimisation searches to a complex hybrid system model which is nearly impossible with conventional optimisation search techniques.

For the design with the use of genetic algorithms, it is necessary to have a tool that is relatively simple to use, is applicable to a wide range of hybrid system design problems, has a high probability of finding the best design and control settings, and is computationally efficient.

The creation of an effective tool requires several methodological steps:

- The general objectives and requirements for a design tool must be considered in a mathematical form that can be implemented in an algorithm suitable for the application.
- The costing and performance model of a hybrid system must be formulated mathematically to allow the design algorithm to be constructed.
- Effective optimisation algorithms such a genetic algorithms must be used to create the optimisation search algorithm consistently and efficiently.
- The tool's performance must be evaluated and its sensitivity tested for different input scenarios.
- The utility of the tool must be demonstrated by creating hybrid system designs for typical application scenarios in remote areas.

In this research, the interdependence between sizing and operation control of a hybrid system is taken into account. The design problem is modelled as generally as possible, little restriction is placed on the type of energy sources and on the type of AC-bus/DC-bus system configurations.

1.3.4 A note of caution: socio-economic and demand considerations

Electrification of remote villages is generally hoped and expected to contribute to education, job opportunities, income generation and better infrastructure. In this context it is important to assess the different electrification options for the rural electrification projects and choose an appropriate technology and energy mix for different regions, applications and needs. Apart from choosing an appropriate technology it is also important to approach rural electrification in an integrated manner – addressing other required services and educational programmes, and putting the users and their expressed needs first. It is important to learn from the financing, project management and operation and maintenance experience of these projects and systems and approach the implementation in an integrated manner.

The assessment of needs and the evaluation of collected data is a difficult assignment, as is the construction of a daily, weekly and seasonal load profile to design an off-grid electricity supply system, especially in areas where there is no prior experience in using electricity. In general, the determination of demand is one of the most pivotal design inputs, but this can require a great deal of time and resources, especially in areas where no prior experience exists with electricity.

The determination of a feasible and integrated project strategy and monitoring procedure form part of the overall project planning which can make a rural electrification project succeed or fail. Therefore the technical and financial design of this type of technology often forms only a part in a larger project design and implementation approach.

Several design strategies emphasise the importance of accommodating possible load growth. Some estimates were at a 1% load growth in addition to an increase in the number of system connections due to population growth. In some experiences, system upgrades are taking place every three years and in these cases modularity of system components was recommended, as well as wiring that can handle the system expansion. The design objectives should include optimum maintainability, possible future grid connection and the use of field-proven technology.

Many of these important issues cannot be integrated in the techno-financial design process but need to be qualitatively discussed. They need to be kept in mind, as the outcome of a design is only as good as is the estimated data we feed it and the estimated appropriateness of an application and its infrastructure we want to carry out a design for.

2 Advantage of Hybrid Designer compared to conventional approaches to the hybrid design problem

2.1 Rule-of-thumb design

Rules-of-thumb give practical guidelines on how to size and operate a hybrid system based on experience with installed systems. They include many technical details derived from expertise which is often difficult to capture in a paper-based design method or even a computer-based design optimisation. However, they do have their limitations, as they can only give broad intuitive recommendations that might still be open to improvement in some areas.

2.2 Paper-based Ampere hour methods

Some of the sizing approaches for PV/diesel hybrid systems are paper-based and employ rule-of-thumb methods [FSEC-87], [Sandia-95]. The paper-based Ampere hours (Ah) method (see also the EDRC Report, Review of Hybrid System Design, G. Seeling-Hochmuth) for sizing PV/diesel systems is useful in that it is relatively simple. It lends itself to being implemented in spreadsheets. Ah methods in general are advantageous in that they largely ignore voltage drops over cables, regulators etc, and variations in the operating voltages, but can, however, take longer than simulating the system with a software tool. Changing weather conditions or different daily, weekly or seasonal demand patterns, environmental concerns are not incorporated or only through an arbitrary weighting system. In addition, other renewable energy sources, such as wind turbines, cannot be included. Even though replacement intervals are calculated for the overall system costing and the number and size of controllers is often determined in the Ah method, no actual guidelines are given on how to operate the system in the paper-based methods.

2.3 Software-based performance assessment for pre-defined system sizes

2.3.1 General

There are a few software tools assess hybrid system performance for pre-defined system configurations ([Bezerra et al–91] *(SIRENE)*, [Borchers-93] *(RAPSYS)*, [Jennings-94] *(RAPSIM)*, [Keiderling-90], [Protogeropoulos et al-91] *(SEU-ARES)*, [Manninen,Lund-91] *(PHOTO)*, [Morgan et al.-95] *(SEU-ARES)*, [Green,Manwell-95] *(Hybrid2)*, [Dijk-94] *(SOMES)*, [Schaffrin,Litterst-97] *(SOLSIM)*). Most of these software tools simulate a predefined hybrid system based on a mathematical description of the component characteristic operation and system energy flow, and often incorporate financial costing of the system configuration. These packages are valuable for assessing a certain hybrid system design and enable viewing the effects of changing component sizes and settings manually. However, the majority of these packages require that the user come up with a pre-designed system, for example through using rule-of-thumb methods as described above. Bettered system performance and lowered costs in many of these designs could be achieved if the system configurations could be optimised.

