OPTIMISATION OF HYBRID ENERGY SYSTEMS SIZING AND OPERATION CONTROL

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Abstract

This thesis focuses on the development of a new approach for the sizing and operation control of a hybrid system with the goal of minimising life cycle costs per kWh and meeting required supply reliability. The optimisation method employed makes use of genetic algorithms. Genetic algorithms do not require gradient calculations. Therefore the hybrid system can be modelled with a high degree of accuracy considering the highly complex workings of actual systems, while still keeping computation time at reasonable levels.

Optimisation algorithms change the values of so-called decision variables of an underlying model in such a way as to optimise the resulting value of the model's objective function. In this thesis an objective function is developed whose value for a specific hybrid system design serves as a classification of merit for the design. The objective function is a combination of life cycle costs per kWh and penalty costs per kWh for unmet demand. In addition, a model for hybrid systems is developed through a precise power flow description of the energy transmission in a hybrid system.

The calculation of the power flow depends on the prior determination of the values of the model's decision variables, which consist of component sizing variables and control setting variables. Where possible, the number of variables is reduced through substitution with characteristic system and component operation equations.

The remaining operating decisions encountered in the power flow are battery and diesel generator outputs. Once either the battery or the diesel generator output is chosen, the other output level and therefore the power flow is determined automatically. However, independent of which component output value is computed, this needs to be carried out at every single time instant during system operation. The number of decision variables to be optimised would then become very high. Therefore, control settings are introduced that indicate the level of battery state of charge and unmet demand at which either the value for the battery output or the diesel generator output is determined first. The computation of the other output value and the complete power flow can then follow automatically. Another advantage of optimising the control settings instead of component outputs at each time instant is that the values for the control settings can be readily implemented in actual systems through the corresponding adjustments of system controllers.

The value of a control setting is determined in the genetic algorithm, together with the values of the sizing variables, and then remains constant during the simulation of the model until it is changed in the next iteration of the genetic algorithm. The algorithm converges when the values of the decision variables, the model's performance and its merit of design do not improve significantly anymore.

The algorithm has been implemented in the computer language MATLAB©. The simulation runs with MATLAB© are useful to present the algorithm as a new and improved tool to use in optimising hybrid system design. MATLAB© is a slow computing language that is not using computer hardware resources in an optimal way, however, it allows flexible programming for research purposes.

To verify the effectiveness of the approach, the developed algorithm is applied to two case scenarios for typical farming demand profiles and for typical remote sites in South Africa for which the use of hybrid systems can be considered. The results are meaningful and give insight into the relation between system operation and sizing and costs.

The results are also compared with other approaches, namely the rule-of-thumb method, the Ah method, spreadsheet methods, the performance simulation tool HYBRID2 and with data from actually installed systems. It can be seen that the recommended designs and the calculated costs by the algorithm are realistic.

Zusammenfassung

Diese Dissertation befaßt sich mit der Entwicklung einer neuen Strategie zur Bestimmung von optimalen Systemgrößen und einer optimalen Betriebsführung für Hybridsysteme, mit dem Ziel, die Gesamtkosten pro kWh zu minimieren und die erforderliche Zuverlässigkeit der Elektrizitätsversorgung bereitzustellen. Die verwendete Optimierungsmethode benutzt genetische Algorithmen. Genetische Algorithmen erfordern keine Berechnung der Gradienten. Daher kann das hybride System unter Berücksichtigung seiner sehr komplexen Funktionsweise mit einem hohen Grad von Genauigkeit modelliert werden, wobei dennoch die rechnergestützte Berechnungszeit in einem vernünftigen Rahmen gehalten wird.

Optimierungsalgorithmen ändern die Werte der sogenannten Entscheidungsvariablen eines zugrundeliegenden Modells so, daß der resultierende Wert der Modellzielfunktion optimiert wird. In dieser Arbeit dient der Wert der entwickelten Zielfunktion für ein entworfenes Hybridsystem als Maß für die Verwendbarkeit des Design. Die Zielfunktion ist eine Kombination von Annuitätenkosten pro kWh und Strafkosten pro kWh für nicht gedeckte Last. Außerdem wird ein Modell für die genaue Beschreibung des Energieflusses im hybriden System entwickelt.

Die Berechnung des Energieflusses hängt ab von den Werten der Modellentscheidungsvariablen, welche aus Anlagengrößenvariablen und Betriebsführungsvariablen bestehen. Diese müssen vor Berechnung des Energieflusses feststehen. Wo es möglich ist, wurde die Anzahl der Systementscheidungs-Variablen reduziert durch Ersetzung mit charakteristischen Gleichungen für das System und für die Komponentenbetriebsführung.

Die verbleibenden Betriebsführungsentscheidungen in der Energieflußbeschreibung sind die Batterie- und Dieselgeneratorströme. Sobald entweder der Batteriestrom oder der Dieselgeneratorstrom festgelegt ist, kann der andere Komponentenausgangsstrom und daher auch der Energiefluß automatisch bestimmt werden. Unabhängig davon, welcher Komponentenausgang zuerst festgelegt wird, muss dies zu jedem einzelnen Zeitpunkt während der Systembetriebsführungsimulation erfolgen. Die Anzahl der Entscheidungsvariablen, die optimiert werden müssen, würde dann sehr hoch. Daher werden sogenannte Betriebs- oder Regeleinstellungen eingeführt, die den Batterieladezustand und die Größe des nichtgedeckten Verbrauchs angeben, bei dem entweder der Wert für den Batteriestrom oder den Generatorstrom zuerst bestimmt wird. Die Berechnung des jeweils anderen Stromes und die komplette Energieflußberechnung folgen dann. Ein weiterer Vorteil, die Regelungseinstellungen statt der Komponentenausgänge zu optimieren, die zudem für jedes Zeitintervall optimiert werden müßten, ist, daß die Werte für die Betriebsführungsseinstellungen im realen System durch die korrespondierende Einstellung der Systemregelung einfach implementiert werden können.

Der Wert einer Betriebsführungseinstellung wird im genetischen Algorithmus bestimmt und optimiert, zusammen mit den Werten für die Komponentengrößen. Der Wert einer Betriebsführungseinstellung bleibt konstant während der Simulation des hybriden Systemmodels, bis er in der nächsten Iteration des genetischen Algorithmus' geändert wird. Der Algorithmus konvergiert, wenn die Werte der Entscheidungsvariablen, d.h. die Betriebsführung und die Systemauslegung, sich nicht mehr beträchtlich ändern.

Der Algorithmus ist in der Computersprache MATLAB implementiert. Die Simulationen mit MATLAB sind nützlich, um den Algorithmus als ein neues und verbessertes Verfahren zu präsentieren, das verwendet werden kann, um das Design von hybriden Energiesystemen zu optimieren. MATLAB ist eine langsame Computersprache, die Computer Hardware Ressourcen nicht optimal nutzt. Es erlaubt jedoch eine flexible Programmierung für Forschungsvorhaben. Um die Effektivität des Verfahrens zu verifizieren, wurde der entwickelte Algorithmus auf mehrere Fallstudien für typische Farmverbrauchsprofile in entlegenen Gebieten in Südafrika, die für den Gebrauch von hybriden Systemen geeignet sind, angewendet. Die Ergebnisse sind aussagekräftig und geben Einblick in die Abhängigkeit zwischen Systembetriebsführung, Komponentenauslegung und Kosten.

Die Ergebnisse wurden zusätzlich mit anderen Designmethoden verglichen, nämlich mit der Daumenregelmethode, der Ah Methode, einer eigens entwickelter Spreadsheet Methode, der Betriebssimulations-Software HYBRID2 und mit tatsächlich installierten Systemen. Es konnte bestätigt werden, daß die von dem Algorithmus empfohlenen Systemdesigns und die berechneten Kosten realistisch sind.