2.3.2 HYBRID2

HYBRID2, developed by NREL in 1993, is a simulation tool written in visual basic that aims to provide a versatile model for the technical and economic analysis of hybrid system performance. The model includes both a time-series and a statistical approach to determining the operation of the hybrid system. This allows the model to determine long-term performances while still taking into account the effect of short-term variability of the renewable resources. A range of systems, components, and control and dispatching options can be modelled with user specified time steps. HYBRID2 contains a set of control strategies that have been researched by [Barley et al–95]. HYBRID2 has been validated extensively.

2.3.3 INSEL

The software INSEL [Schuhmacher-93], which was developed at the University of Oldenburg, is a logistic simulation model for renewable energy systems. It is a block-diagram simulation system where each block represents a system component or is assigned a certain task like file handling, looping through iterations, converting meteorological data and manipulating variables. The user selects blocks from the program library and interconnects them to define the layout of the energy system. Time series analysis can be carried out of the system operation with a user specified time step. The flexibility in creating system models and configurations compared to simulation tools with fixed layouts is an advantage. A disadvantage is that INSEL does not perform system optimisation. In addition, components such as diesel generators and inverters have no default models and the user must create these within the modelling block.

2.3.4 PHOTO

PHOTO, developed at the Helsinki University of Technology in Finland, simulates the performance of a hybrid system when it is given the component configuration, weather and demands data and control settings. In 1991 verification of the package was under progress. Battery ageing and temperature effects had not been incorporated at this stage.

2.3.5 RAPSIM

RAPSIM is a C++ based computer simulation model developed over the last 7-8 years at Murdoch University in Perth, Australia, using mathematical models to simulate the performance of hardware components in separate subroutines. It is now out for beta-testing. The user selects a system and operation strategy from a few pre-defined options and optimisation is sought by varying component sizes and by experimenting with control variables that determine on-off cycling of the diesel. No battery ageing or thermal battery model is implemented.

2.3.6 RAPSYS

The Renewable System Section at the University of New South Wales, Australia developed a software package RAPSYS (version 1.3) in 1987 which can simulate a range of components that may be included in a system configuration. The software is not user-friendly, and is suited for use by RAPS specialists rather than general users. RAPSYS does not optimise the size of components. The user predefines generating sources and components. The simulation recommends when the diesel generator be switched on or off. The RAPSYS software only calculates operating costs for the system specified; life-cycle costs or similar indicators are missing.

2.3.7 SEU/ARES

SEU/ARES is being developed at the University of Cardiff by [Morgan et al.-95] and determines whether a system yields the desired autonomy while meeting the project budget based on the user specified cost data. The cost ($/kW) for the hybrid system is compared with the corresponding costs of other conventional power sources. The battery size is determined by the discharge rate required during system operation. The battery 'state of voltage' instead of the battery state of charge is taken as the most crucial factor for the overall long-term performance and the size of the system components. The simulation technique has been validated by comparing the predicted system component performance with measured data. Accurately predicting battery voltage requires a fairly extensive knowledge of the descriptive parameters of system components. This operation can prove to be time-consuming and it would be advantageous if a data bank with such parameters were to be made available. Battery ageing and its effect on system performance have not been addressed as part of this program.

2.3.8 SIRENE

SIRENE, developed in 1991 by [Bezerra et al--91], aims to simulate the electrical network and economic performance of a given type of hybrid system supplying electricity to an isolated grid in order to avoid costly parameter adjustment work during on-site installations. The central control parameter is the grid frequency. The simulation tool can determine the frequency to power ratio of components. It can either be held as quasi-stationer of the isolated grid (for example, for the annual simulation in hours) or as a dynamic behaviour in short time steps.

2.3.9 SOMES

SOMES (Simulation and Optimisation Model for renewable Energy Systems, 1992, updated 1995) is a DOS-based software package for the performance analysis of hybrid systems consisting of renewable energy sources, storage, diesel generator or grid connection. It has been developed at the University of Utrecht. The simulation time step is one hour. The system performance is evaluated technically and financially. SOMES does not size a system per se, but is able to perform multiple runs by varying the component nominal power ratings stepwise in a user-specified interval (initial power, final power, step size). From this sample the lowest cost system is recommended. However, configurations outside the specified power range or even other component combinations could prove even more optimal. Criteria for the starting and stopping of the diesel generator will have to be provided by the user and the software does not give optimal operating strategies.

2.3.10 SOLSIM

SOLSIM has been developed over the last ten years at the Fachhochschule Konstanz in Germany. It has detailed technical models for PV, wind turbine, diesel generator and battery components as well as for biogas and biomass modeling. It simulates system performance and can give a financial costing of the PV panels at the end of the simulation. The program is in the process of verification. The control option are limited, but the PV installation angels can be optimised.

2.3.11 Others

The simulation software of [Keiderling-90] is directed at improving a given system through control and adaptation of its components (use of converters in the best way, etc). The sizing of the battery is handled by using rules-of-thumb and in a way to best fit given demand and supply characteristics. It is not part of the system sizing.