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Frequently used Nomenclature

Symbol	Meaning	Unit
$\%_{Max(Min)}$	Percentage battery state of charge	%
$\%ofCC_{Bat}$	Percentage of capital costs added for installation and bos parts for battery banks	%
$\%ofCC_{D,size,i}$	Percentage of capital costs added for installation and bos parts for diesel generator type i	%
$\%ofCC_{PV}$	Percentage of capital costs added for installation and bos parts for PV	%
$\%ofCC_{WT}$	Percentage of capital costs added for installation and bos parts for wind turbines	%
η	Battery charging efficiency	%
σ	Selfdischarge rate	%
η_{losses}	Efficiency losses due to conversion losses, wire losses, battery cycling losses	%
c	Charge/discharge indicator	
$corr_{Factor}$	Correction factor to account for increases in fuel needs during start-up	
$Cost_{Bat}$	Battery cost according to size and type of battery	ECU
$Cost_{Dies}$	Diesel generator cost according to the size of the diesel generator type	ECU
$Cost_{PV}$	PV panel cost according to the size of the PV panel type	ECU
Costs	Vector of component costs	ECU
$Cost_{WT}$	Wind turbine cost according to the size of the wind turbine type	ECU
$Demand_{Wh/day}$	Average demand in Wh/day	Wh/day
$eff_{bc}(t)$	Efficiency of battery charger	%
$eff_{inv}(t)$	Efficiency of inverter	%
$FixedCosts_{Bat}$	Added fixed costs accounting for installation and BOS parts, Battery	ECU
$FixedCosts_{Dies}$	Added fixed costs accounting for installation and BOS parts, Diesel	ECU
$FixedCosts_{Diesel,type,i}$	Added fixed costs accounting for installation and BOS parts for diesel generator type i	ECU
$FixedCosts_{perYear,Bat,i}$	Fixed operaion costs arising during battery type i operation each year	ECU
$FixedCosts_{perYear,Dies,i}$	Fixed operation costs arising during diesel generator, type i, operation each year	ECU
$FixedCosts_{perYear,PV}$	Fixed operaion costs arising during PV operation each year	ECU
$FixedCosts_{perYear,WT,i}$	Fixed operaion costs arising during wind turbine type i operation each year	ECU
$FixedCosts_{PV}$	Added fixed costs accounting for installation and BOS parts, PV	ECU
$FixedCosts_{WT}$	Added fixed costs accounting for installation and BOS parts, Wind	ECU
f_{MM}	Mismatch factor for different PV panel current outputs	
Fuel Cost/ Litre	Cost of fuel in ECU/litre	ECU/litre
fuel_costs	Fuel cost measure	ECU
$Hours_{sunshine/day}$	Average number of estimated sunshine hours per day	hour
$I_{ACBus,o/p}$	AC bus current output	Ampere
$I_{ACload}(t)$	AC load current	Ampere
$I_{ACsupply}(t)$	Current arriving at AC load	Ampere
$I_{bat}(t)$	Battery current	Ampere
$I_{bat,ch}(t)$	Charging current	Ampere

Symbol	Meaning	Unit
$I_{bat,dis}(t)$	Discharging current	Ampere
$I_{bat,max,ch(dis)}(t)$	Maximum battery charging (discharging) current at time t	Ampere
$I_{BatsysCh(Dh)}(t)$	Current with which system can charge battery (discharge current system requires)	Ampere
$I_{bc\text{-}DC}(t)$	Battery Charger DC output current	Ampere
$I_{BC\text{-}i/p}(t)$	Battery charger input current	Ampere
$I_{bcmean}(t)$	Maximum efficient battery charger output current	Ampere
$I_{BC\text{-}o/p}(t)$	Battery charger output current	Ampere
$I_{DCBus}(t)$	DC bus current	Ampere
$I_{DC\text{-}bus}(t)$	DC bus current	Ampere
$I_{DCload}(t)$	DC load current	Ampere
$I_{DCSources}(t)$	DC current generated from the DC sources	Ampere
$I_{DCsupply}(t)$	Current arriving at DC load	Ampere
$I_{Demand,Daily}(t)$	Daily demand at time t	Ampere
$I_{diesel}(t)$	Diesel current	Ampere
$I_{Diesel,Array,Bus,k}(t)$	Diesel generator array output current on bus k at time t	Ampere
$I_{Dieselmax,i}$	Maximum possible output current of diesel generator type i	Ampere
$I_{Dieselmax,i,Bus,k}$	Maximum possible output current of diesel generator of type i on bus k	Ampere
$I_{IndBat,i}(t)$	Battery current of an individual battery of battery bank i	Ampere
$I_{inv}(t)$	Inverter input current	Ampere
$I_{Inv\text{-}i/p}(t)$	Inverter input current	Ampere
$I_{invmean}(t)$	Maximum efficient inverter output current	Ampere
$I_{Inv\text{-}o/p}(t)$	Inverter output current	Ampere
I_{max}	Max possible battery current	Ampere
$I_{max,Ch(Dh)}$	Maximum charging (discharging) current) as given by manufacturer	Ampere
$Imbalance_{AC}(t)$	AC over or under supply	Ampere
$Imbalance_{DC}(t)$	DC over or under supply	Ampere
$InitCost_{Diesel}$	Overall initial costs incurred by the diesel generator installation	ECU
$InitCost_{Diesel,type,i}$	Diesel generator initial costs of type i	ECU
$InitCost_{PV}$	Overall initial costs incurred by PV installation	ECU
$InitCost_{WT}$	Overall initial costs incurred by the wind turbine installation	ECU
$InitCost_{WT,type,i}$	Wind turbine initial costs of type I	ECU
$I_{OtherRESources\text{-}AC}(t)$	AC output current from other renewable energy sources at time t	Ampere
$I_{OtherRESources\text{-}DC}(t)$	DC output current from other renewable energy sources at time t	Ampere
$I_{PV,Array}(t)$	PV array current output at time t	Ampere
$I_{PV,Array\text{-}AC}(t)$	AC output current from PV array at time t	Ampere
$I_{PV,panel}(t,x_{Size,Type,PV})$	PV panel current output at time t depending on panel type	Ampere
$I_{re}(t)$	Renewable energy current	Ampere
$I_{RE\text{-}AC}(t)$	Overall AC current from renewable energy sources at time t	Ampere
$I_{RE\text{-}DC}(t)$	Overall DC current from renewable energy sources at time t	Ampere
$I_{WT,Array,Bus,k}(t)$	Wind turbine array output current on bus k, i.e.in DC or AC	Ampere
$I_{WT,Array\text{-}AC}(t)$	AC output current from wind turbine array at time t	Ampere
$I_{WT,Array\text{-}DC}(t)$	DC output current from wind turbine array at time t	Ampere
$I_{WT,i,k}(t)$	Individual wind turbine current output of wind turbine type i on bus k	Ampere
k	Bus k, k equals mainly AC or DC	
Litres (:)	Function relating the diesel generator output power to its fuel consumption	
LitresUsed	Fuel used during the time interval T in litres	litres
n	Year n	year
$n_{Bat,series}$	Number of batteries in series	
no	Vector with numbers of devices	
no^*	Vector with optimal number of devices	
NOofBatBanks	Number of different battery types available for the optimisation	

Symbol	Meaning	Unit
	from a pool of batteries	
NOofBC	Number of different battery chargers available for the optimisation from a pool of battery chargers	
NOofBusTypes	Number of different DC and AC busses in the system	
NoofDieselTypes	Number of different diesel generator types available for the optimisation from the diesel generator pool	
NOofInv	Number of different inverter available for the optimisation from a pool of inverters	
NOofWTtypes	Number of different wind turbine types available for the optimisation from a pool of wind turbines	
$n_{PV,series}$	Number of PV panels in series	
$Opas\%ofCC_{perYear,Bat,i}$	Percentage of capital costs arising as battery type i operation cost each year	%
$Opas\%ofCC_{perYear,Dies,i}$	Percentage of capital costs arising as diesel generator, type i, operation cost each year	%
$Opas\%ofCC_{perYear,PV}$	Percentage of capital costs arising as PV operation cost each year	%
$Opas\%ofCC_{perYear,WT,i}$	Percentage of capital costs arising as wind turbine type i operation cost each year	%
OpCo	Operating cost	ECU
$Opcost_{Bat}(n)$	Overall battery operation costs after n years	ECU
$Opcost_{Diesel}(n)$	Overall diesel generator operation costs after n years	ECU
$Opcost_{PV}(n)$	Overall PV operation costs after n years	ECU
$Opcost_{WT}(n)$	Overall wind turbine operation costs after n years	ECU
$P_{BC\text{-}i/p}(t)$	Battery charger input power	Watt
$P_{BC\text{-}o/p}(t)$	Battery charger output power	Watt
$P_{diesel}(t)$	Diesel genset output power	Watt
PeakDemandPower	Maximum demand in W required by the application	Watt
$P_{i/p}(t)$	Battery charger input power	Watt
$P_{inv\text{-}i/p}(t)$	Inverter input power	Watt
$P_{inv\text{-}o/p}(t)$	Inverter output power	Watt
$P_{max,diesel}$	Maximum diesel genset output power	Watt
$P_{o/p}(t)$	Battery charger output power	Watt
$Power_{PV,Array}$ (t)	PV array power output at time t	Watt
$P_{WT,Array}(t)$	Wind turbine array output power at time t	Watt
r	Discount rate	%
R(n)	Discount factor for the same yearly expenditure which occurs for n years	
$Replacementcosts_{Diesel}$	Overall diesel generator replacement costs	ECU
$replacementcosts_{PV}$	Overall PV replacement costs	ECU
$replacementcosts_{WT}$	Overall wind turbine replacement costs	ECU
$Replacement_{year,PV}$	Lifetime of the PV panels in number of years	
$Replacement_{year,WT,i}$	Lifetime of the wind turbine type i in number of years	
$Repl_{year,Bat}$	Lifetime of the batteries in number of years	
$Repl_{year,Dies,i}$	Lifetime of the diesel generator type i in number of years	
$SOC\%_1$	Control setting 1: (both inverter output and diesel generator output can cover the load): If battery state of charge is below $SOC\%_1$, then prefer the diesel generator to cover the load, else prefer the inverter output	%
$SOC\%_2$	Control setting 2: (neither inverter output nor diesel generator can cover the load alone): If the battery state of charge is below $SOC\%_2$, then NORMAL INVERTER : allow the diesel generator to supply the AC load through the inverter (together with the DC supply) if this lowers unmet demand, else don’t allow this option and choose lowest unmet demand supply option (either inverter output or diesel generator output supplies load)	%