Another interesting approach has been taken to assess, improve and optimise the performance of a hybrid system by a project carried out under Joule [JouleII-93] that looks at developing a neural-network based hardware controller that can optimise system performance. In addition, a lot of work has been done on improving individual component and bus performance.

2.4 Summary

Simple paper-based methods exist, as well as different software packages with varying degrees of user-friendliness, validation of simulation models, accuracy of system models, and possible configurations to simulate. The paper-based methods are in most cases too limited to yield a useful design recommendation. Most of the software tools simulate a given and predefined hybrid system based on a mathematical description of the component characteristic operation and system energy flow, and often incorporate financial costing of the system configuration. These packages (see **Table 2-1**) are valuable for assessing a certain hybrid system design and enabling a view of the effects of changing component sizes and settings manually. However, the majority of these packages require the user to come up with a pre-designed system, through using, for example, rule-of-thumb methods. Therefore, a better system performance with lower costs could be achieved in many of these designs if the system configurations could be optimised as well such as is possible with Hybrid Designer. **Table 2-1** gives a rough comparison of the different software tools available to simulate a the performance of a given hybrid system.

Table 2-1 Comparison of the different software tools

	Simulated technical accuracy	*Optimisation*	*Financial evaluation*	*Choice of system configuration*
Hybrid2	Very high	No	Yes	Lots
SOMES	High	Random within user-defined interval	Yes	Many
HOMER	Low	Linear/Random	Yes	Few
INSEL	Very high	No	Not an existing user block	Lots
RAPSIM	? High	No (Recommendations from rule table?)	Yes	Many
SEU/ARES	? High	No	?	?
SOLSIM	Very high	No	Only macro after simulation	Many
HYBRID DESIGNER	High	Yes	Good	Many

3 Hybrid Designer compared to other software-based optimisation of hybrid system designs

3.1 General

Based on a hybrid system performance formulation, a model can be structured which can be optimised for a set of decision variables using some type of computer algorithm. Thereby the formulated objective function, usually the life cycle costs, is aimed to be minimised while meeting constraints placed on the system and system performance. Various computer techniques exist to optimise such problems.

In addition to optimising a deterministic model, stochastic models [Braun-93], [Dantzig,Infanger-93] address uncertainties in demand, component failure and weather patterns, but can be even more intensive in computation because of the complexity involved.

For the hybrid system design problem, so far only a few software tools exist, using a simplified and linear model [Lorenz-88], [Lilienthal et al-95] or a complex model but varying the design randomly within a chosen range of component sizes [Dijk-94].

The advantage of the simplified linear model is that it lends itself to fast estimates of a possibly near optimum estimate. However, this estimate might not be near optimum because of the complexities involved in an actual system. The advantage of varying a complex model randomly around a range of pre-chosen sizes lies in the potential to obtain an impression of what effect variations of the pre-defined system configuration will have. The ranges over which the variations take place might not lead to finding an optimum system, however.

This research develops a design algorithm that optimises a complex model using optimisation techniques. [Seeling-95a] describes the design of hybrid systems, which considers optimisation of the non-linear hybrid system description, taking into account the complex interdependence of operating strategy and sizing. [Marrison,Seeling-Hochmuth-97] formulated the appropriate cost/benefit function for this non-linear optimisation of hybrid systems.

3.2 Conventional computer-based design optimisation techniques

The optimisation problem is defined as minimising a function F(x) through optimising the values of its variables x:

$$\underset{x}{Min}\ F(\underline{x})$$

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ .. \\ x_n \end{bmatrix} \quad or \quad \underline{x} = [x_j]_n \ \ j = 1,2,......,n$$

Equation 1: The minimisation function of the optimisation problem

Often constraints are placed on the system and its performance which are expressed in g(x). The solution of the optimisation problem needs to lie within these constraints.

$$\underline{g}(\underline{x}) \geq 0$$

$$\underline{g} = \begin{bmatrix} g_1 \\ g_2 \\ .. \\ g_n \end{bmatrix} \quad or \quad \underline{g} = [g_i]_m \ \ i = 1,2,......,m$$

Equation 2: The constraints placed on the optimisation problem

Therefore the goal is to find a vector x that minimises the real-valued function F(x) while satisfying the constraints g(x). The function F(x) is called the cost, objective or energy function and x is an n-dimensional vector called the design vector.

The solution to the optimisation problem can be found for linear problems and for non-linear problems with existing first and second derivatives of the cost function and each of the constraints. If these derivatives exist, the solution for unconstrained problems equals the values of the design vector x for which all the partial derivatives of the cost function equal zero. In case of constraints, the solution are the values of the design vector x, for which for each summed partial derivatives of the cost function and the weighted constraints zero is obtained. The weight vector λ for the constraint vector is called the "Lagrange multiplier", and its plane needs to be rectangular to the plane of the vector g.

$$\frac{\partial F(\underline{x}^*)}{\partial x_j} = 0 \qquad (unconstrained),\ j = 1,2,......,n$$

$$\frac{\partial F(\underline{x}^*)}{\partial x_j} + \sum_{i=1}^{m} \lambda_i^* \cdot \frac{\partial g_i(\underline{x}^*)}{\partial x_i} = 0 \quad (constrained), \quad where\ \lambda^* \cdot g(\underline{x}^*) = 0$$

Equation 3: The calculus-based solution to the optimisation problem

The current literature identifies three main types of search methods to derive the optimum: calculus-based, enumerative, and random methods.

3.2.1 Calculus-based optimisation techniques

Calculus-based methods subdivide into two main classes, indirect and direct [Goldberg-1989]. Indirect methods seek local extrema by solving the usually non-linear set of equations resulting from setting the gradient of the objective function to zero. Direct search methods seek local optima by hopping on the function and moving in a direction related to the local gradient. This is the notion of *hill-climbing*: finding the local best through climbing the function in the steepest permissible direction. Depending on the linearity or non-linearity of the function and constraints, linear or non-linear gradient search techniques are used, often also called "linear programming" and "non-linear programming" techniques. Both the direct and indirect methods are local in scope. The optima they seek are the best in a neighbourhood of the current point. Secondly, calculus-based methods depend upon the existence of derivatives, which is equivalent to well-defined slope values. Even if numerical approximation of derivatives are allowed, this is a severe shortcoming, as many practical parameter spaces have little respect for the notion of a derivative and the smoothness this implies. The real world of search is full with discontinuities and vast multimodal, noisy search spaces as depicted in a less calculus-friendly function in Figure 4-1.

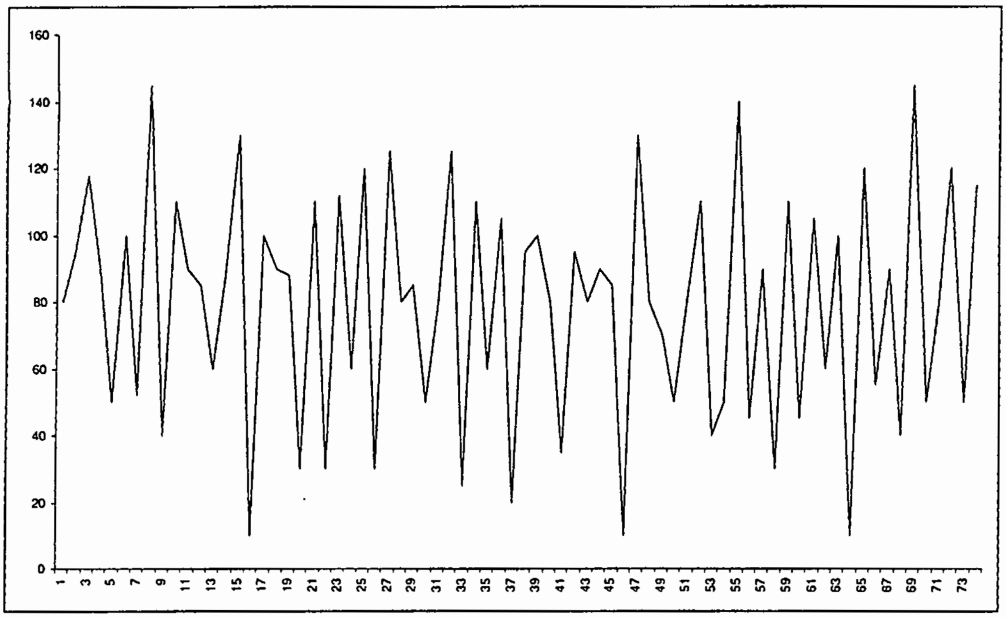

Figure 3-1: Noisy and discountinuous function, unsuitable for optimisation searches by traditional methods

It comes as no surprise that methods depending upon the restrictive requirements of continuity and derivative existence are often unsuitable for all but a very limited problem domain.

3.2.2 Enumerative schemes

The ideas of enumerative schemes is fairly straightforward within a finite search space, or a discretised infinite search space. The search algorithm starts looking at objective function values at every point in the space, one at a time. Although the simplicity of this type of algorithm is attractive, such schemes lack efficiency. Many practical spaces are simply too large to search one at a time and still have a chance of using the information to some practical end. Even the enumerative scheme *dynamic programming* breaks down on problems of moderate size and complexity.

Dynamic programming is often used for problem situations involving a sequence, so-called stages, of interrelated decision processes that extend over a number of time periods or events [Markland-89]. The problem is to make decisions in such a way that the costs of the system during a certain planning horizon are minimised. In dynamic programming problems, one starts with the last decision at the so-called stage 1. Next, the costs of the decisions at stages 2, 3, 4 are evaluated, the lowest cost path up to that stage at a time interval is chosen and so on, until the optimal decision path for stage n is found, which is the present decision (**Figure 3-2**).

If the dynamic programming problem involves stochastic inputs, the expected costs and stochastic occurrence of the variables involved need to be modelled. One way to do that is to use Markov Chains where only the last point in time or the last few points in time influence the current time instant, which simplifies the stochastic analysis.