Symbol	Meaning	Unit
	PARALLEL INVERTER: prefer the diesel generator to cover load and take any additional energy from the inverter output, else the other way round	
SOC(t)	State of charge	Ah
$SOC_{crit}(t)$	Critical state of charge	Ah
$SOC_{max}(t)$	Maximum state of charge	Ah
$SOC_{min}(t)$	Minimum state of charge	Ah
t	Time instant t	hour
T	Length of time interval over which the assessment/simulation is carried out	hour
t_0	Starting time	hour
type	Vector of component types (PV,wind,etc)	
Type	Matrix with type on 1st diagonal	
$type^*$	Optimal vector of component types	
U_{ac}	Nominal AC bus voltage	Volt
$U_{Bat,Nom,Bank,i}$	Nominal voltage of battery, bank i	Volt
$U_{Bus,k,Nom}$	Nominal voltage of bus k	Volt
$U_{Bus,Nom}$	Nominal bus voltage	Volt
U_{dc}	Nominal DC bus voltage	Volt
$U_{Panel,Nom}$	Nominal PV panel voltage	Volt
$U_{WT,i,Nom}$	Nominal voltage of wind turbine type i	Volt
$W_{expected,PVpanel}(t)$	Expected PV panel output power	Wp
x	Vector of decision variables	
x^*	Optimal decision vector	
x_{bat}	Battery charge/discharge decision as percentage of maximum possible battery current at time t	%
$x_{Bat,parallel,Bank,i}$	Number of battery strings of type i	
$x_{Diesel,i}(t)$	Output of diesel generator type i at time t as percentage of maximum possible nominal output power in W	%
$x_{Diesel,i,parallel}$	Number of diesel generators of type i installed in parallel	
x_{load}	Load management decision	%
$x_{PV,parallel}$	Number of PV strings in parallel	
$x_R(t)$	DC bus current routing	%
$x_{R,BC,j}$	Routing decision to battery charger j	%
$x_{R,Inv,j}$	Routing decision to inverter j	%
$x_{RD}(t)$	Diesel current routing	%
$x_S(t)$	Transfer switch position	%
$x_{size,Bat,Bank,i}$	Size of wind turbine type i	W_p
$x_{size,BC}$	Size of battery charger	Watt
$x_{Size,D,i}$	Size of diesel generator type i	W
$x_{size,Inv}$	Inverter size	W
$x_{Size,Type,PV}$	PV panel size of a certain PV panel type	W_p
$x_{Size,Type,WT,i,k}$	Size of wind turbine type i on bus k, i.e. DC or AC wind turbine size	W_p
$x_{sizeD,i}$	Nominal output power in W of diesel generator type i	W
$x_{WT,i,parallel,k}$	Number of wind turbine strings of wind turbine type i on bus k, i.e. Dc or ac strings	

Chapter 1

Introduction

1.1 Introduction to the hybrid energy system design problem

1.1.1 The rural energy context

Energy, next to water, transport, education, training and other factors impacting development, forms part of a number of services often urgently needed in remote villages to contribute to rural development and the creation of job opportunities.

The price of conventional energy sources in remote areas, such as candles, paraffin, gas, coal, batteries, is often more expensive than in urbanised areas due to the remoteness of the retailers, rural people obtain their goods from, and the corresponding overheads. Moreover the cost per energy service, for example for lighting, is more expensive for a rural inhabitant than for their urban counter-parts who often have access to grid electricity.

There are also other factors associated with conventional energy supply in remote areas, such as the, often long, transport required to obtain these energy supplies and the dangers in their use or storage. For example, women might have to walk for up to four hours each day to collect sufficient wood to cook for their family or heat the house. To charge batteries might take a whole day of travel for a family member. The nearest local shop might be many walking hours away. Many health problems are reported related to burns from the use of paraffin and respiratory conditions due to the constant smoke exposure.

1.1.2 Electricity provision in rural areas

The provision of grid electricity in rural areas is often associated with higher costs to the grid supplier than off-grid RAPS (remote area power supply) electricity technology options would be. Grid electrification in rural areas in many cases is financially inefficient particularly due to the low consumption take-up in the remote areas.

To give an example in the South African context[1], in December 1996, 51.8% of South Africans were living rural areas, of which 3.1 million households (73%) had no access to electricity [NER-97], Figure 1. The majority of unelectrified dwellings (27%) are in the Eastern Cape, followed by Kwazulu-Natal (26%) and Northern Province (21%) (see Figure 2). It is estimated that in 1999 one million rural households will still be unelectrified due to the high costs for grid extensions to very remote communities whereby average monthly household electricity consumption can be as low as some 30-50 kWh.

[1] In the following, the text will often refer to example situations in South Africa because the case studies for this thesis are taken from there.

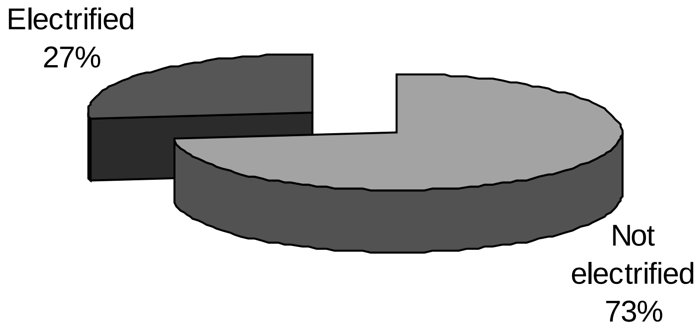


Figure 1: Percentage of unelectrified/electrified rural population

Rural areas in South Africa suffer from high levels of poverty and unemployment, with some 68% of the rural population defined as poor [May et al-95]. The level of unemployment in rural areas is significantly higher than in urban areas [CSS-95]. To provide services to contribute to rural economic development and improve social equity has been a goal of the post-apartheid government. “Rural people, and rural women in particular, bear the largest burden of poverty in South Africa. If we can change the inequalities and inefficiencies of the past, rural areas can become productive and sustainable. The Government of National Unity is committed to an integrated rural development strategy, which aims to eliminate poverty and create full employment by the year 2020. Rural people must be at the heart of this strategy [Ministry of the Office of the President-95].”

Figure 2: Map of South Africa

ESKOM (the electricity utility) has embarked on electrifying 300 000 rural households each year until 2000, based on government targets. The likelihood of recovering costs through rural user consumption is very bleak, at least in the short and medium term. ESKOM is financing most of its rural electrification drive through cross-subsidies from urban and industrial electricity users and from borrowings on the open financial markets, with limited funding from foreign aid agencies. A National Electrification Fund or Regulator will in future obtain funds from ESKOM through levy/tax arrangements, allocate funds to rural electrification projects, and choose suitable implementing agencies (that may also be non-ESKOM). An expected splitting up of ESKOM’s distribution sector into regional electricity distributors supports this process.

Off-grid technology options, single source and hybrid system options, can in some cases be an economic alternative to remote grid extensions. South Africa has many regions with very good solar resources of up to 6000Wh/m^{2}d and wind resources up to 7m/s - 8m/s in some regions (see Figure 3). There are also areas where micro-hydro dams are an economic option.

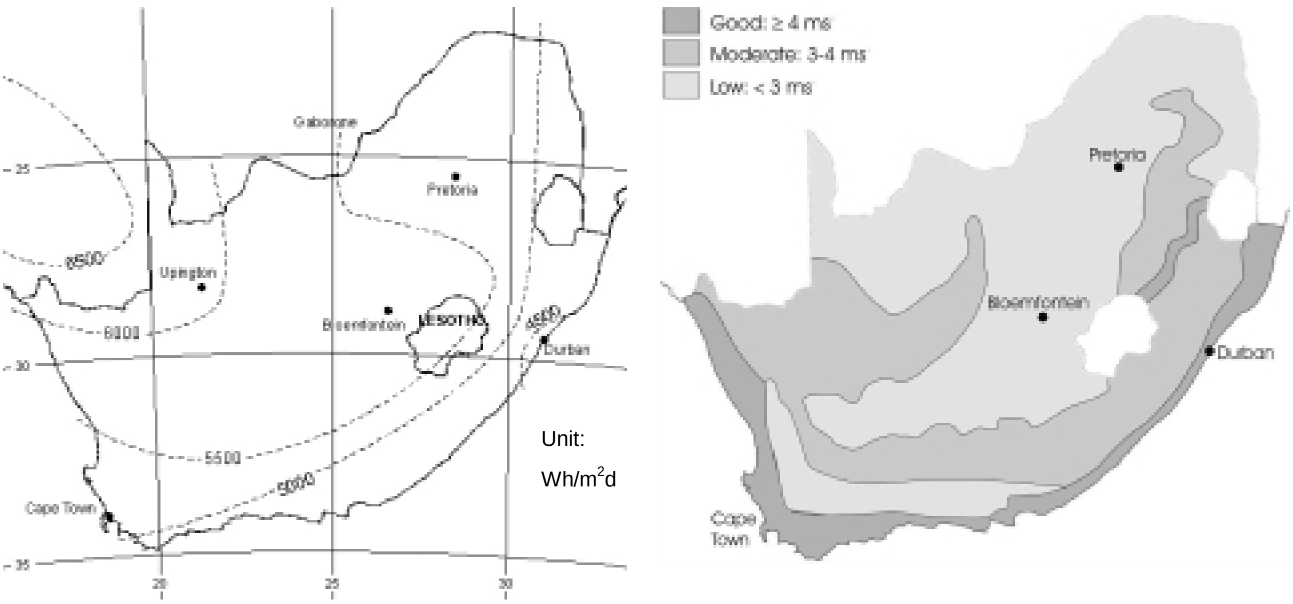


Figure 3: Radiation and wind speed resources in South Africa ([Eberhard-90], [Diab-95])

1.1.3 Off-grid electricity from hybrid systems

Off-grid electricity can be generated by single-source systems using solar photovoltaic panels, wind turbine generators, micro-hydro plants or fuel-powered combustion engine generator sets, or by combining two or more types of these electricity generating sources in a so-called hybrid system (see Figure 4). The systems often include energy storage in form of lead-acid batteries. A hybrid system can supply power to AC or DC loads or both. It may require AC, DC or both types of electric buses. Power conversion devices are used to transform power between DC and AC buses. Component or system control or both is used to regulate the overall system operation.

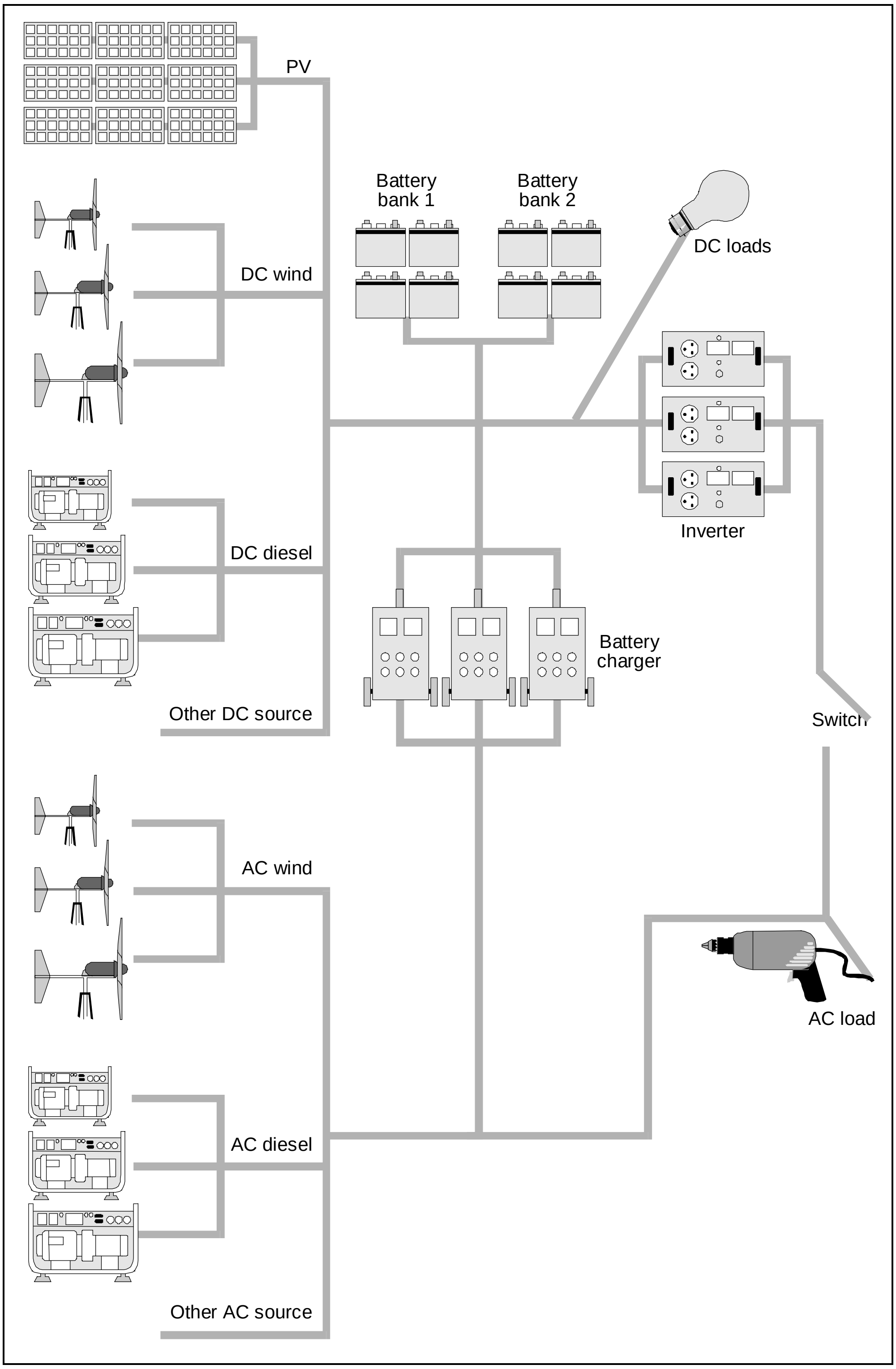


Figure 4: Components in a hybrid system set-up

1.1.4 Applications and potential for off-grid and hybrid systems in South Africa

1.1.4.1 Installed and planned hybrid systems

Several systems and hybrid systems (see Figure 5, Figure 6), mainly PV/diesel, are installed on commercial farms, and a few remote clinics operate PV/diesel or PV/wind hybrid systems. As yet, few of these PV/diesel hybrid systems also include wind turbine generators. In most cases, however, the remote farms use individual diesel systems to power their demand. Other typical hybrid applications include electricity provision for telecommunications and tourist facilities in remote areas. Hybrid demonstration systems are being considered to supply community centres and productive activities with electricity.