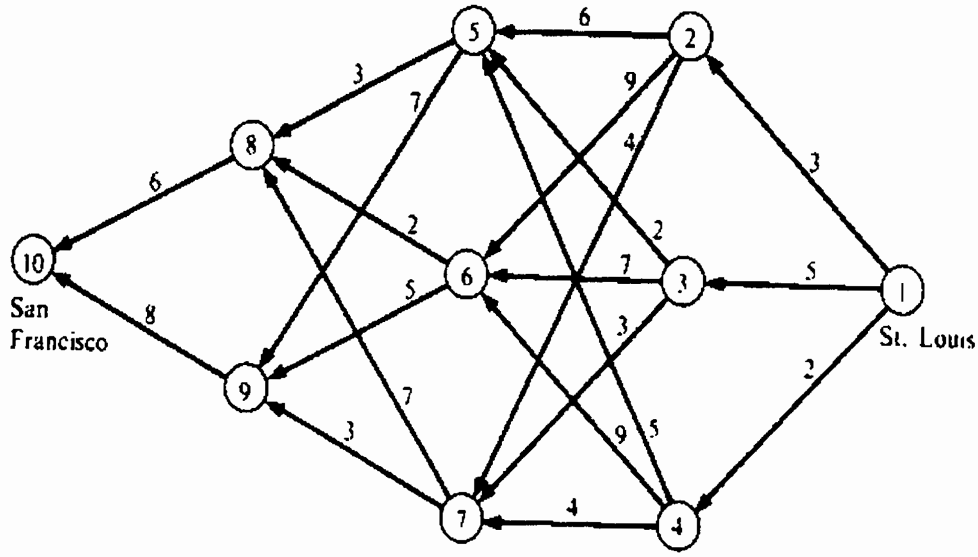

Figure 3-2: Decision-making in the dynamic programming process
(Example: Lowest cost travel from San Francisco to St. LouisFi)

3.2.3 Random search techniques

In general, the methods that follow the trajectory of a system of ordinary differential equations are local – that is, they depend on the behaviour of the cost function along the trajectory, and there is no hope of building a completely satisfactory algorithm for global optimisation based only on a system of deterministic differential equations. The most widely used methods for global optimisation are of a stochastic nature. In these methods random fluctuations or noise are introduced into the system in order to avoid being trapped in local minima.

Random search algorithms have achieved increasing popularity as researchers have recognised the shortcomings of calculus-based and enumerative schemes. Yet random walks and random schemes that search and save the best must in many cases be discounted because of the efficiency requirement. Purely random search algorithms often cannot be expected to perform better than enumerative methods; randomised techniques, however, can. The genetic algorithm is an example of a search procedure that uses random choice as a tool to guide a highly exploitative search through a coding of a parameter space. Another currently popular search technique, simulated annealing, uses random processes to help guide its way of search for minimal energy states. The important thing to recognise is that randomised search does not necessarily imply directionless search.

3.2.3.1 Simulated annealing

Simulated annealing is a stochastic strategy of searching for the values of decision variables corresponding to the global minimum of the cost function. The technique can be compared to the following example. At a high temperature all particles of a metal lose the solid phase so that the positions themselves are random according to statistical mechanics (that is, at high temperature the particles are in violent random motion). As with all physical systems the particles of the molten metal tend toward the minimum energy state, but a high thermal energy prevents this. The minimum energy state usually means a highly ordered state such as a defect-free crystal lattice. In order to achieve the defect-free crystal the metal is annealed – that is, at first it is heated to an appropriate temperature above the melting point and then cooled slowly until the metal freezes into a defect-free crystal state corresponding to the local minimum of the thermal energy. The slow cooling is usually necessary to prevent dislocations and other crystal lattice disruptions.

In the simulated annealing algorithm, artificial thermal noise in the form of uniform random perturbations is applied when changing the values of the decision variables. The artificial thermal noise is gradually decreased over time. The change in value of the cost function, resulting from the changed values of the decision variables, is determined. The magnitude of the incurred fluctuations in the cost function is controlled by the so-called computational temperature T, which is a parameter in the uniform Boltzmann distribution. The variation of the computational temperature in time is called the cooling or an annealing schedule.

The introduced noise allows occasional hill climbing interspersed with descents to be able to get out of local minima of the cost function. If the cost is reduced the new configuration – that is, the combination of decision values – is accepted. If the cost is increased, however, the new configuration may also be accepted with a certain probability related to the computational temperature. At high temperature the probability of up-hill moves is large; however, at a low temperature the probability is low – that is, fewer uphill moves are allowed.

The efficiency of the simulated annealing approach crucially depends on the choice of the cooling schedule for the control parameter, the so-called temperature. Such a temperature-cooling schedule is rather slow, often too slow to be practical. Generally speaking, if the cooling schedule is too slow, a satisfactory solution might never be reached, and, if it is too fast, a premature convergence to a local minimum might occur. The main drawback of the simulated annealing algorithm is a very long computation time, since it is necessary to perform a large number of random searches at each temperature step to arrive near the equilibrium state.

In some instances, the poor performance of the simulated annealing in terms of its large computational requirements might be improved when introducing deterministic gradient search technique when changing the values of the decision variables and applying the "thermal noise". This so-called gradient stochastic algorithm can be then viewed as the movement of the cost function value in dependence of its n decision variables subject to two different elements, one representing random fluctuations, the other one following down-hill trajectories along the gradient direction of steepest descent.