Figure 5: Hybrid test system at ESKOM

Figure 6: Hybrid system on a farm in Namibia

1.1.4.2 Potential of upgrading existing diesel systems to hybrid systems

Next to individual diesel systems on farms, some diesel-only systems have been installed in rural communities by the South African Department of Water Affairs for water pumping and water desalination (Figure 7, Figure 8). Diesel generators are in some cases owned by rural shopkeepers to supply refrigerators, shop lighting and domestic energy needs.

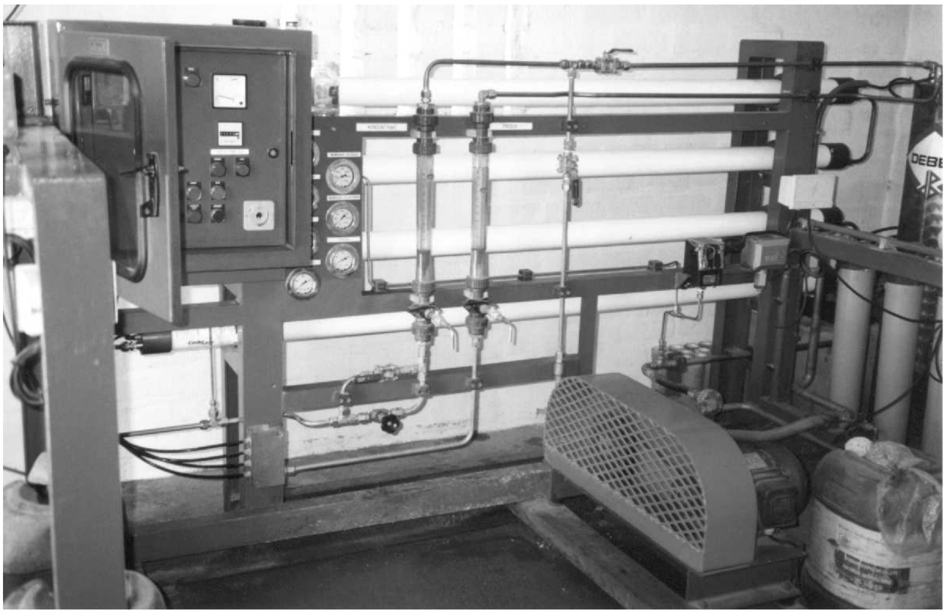


Figure 7: Desalination plant

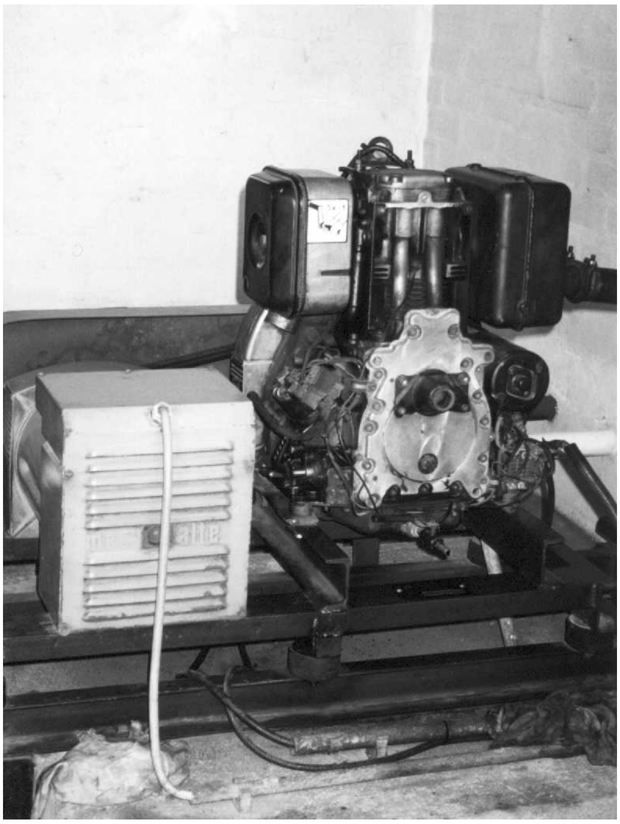


Figure 8: Diesel generator powering the desalination plant (10kVA Hatz diesel generator, 50Hz, 230/400V)

The advantages of individual diesel systems are that they provide grid-type electricity and can supply high power consumption appliances. The disadvantages of an individual diesel system are the maintenance-intensive and energy-inefficient operation, mainly arising from running the diesel with low load factors to satisfy the demand. This leads to increased diesel degradation and maintenance needs as well as decreased lifetime.

In many cases a retrofit of the individual diesel systems using additional renewable energy sources would make the overall system performance more economic. Some examples are given in this thesis.

1.1.4.3 Potential of upgrading existing petrol generators into hybrid systems

Petrol generators are widely used in South Africa, especially by rural shop owners, as petrol generators are cheaper in the smaller power ratings than diesel generators and can be transported more easily in case repair is required. Diesel generators are difficult to move and therefore often need maintenance on site. It seems that for the power consumption range a petrol generator usually supplies, retrofits with renewable energy sources or substitution with a hybrid system need to be carefully considered.

1.1.4.4 Potential of retrofitting existing individual renewable systems into hybrid systems

A renewable single-source system for a higher power demand application such as a farm or shop is often high in costs due to a need for over-sizing the single source supply to meet specified reliability requirements. In these cases hybridising the renewable single-source systems with another renewable energy source or a fuel-powered generator based on life cycle costing and overall system performance would be a promising consideration.

For basic energy needs such as lighting and powering TV and radio, small single-source energy systems like solar home (Figure 10) are already providing electricity in remote areas in South Africa. The solar home systems are purchased individually by households or financed within the SELF (Solar Electric Light Fund, [Cawood-97]) project in KwaZulu-Natal or by the district councils in the Free State for farmworker households [Hochmuth,Morris-98]. In addition, a few PV battery-charging systems have been installed. To market some of the battery charging equipment, industry is generating rural franchise opportunities (see Figure 10). The PV electrification of remote schools is carried out by ESKOM and is maintained by the Department of Education, and the PV electrification of clinics is largely managed by the Independent Development Trust (IDT). In addition there are quite a few projects and initiatives using PV and wind energy systems for water pumping.

According to the National Electricity Regulator [NER-97] there are 27 698 schools in South Africa, of which 16 057 (59%) are unelectrified. So far 1200 rural schools have received solar systems (Figure 9) through ESKOM using donor funds. The 400-600W_p systems can power lights, VCR's and overhead projectors. Due to the remoteness of some schools, non-grid technology will continue to play a role in electrifying these rural schools.

According to the Independent Development Trust [IDT-97], there are at least 600 out of 3000 rural clinics without electricity. To date, more than 150 such clinics have been PV-electrified. The (on average) 600W_p systems supply lights for medical examination and nurses, vaccine refrigeration and two-way radios. The suppliers are contracted to perform operation and maintenance of the systems.

In this context, a number of PV electricians have been trained within the PV school electrification program and the SELF SHS program, creating employment. In general, there is a good and established PV industry infrastructure in South Africa.

Figure 9: PV electrified school

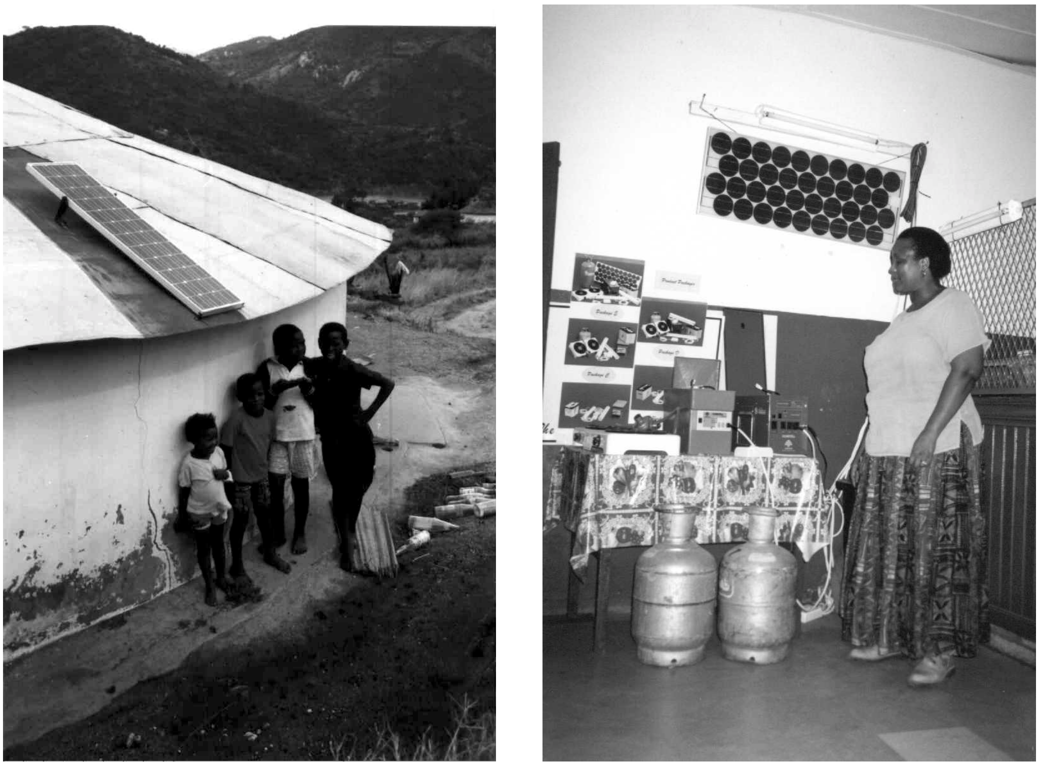


Figure 10: Typical SHS (left), Shop owner marketing equipment: a rural/urban franchise (right)

Figure 11: PV electrified community centre

However, the single-source renewable energy systems often constitute an unreliable and maintenance-intensive energy source particularly if training for users and maintenance personnel is lacking or maintenance is missing sometimes altogether. In addition, users are often not satisfied with the small range of appliances they can use. For example, women would often like to cook and iron with their systems, schools would like to run workshops and photocopy machines. For these higher power requirements at community centres (Figure 11) or schools a hybrid system is a possibility to be looked into. Two remote clinics with PV/diesel hybrid systems exist in South Africa so far.

In some cases the households of remote villages will be sufficiently close to each other to investigate the potential economics of a mini-grid powered by a diesel or hybrid system [Seeling-Hochmuth-97c]. Frequently, however, households are so scattered that the SHS option seems the economically better alternative.

1.1.5 Design and economics of hybrid systems

1.1.5.1 General

The use of hybrid off-grid electricity depends on the comparative costs, affordability, quality of service, and accessibility of other energy options which are locally available. It further depends on user acceptance of a system technology: perceptions of how 'good' and reliable the electricity generating technology is. This thesis will concentrate on hybrid system design in terms of minimising life cycle costs while meeting a given demand reliably.

1.1.5.2 Life cycle costs

Life cycle costs (LCC) are the sum of the equipment costs and discounted operation costs arising during the project until the end of the project horizon, which is usually set between 20 and 30 years. The equipment costs are the initial costs incurred at the beginning of a hybrid system electrification project; operation costs include running costs, maintenance and replacement costs

1.1.5.3 Can life cycle costs be lower in a hybrid system than a single source off-grid system?

Life cycle costs 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 ability to complement each other 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 tear and wear, often associated with low load factors, and adjusting the supply to rapidly changing and peaky demand levels in single source systems are increasing 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 life-cycle costs and maintenance wear of its components, it could in some cases need more costly control equipment and balance of system components.

1.1.6 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 life cycle costs. 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 ([Rehm et al-95],[Rehm,Seeling-Hochmuth-97]) and adjustment to the renewable energy supply, and maximisation of load factors is very important and has a significant influence on life cycle costs and sizing. This will also be discussed in this thesis 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 many others exist. It is the task of the design optimisation to recommend a least-cost and reliable design suitable for a given application with the aim to improve 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 stage. This thesis, however, mainly deals 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 mostly lies 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.

1.1.7 Need for a method to size and operate 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 developed.

The intricate problems of prolonging component life times and operating with high capacity and saving fuel, while meeting demand and minimising overall life cycle costs, can only be simulated in a well designed and tested tool.

The challenges 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 modelling accuracy.

The tool aimed at in this thesis is desired to yield optimal component sizes in terms of component sizes 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 it needs to simulate hybrid system performance with quite an accurate system model. Even though a clear need for such a tool exists, its development imposes modelling and computational challenges.

1.1.8 Socio-economic and demand considerations

Apart from choosing an appropriate technology it is also important to approach the rural electrification in an integrated manner addressing other required services and educational programmes to meet needs.

The assessment of needs and the evaluation of collected data is a difficult assignment as is the construction of a load profile to design an off-grid electricity supply system, especially in areas where no prior experience in using electricity exists ([Smith-95],[Seeling-Hochmuth-95b]). 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.

Electricity can contribute, together with other inputs, to increasing production and growing businesses in areas like retail, sewing and carpentry. Irrigation often contributes substantially to increased agricultural productivity [James-95]. However, the provision of electricity is one factor in a basket of services needed to stimulate the transformation from a survivalist enterprise to a small enterprise that can employ a number of people [Thom-97].

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

1.2 Conventional approaches to the hybrid design problem

Many practical hybrid system designs and implementations (see also [Gonzales,Mayer-91], [Loois et al-93], [Riess et al-94] [O'Riordan et al-94] [Sibuet et al-95], [Schmidt-95], [Valente et al-95], [Vallve,Serrasolses-95], [Warner et al-95], [Weiden et al-94]) are often based on progressive experience, including trial and error [Smith-95]. 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].

1.2.1 Rule of thumb methods

Rules of thumb give practical guidelines on how to size and operate a hybrid system based on experience with installed systems. Some of the most common rules of thumb are compiled in Table 1 and are described briefly in the following sections.

Table 1: Rule of Thumb design (compiled at a hybrid system design workshop held at NREL in 1996 [Seeling-Hochmuth-96])

DESIGN		Rule of Thumb
SIZING	Renewable energy sizing	40%-60% of load
	Diesel generator size	Peak load demand in Watt
	Battery size	1 day of battery storage
	Inverter size	Peak (surge) load in Watt
	Battery charger size	Maximum charge current, Diesel capacity rating
	DC Bus voltage	24V-48V (<5kW), 96V (≈5kW), 120V(>5kW)
OPERATION	Diesel generator operation	Load factor ≥ 50%
	Battery operation	40% maximum DoD, regular equalisation, topping up with water
LOAD PROFILE	Household load	150Wh/day (DC), 1kWh/day (AC)

1.2.1.1 Renewable energy sources

In a hybrid system design workshop held at the National Renewable Energy Laboratory, Colorado, U.S., in 1996 [Seeling-Hochmuth-96], workshop participants felt that the optimum percentage share of renewable energy sources in terms of system capacity was 70%-85% of load to achieve an optimum reliability versus cost ratio. It was mentioned that in practice the share of renewable sources in a system would mostly be around 40%-60%.

1.2.1.2 Diesel generator sizing

If reliability is important, the diesel should be sized to be able to meet full load; however, customers often do not want to pay for such high reliability. The renewable energy sources could then cover maintenance intervals or fuel shortage intervals. This is especially applicable if a customer wants to utilise the diesel as much as possible. For systems around 50kW or larger, it might make sense to operate multiple diesels of different sizes. It becomes clear that the percentage of diesel coverage and the number of diesels in a system seem very much driven by customer wishes.

1.2.1.3 Diesel generator operation

It was recommended in the 1996 hybrid system expert workshop to bring the diesel up to speed and allow some time before adding the load. A variety of views were expressed on diesel operation times, e.g., to run the diesel once every 3-5 days, once a day, or every morning and afternoon. Some estimates of a minimum diesel running time were 30 minutes. Some suggested to take the diesels off-line when the load drops under 50% as this would improve life cycle costs. Low loading, such as loading of less than 40%, is a problem because the diesel temperature is sub-optimal and incomplete combustion occurs leading to low fuel efficiency.

1.2.1.4 Battery sizing

One rule of thumb is to roughly size the battery six times the rated amperes of the renewable energy sources. Other rules recommend around one day of battery storage in a hybrid system as opposed to 3-5 days of storage in a renewable only system or 5-10 days of storage in a telecom repeater station. The smaller the battery capacity the cheaper are the initial battery costs however batteries are being deeper discharged and replacement costs are increased. The decision around battery size and operation is, again, also customer-driven. Some experts expressed the view that two strings of parallel batteries are a minimum and eight strings are the maximum.

1.2.1.5 Battery operation

A charging rule was mentioned by some which said that above 85% state of charge the renewable energy sources only should charge the battery. This is due to the fact that the diesel might run with low loading and therefore low efficiency if only charging the battery for a period of time. The batteries charging rate especially at high SOC needs to be chosen carefully so as to avoid extensive gassing. In addition, stratification is likely to happen very quickly with high charging rates.