3.2.3.2 Genetic algorithms

Genetic algorithms were developed in the 1970s by Holland and have been widely used since in every thinkable field and application in engineering. Genetic algorithms are search algorithms based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures with a structured yet randomised information exchange. In every generation, a new set of artificial objects (strings representing values of system variables) is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure. While randomised, genetic algorithms are no simple random walk. They exploit historical information to speculate on new search points with expected improved performance. Genetic algorithms use payoff (objective function) information, not derivatives or other auxiliary knowledge. In addition, they use probabilistic transition rules, not deterministic rules. Genetic algorithms try to imitate biological evolution by creating a whole population of the initial model through varying its variables randomly by processes called selection mutation, crossing-over and recombination. Selection is a process in which individual strings are copied according to their fitness – that is, their objective function values. Copying strings according to their fitness values means that strings. with a higher value have a higher probability of contributing one or more offspring in the next generation. Crossing-over entails swapping bits of string information between selected objects. Mutation is the occasional random alteration of the value of a string position. By itself, mutation is a random walk through the string space. When used sparingly with selection and cross-over, it is an insurance policy against premature loss of important notions.

The best ones of a population, which best meet a chosen criterion (such as minimising the objective cost function), survive; the rest are discarded. Then again, a certain number of members of a population are chosen and a certain number of their parameters are randomly changed (with a binomial distribution as in biological processes). Learning populations are such that change the mutation steps adaptively according to how well they fulfil the quality criteria for the survival/discard process. The more parameters involved the faster the evolution strategies converge compared with classical optimisation techniques like steepest descent and gradient techniques.

Techniques similar to genetic algorithms are used in scheduling and parameter variation. Genetic algorithms have become more and more popular due to the non-linear, non-smooth, discontinuous engineering problems very often encountered in the real world and which are difficult to capture in gradient-friendly models. Genetic algorithms have been compared to random searches in control problems in [Marrison,Stengel-94],[Marrison-95], [Pohlheim-95] and have been found highly superior in terms of speed and efficiency.

Genetic algorithms are used in this research to optimise the developed hybrid system design model through minimising its life cycle costs while still meeting required system performance.

3.3 Existing hybrid system optimisation software

3.3.1 HOMER

HOMER is being developed by NREL as a tool to optimise a hybrid system. Some remodelling of HOMER is carried out which will change the linear mixed-integer optimisation technique provided by a commercial optimisation package GAMS, into a randomised optimisation method using random search techniques or simulated annealing. This change in optimisation technique happened in order to tackle non-linear component characteristics such as the diesel fuel curve more accurately. HOMER uses an hourly time-step, a very simplified model of a hybrid system and offers some load management recommendations. After entering site data, HOMER can determine a near-optimal solution that can then be analysed further with more sophisticated dynamic simulation models such as HYBRID2.

3.3.2 SOMES

As described in the previous section, SOMES, developed by the University of Utrecht over a number of years, simulates the performance of a hybrid system rather than its design. However, a pre-defined system can be varied within user-defined boundaries to assess the impacts changes in component sizes will have.

3.3.3 Other software

In the software of [Lorenz-88] the battery is sized only to achieve a daily balancing between demand and supply, not for longer periods. Only a small number of predefined systems can be compared and from these the best configuration is evaluated. A prerequisite for this selection is that the different energy supplies are ordered in a sequence of preferred use. The work of [Lorenz-88] gives guidelines on how to extend the systems in case of demand increases.

3.4 Summary

A very limited number of software design packages exist to optimise the hybrid system design problem even though extensive research into optimisation techniques exist. Therefore there is a need for a package such as Hybrid Designer that simulates a hybrid system with some accuracy but can at the same time still optimise the system configuration and its control settings. These requirements introduce computational complexities as an optimisation and a performance simulation need to be carried out. Homer is the only other available optimisation package at the moment; however, it uses a simple technical model and offers only a limited number of configurations; it is in the process of being revamped.

The system performance simulation in Hybrid Designer contains the simulation for choosing the sizing, control setting and calculating life cycle costing. In order to tackle these challenges genetic algorithms have been used in this research to optimise the non-linear hybrid system model. Genetic algorithms have been applied to the design hybrid systems in [Seeling-95a], [Marrison,Seeling-Hochmuth-97], [Seeling-Hochmuth,Marrison–97], [Seeling-Hochmuth-98]. The approach takes into account the interdependency between sizing and system operation strategy.

4 Overview of the developed Hybrid Designer

4.1 What is Hybrid Designer?

Hybrid Designer is a program that will design hybrid energy systems best suited for a particular site. In order to make these decisions, Hybrid Designer needs the following information:

- weather information about the site: wind speeds, temperature, irradiation;
- demand information about the site: AC & DC demand requirements;
- available components and their characteristics: operating costs lifetimes, installation costs;
- efficiency information, etc; and
- general options: such as title, duration, time intervals, optimisation options.

Based on this information Hybrid Designer uses optimisation and simulation techniques to determine and evaluate the best configuration of components as well as produce information on how to operate them. Output from Hybrid Designer includes:

- sizing configuration;
- operation strategy information;
- simulation data.

4.2 Requirements

Hybrid Designer can run quite slowly, so at least a Pentium 150Mhz, with 64M RAM is required.