Equalisation also needs to be scheduled. Equalisation is a matter of eliminating voltage diversion between cells. Some rules with regard to equalisation were given saying that equalisation should take place every two weeks for 4 hours, or every month for 8-12 hours. These rules also depend on the battery type. For new batteries it was mentioned that equalisation can take place every 6 weeks to 2 months.

Some participants expressed the view not to go below 60% state of charge (i.e. 40% depth of discharge) for lead acid batteries. Batteries are more efficient in the middle range of the state of charge, but this leads to partial charging and sulphation.

The overall battery lifetime seems to be mainly influenced by the right treatment of the battery in the system. Regular topping up with clean distilled water is important for long battery life.

1.2.1.6 DC bus voltage:

The DC bus voltage seems balance of system (BOS) product driven. For example, 48V are often used to accommodate certain inverters, and 24V as plenty of 24V components are available on the market. The minimum for village power system seems to be 48V on the DC bus. Many experts recommend choosing the DC bus voltage as high as possible and be limited only through equipment availability. The reason is that the higher the currents, the higher are the BOS costs. At some point packaged systems might be available with enough customer protection so that the DC bus voltage can go as high as possible, with e.g. 600V batteries. For the present, the following rules were compiled: a 24V or 48V DC bus voltage for a system with less than 5kW, 96V around 5kW and above 5kW the DC bus voltage was recommended to be 120V.

1.2.1.7 Load profile estimate

Workshop participants shared their experience that data collection for constructing a load profile is difficult as potential users often do not know what kind of electricity demand they will have and how much they are able to pay for it. Some rules given by some of the workshop participants regarding average encountered rural load demand were 150Wh/per day for a DC load service, and 1kWh/day for an AC load service. However, these are very rough estimates. Innovative ways to limit load growth were discussed such as tariffs, and moving and exchanging systems. Deferrable and optional ‘managed’ load possibilities were mentioned as well as to accommodate load growth. Low quality loads can introduce problems with other system components such as inverters and vice versa, low quality inverters can cause interference with certain appliances, or even malfunction thereof.

1.2.1.8 Inverter

An inverter needs to be sized to cover peak or non-surge peak load. The surge currents can be up to 3-6 times the normal current. Some experts size the inverter for the peak demand plus an extra 30%, some will try to account for load growth. In a parallel hybrid system [Infield et al-83] the inverter does not have to be sized to meet peak demand. In general, the use of a sine wave inverter is recommended instead of a square wave inverter. A three-phase supply might be less expensive than single-phase supply. Some large three-phase, tri-mode inverters units of 30kW, and even 200kW and 2MW units, are available.

1.2.1.9 Battery charger

The battery charger is sized such that up to the maximum charge current allowed by the battery can be supplied through it. The battery charger should not be much larger than the diesel capacity rating as then the diesel input to the battery charger might be transformed from AC to DC at very inefficient ranges of the battery charger.

1.2.1.10 Fuses / breakers

A consideration for thermal breakers is their surge durability. Fuses or breakers need to be available in country. Awareness should be paid to the fact that users sometimes attempt to bypass fuses.

1.2.1.11 Merit of Rule-of-thumb method

Rule-of-thumb methods are easy to use design guidelines derived from experience. The rules include a lot of 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.

1.2.2 Paper-based 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 following describes the paper-based Ampere hour method for sizing PV/diesel systems. Table 2 summarises the main steps carried out during a hybrid system design using this method. The Ampere hour method 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.

Table 2: Ampere hour design method [Sandia-95]

DESIGN	Ah METHOD
LOAD PROFILE ESTIMATE **[Wh/day] and [Ah/day]**	Compile load in Wh/day
	Multiply by loss factors (power conversion, battery cycling, wire inefficiency)
	Divide by system voltage yielding load in Ah/day
BATTERY **number of batteries in series and in parallel**	Select battery type and number of days of storage
	Number of batteries in series obtained through dividing system voltage with battery voltage
	Number in parallel battery strings obtained through matching Ah load current with the maximum discharge rate
PV **number of PV panels in series and in parallel**	Divide the load in Ah/day by peak sun hours per day, yielding so-called 'DC bus current' in A
	Number of panels in series obtained through dividing system voltage with panel voltage
	Number of panels in parallel obtained through dividing DC bus current with panel output current
HYBRIDISE? **Yes or No**	Follow decision guide
BATTERY **redefine storage size?**	In case smaller battery storage is desired in the hybrid system configuration, redo the calculation on number of batteries required with new number of days of storage
DIESEL **Choose kW size**	Choose diesel generator size to cover peak demand plus maximum charging rate simultaneously
PV **redefine number of PV panels in series and in parallel**	Redo PV calculation taking account of battery and diesel generator sizing
Round off **BoS and costing**	Choose inverter size, wiring sizes and determine life cycle costs (LCC)

1.2.2.1 Ampere hour method

With the 'Ampere hour' method, All loads are compiled with their power ratings in Watt which are multiplied by the number of hours run each day and losses incurred through power conversion, battery cycling and energy transport inefficiency. Then the system voltage divides this value to give the load in Ah per day. With a given battery storage requirement in number of days, the maximum discharge specification and a given selected battery size in Ah, the number of batteries in series and parallel is selected for a chosen DC bus voltage.

In order to select the number of panels of a chosen PV module, the load in Ah/day is divided by the number of peak sun hours per day for different tilt angles to yield values of the DC bus current. The tilt angle giving the minimum DC bus current value is selected. This DC bus current is divided by the PV module current to yield the number of parallel panels required. The number of modules in series is calculated by dividing the DC bus voltage through the panel operating voltage.

The choice whether to go for a hybrid system configuration rather than a single source system can be made based on different criteria.

In [Sandia-95] the decision to hybridise is based on whether more than a certain percentage of the given load per day in Watt hours is required to be covered by the output power of the PV array. For example, "hybridise if 60%-80% of the load", for loads under 2000 Wh/day, or if 40%-60% for loads between 2000 and 5000 Wh/day or if 20%-40% for loads between 5000 and 10000 Wh/day, need coverage from PV.

The FSEC manual [FSEC-87] attempts to derive the hybridisation decision by weighting some design-related factors, such as access to the site, environmental factors around diesel generator usage and battery usage, variability of the demand, accessibility of funds, availability of renewable resources. Based on the weighted sum of these factors, a decision is made whether to go for a PV/diesel hybrid system or for a single source system.

If the decision is to hybridise the system, the number of days of storage needs to be redefined in case it is preferred to be smaller than in the previous single-source case. The diesel generator size is chosen to be able to cover the peak demand and to charge the battery at the maximum rate simultaneously. The number of modules and battery is again specified, a suitable inverter size and wiring sizes are chosen and the life cycle costs are determined.

1.2.2.2 Merit of the Ampere hour method

The Ampere hour methods become useful, as its relative simplicity makes its use easy, and the straightforward implementation with spreadsheets is a further advantage.

This type of method 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.

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

There are a few software tools that assess hybrid system performance for pre-defined system configurations: *SIRENE* [Bezerra et al–91], *RAPSYS* [Borchers-93], *RAPSIM* [Jennings-94], *SEU-ARES* [Morgan et al-95], [Protogeropoulos et al-91], *PHOTO* [Manninen,Lund-91], *HYBRID2* [Green,Manwell-95], *SOMES* [Dijk-94], *SOLSIM* [Schaffrin, Litterst-97]. Most of these software tools simulate a predefined hybrid system based on a mathematical description of the component characteristic operation and system energy flow ([Bodgan,Ziyad-94],[Beyer,Langer-95],[Kaiser et al-97]), and often incorporate financial costing of the system configuration. These packages are valuable to assess a certain hybrid system design and enable to view 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. Better system performance and lowered costs in many of these designs could be achieved if the system configurations could be optimised.

1.2.3.1 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.

1.2.3.2 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. Advantageous is the flexibility in creating system models and configurations compared to simulation tools with fixed layouts. A disadvantage is that INSEL does not perform system optimisation. In addition, components such as diesel generator, inverters have no default models and the user must create these within the modelling block.

1.2.3.3 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.

1.2.3.4 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 ([Jennings et al-95], [Remmer,Dymond-93]). 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.

1.2.3.5 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 according to [Borchers-93], 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.