5 Development process of Hybrid Designer

The software was produced in several steps:

1. Modeling
2. Software implementation
3. Database production
4. Evaluation and sensitivity analysis

The components of a hybrid system were modelled with respect to their operating characteristics. The modeling of the overall system and its energy flows then incorporated the component models. After that the optimisation model for the hybrid system was defined on which the optimisation algorithm is performed. The models and their interdependence have been documented. The model was tested using a Matlab prototype implementation.

The computer program was developed with the help of Edward van Kuik who implemented the developed model in C++, which was chosen because it allows for a fast execution of the software and the creation of an user-friendly interface. After the choice of software, van Kuik and a visiting student (Peter Weber) worked out a concept for coding the algorithm. The work was split into coding for the user interface and for the system simulation and optimisation. This was then implemented by van Kuik. During the in-between testing of the code, up-coming issues of speed and implementability were discussed and conceptualised. Finally the code was tested in-depth by van Kuik, Seeling-Hochmuth, Ingo Knoblich (a visiting student) and Frank Hochmuth, and run by Ahilan Kailasanathan (an EDRC MSc student). The software is called Hybrid Designer and optimises an off-grid/hybrid system configuration, its sizing and operation strategy through simultaneously running financial and technical performance assessments and using genetic algorithms for optimising these. A comprehensive software manual has been produced by van Kuik to help a user in running Hybrid Designer. The user enters weather and demand data and can make use of a provided component database, containing over 100 components available on the market. This component data for the software database was obtained from industry documentation about existing products on the market. The components are entered with their characteristic performance and efficiency values, and their costs for purchase and operation. The user can also enter new components into the database. The software outputs all values for sizing, configuration, and operation settings. They can be viewed for its component individually, graphed or exported to a spreadsheet program like Excel.

6 Evaluation and sensitivity analysis of Hybrid Designer

6.1 Overview

An important step in evaluating and refining a developed computer program is to compare its calculated recommendations with the design, life cycle costing and performance of actual systems with the assistance of logged operating data. So far there exists no logged data of hybrid systems in enough detail in South Africa that such a comparison could have taken place. Data obtained was from a PV/wind system at a school/clinic application in Mabibi. This data was only useful for a period of three months, however, as then changes in the measured data took place – maybe due to some technical difficulties. In addition, the data measured only the wind and solar current that charge the battery and battery voltages. It did not measure demand, therefore it was impossible to use this data for verification with the design tool. Other measured data available in South Africa is daily measurements from farms, but these time steps are too big to enable proper performance comparison with a software tool. Internationally, there are very few well logged hybrid systems. It was hoped to obtain data from a system in Utrecht, Holland, but the system stopped operating because of a lack of funds, and the existing data reflected experiments in its operating strategy and was therefore not easily usable for a comparison with software recommendations. Another hoped-for source of data – from installed systems in the south of Spain – did not materialise, as the projects concerned had insufficient funds for data logging. The route chosen for the evaluation of the developed Hybrid Designer then was to utilise other software programs that had been verified intensively with logged data in the comparison with the Hybrid Designer outcomes. The software programs chosen (Hybrid2 by NREL and SolSim by the Fachhochschule Konstanz) simulate hybrid systems (not optimising them) and use quite accurate models as they do not have to worry about speed considerations. Both Hybrid2 and SolSim have been verified extensively with actual data. The outputs of Hybrid Designer have been compared with the performance predictions of SolSim and Hybrid2 by I Knoblich ('Investigation of system performance of software tools for simulation of solar hybrid system', EDRC 1998). An additional evaluation and sensitivity analysis of the Hybrid Designer performance was carried out by F Hochmuth ('The hybrid designer: Testing, evaluation, and identification of additional features', EDRC 1998), who tested its outcomes according to the technical and financial sense they made in engineering terms and suggested corresponding improvements that were implemented.

6.2 Sensitivity analysis

Different design scenarios were investigated for different demand applications and different locations in South Africa. Five different hybrid and single-source systems have been designed, based on rule-of-thumb methods, for each of the demand scenarios developed by Kailasanathan for 11 different locations in South Africa using rule-of-thumb design (Kailasanathan 1998). Demand data was collected by Marcus Rehm, from Eskom (from a commercial farm), and also from the literature. Weather data was used from the EDRC database as well as being obtained from the South African Weather Bureau. The designs were run with Hybrid2 and the financial costs were determined for the different scenarios. It was seen that the sensitivities in demand and weather could thereby be investigated in a useful manner in terms of locating relevant site conditions for South Africa. It was shown from a financial analysis that hybrid systems are technically and financially the recommendable option for low and medium load levels around $2kW_p$ – $50kW_p$ power requirements and 4kWh – 200kWh of daily energy needs. The economic analysis didn't change this picture to a great extent. Based on these designs recommendations on where what type of system seems financially cost-effective were given. Some of the designs were also run with Hybrid Designer towards the end of the project when Hybrid Designer was released. The optimisation with Hybrid Designer indicated an increased recommended use of hybrid systems. This is due to the fact that the systems obtained with the rule-of-thumb approach were not designed optimally and were therefore tending to single source systems rather than to badly designed hybrid systems. However, the investigation of these sensitivity scenarios needs further resources and detailed analysis.

6.3 Summary of evaluation and sensitivity outcomes

The performance of Hybrid Designer was compared with the software SOLSIM for PV, wind turbine, diesel generator and battery single source systems with different demand profiles. Subsequent to this, the behavior of a hybrid system in both programs was compared. The documenting thesis is in Appendix B. Several interesting points were made. For example, the technical performance of PV and wind turbine generators could be corrected through inserting additionally necessary parameters for wind turbine and PV module operation into the Hybrid Designer model. The results shown by Knoblich have therefore been corrected for Hybrid Designer since his thesis was written. Similarly, the battery model in SOLSIM could be corrected through the comparison. An analysis of the operating strategies employed in SOLSIM and Hybrid Designer showed that the control options available in Hybrid Designer and their optimisation has a beneficiary effect on system performance.

Evaluation of the outputs of Hybrid Designer with the software tool Hybrid2 were only started. They were made difficult due to the difference in the format required to input data and an error found in Hybrid2's costing. Hybrid2 has just recently been updated and therefore it will be in future a valuable tool for further evaluations. The work done so far has shown that, through the optimisation with Hybrid Designer, some system designs are recommended to be hybridised (Kailasanathan 1998). Before the optimisation, in many cases single-source systems were prefered to badly designed hybrid systems.

In addition, the obtained results from Hybrid Designer were investigated according to the technical and financial quality of the recommendations. Different parameters were varied – such as populations size, complexity of runs, speed, repeatability, stability of runs and runs with a large number of components in the database. A number of software bugs were identified and fixed during the evaluation process. A list of additional features to put into Hybrid Designer is given in the report in Appendix A.

It was said in the report that while a population size of ten is definitely too small for the problem it was applied to, higher population sizes produced good results. There are many debates internationally about what population sizes are required for certain problems. At population sizes of 250 the software produced good and reliable results (see also publications of Prof D.E. Goldberg form the Illinois Genetic Algorithms Laboratory (http://www-illigal.ge.uiuc.edu/). The software works well with some minor problems still to be sorted out and some additions still to be made. Hybrid designer can be used to design and simulate hybrid energy systems using genetic algorithms. The system is recommended to be used by trained experts only. While it has been made user-friendly using a Windows 95 interface, the degree of sophistication and the nature of the genetic algorithm make some training for the user necessary to be able to fully exploit the program's abilities. Alternatively, the users manual could include an in-depth section about the impact of the various options on the validity and the time required by the run. The system is not supposed to be used with more than one battery type, or more than one panel type.

In summary it can be said that Hybrid Designer is an effective tool in optimising off-grid and hybrid systems for rural electrification but can benefit from further development and resources. It is recommended that the evaluation and utilisation of the developed Hybrid Designer continue in future and that data logging programs be established in conjunction with the installation and operation of hybrid systems.

7 Conclusions and recommendations

There exists a niche for hybrid systems and a need for an integrated optimisation design software for hybrid systems. Hybrid Designer was based on the modeling of the hybrid system, its energy flow and the adaptation of the models for the optimisation algorithm. The results of Hybrid Designer were compared with the outcomes obtained by Hybrid2 and SolSim which had been verified extensively with logged data. In addition, the results of Hybrid Designer were analysed in terms of the technical and financial sense they made. It was found that Hybrid Designer constitutes an effective tool subject to the input data being entered intelligently by the user.

Hybrid Designer has the potential to become one of the most powerful hybrid system optimisation tools available, and it has already a unique status. The software should be further developed and maintained for the next five years to realise this potential. Workshops should support users in how to enter data, run scenarios and evaluate outcomes. Hybrid Designer can then be a useful tool infuture to determine technology selection criteria and decision regions for the technology implementation.

Recommendations for follow-up work therefore are to:

- support further development and evaluation work;
- develop software into a commercial package from the present beta version;
- support maintenance of software for the next five years;
- support training seminars on how to use the software;
- support research to select and find decision criteria for rural off-grid technology selection in providing electricity to rural areas, using the developed software.

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Publications stemming from the development of Hybrid Designer

As part of the DME supported project the following publications were made possible (order according to date of publication):

1) Seeling-Hochmuth G. (1998), Village Power, ISES Utility Initiative for Africa/ Initial Implementation Conference, DBSA Johannesburg, Proceedings of Conference
2) Seeling-Hochmuth G. (1998), Alternative Energy Sources: Renewable Energy, Business map, SA insider, Quaterly Review, Development Finance / Electricity, PO Box 93814, Yeoville, 2143 South Africa
3) Seeling-Hochmuth G. (1998), Remote Area Power Supply in South Africa with a focus on productive activities – Challenges and Potential, 3rd STRC/OAU Inter-African Symposium on new renewable and solar energies, Pretoria, South Africa

4) Seeling-Hochmuth G. (1997), Optimisation of Design and Operation of PV-Hybrid Systems For Remote Area Power Supply – Results And Evaluation Of A Rural Case Study, Proceedings of the 14th EU PV Solar Conference, Barcelona

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EDRC REPORT SERIES

Draft report on the evaluation of the developed software tool Hybrid Designer

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