1.2.3.6 SEU/ARES

SEU/ARES is being developed at the University of Cardiff, U.K. 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.

1.2.3.7 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 (e.g. for the annual simulation in hours) or as a dynamic behaviour in short time steps.

1.2.3.8 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 in Holland. The simulation time step is one hour. The system performance is evaluated technically and financially. SOMES does not size a system per se, however the program has the ability to perform multiple runs by varying the component nominal power ratings stepwise in an 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.

1.2.3.9 SOLSIM

SOLSIM has been developed over the last 10 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 modelling. 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 options are limited, but the PV installation angles can be optimised.

1.2.3.10 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.

1.2.3.11 Comparison

Different software packages exist with a varying degree in user friendliness, validation of simulation models, accuracy of system models, and possible configurations to simulate. Most of these 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 3) are valuable to assess a certain hybrid system design and enable to view 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, for example through using 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.

Table 3: 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**

1.3 Previous work on software-based optimisation of hybrid system design

1.3.1 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, are 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 due to 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 what effect variations of the pre-defined system configuration will have. However, the ranges over which the variations take place might not lead to finding an optimum system.

According to [Papalexopoulos-93] and [Glavitsch-93] minimising the instantaneous cost of active power generation on an operating power system subject to preventing violations of operating constraints in the event of any planned contingency is a complex optimal power flow problem. [Hollenstein,Glavitsch-90] attempt to solve the problem with Newton's algorithm, a simple calculus-based search method."

This thesis develops a design algorithm that optimises a complex model using optimisation techniques. [Seeling-95] 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.

1.3.2 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 [Chichocki,Unbehauen-93]:

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

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

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.

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

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

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 is the value of the design vector x, for which for each summed partial derivative of the cost function and the weighted constraints zero is obtained. The weight vector λ for the constraint vector is called "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.

1.3.3 Calculus-based optimisation techniques

Calculus-based methods subdivide into two main classes, indirect and direct [Goldberg-89]. 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 12.

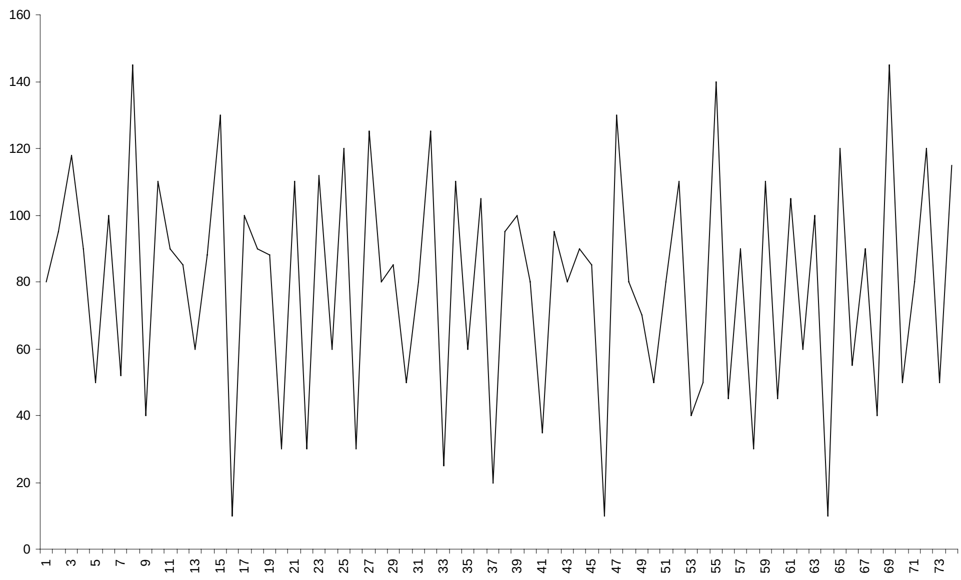


Figure 12: Noisy and discontinuous function, unsuitable for optimisation searches by traditional methods

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.

1.3.4 Enumerative schemes

The idea of enumerative schemes is fairly straight forward 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 (see Figure 13).

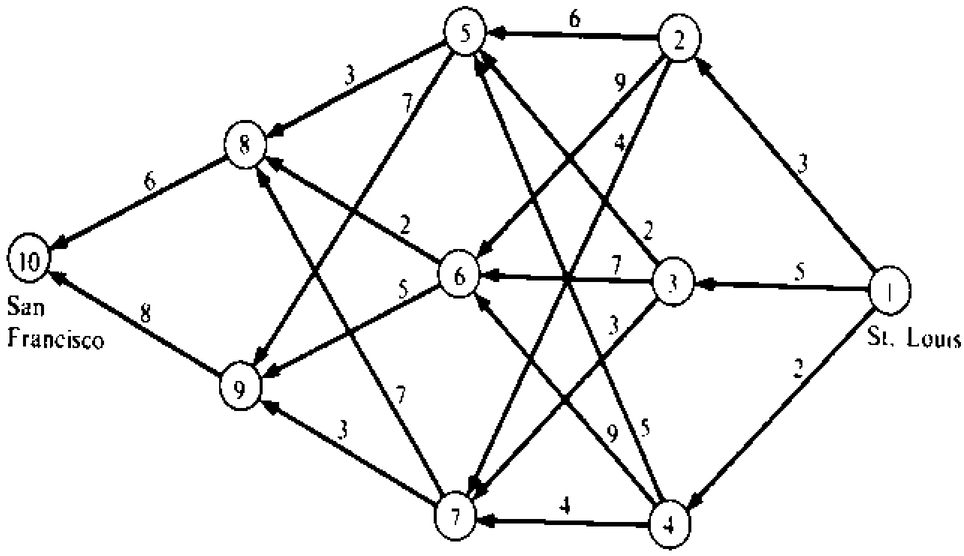


Figure 13: Decision-making in the dynamic programming process (Example lowest cost travel from San Francisco to St. Louis, going backwards from St. Louis along the lowest cost route)

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.

1.3.5 Random search techniques

In general, the methods that follow the trajectory of a system of ordinary differential equations are local, i.e. 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, however randomised techniques 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 direction-less search.

1.3.5.1 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 (i.e. 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 i.e. 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 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, i.e. the combination of decision values, is accepted. However, if the cost is increased, 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, i.e. 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 then be 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.

1.3.5.2 Genetic algorithms

Genetic algorithms were developed in the 1970’s by [Holland-73] 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 the 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, i.e. 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 fittest ones of a population, which fulfil a chosen criterion best such as minimising the objective cost function, survive, the rest is 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 are 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 thesis to optimise the developed hybrid system design model through minimising its life cycle costs while still meeting required system performance.

1.3.6 Existing hybrid system optimisation software

A very limited number of software design packages exist to optimise the hybrid system design problem, even though extensive research into optimisation techniques exists.

1.3.6.1 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.

1.3.6.2 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.

1.3.6.3 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. The work of the Australian hybrid systems group at the University of New South Wales started conceptualising a hybrid system modelling and optimisation approach with conventional optimisation methods involving gradient calculations [Kaye-91],[Kaye-94], [Hancock et al-95]. The group has now moved to also include evolutionary and other optimisation methods [MacGill,Kaye-97], [Wichert,Lawrence-97]. The group, to the author’s knowledge, has not, however, developed a software tool.

1.3.6.4 Identified need

There is a need for a package 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. The system performance simulation contains the simulation for choosing the sizing, control setting and calculating life cycle costing. In order to tackle these challenges genetic algorithm have been used in this thesis to optimise the non-linear hybrid system model. Genetic algorithms have been applied to the design hybrid systems in [Seeling-95], [Seeling-Hochmuth-95a], [Seeling-Hochmuth-97a], [Seeling-Hochmuth-97b], [Marrison,Seeling-Hochmuth-97], [Seeling-Hochmuth,Marrison–97] and the modelling and results are described in this thesis. The approach takes into account the interdependency between sizing and system operation strategy.

1.4 Research objectives

As outlined in the previous sections, there is a need for an integrated optimum design tool that optimises hybrid system design satisfactorily while incorporating an underlying system model with adequate accuracy. The objectives of this thesis research are:

> *Development of 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;
- genetic optimisation algorithm; also implementing a decision making tool of optimal operating strategies for a set of system components

The reviewed 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 as genetic algorithms must be used to create the optimisation search algorithm consistently and efficiently.
- The utility of the tool must be demonstrated by creating hybrid system designs for typical application scenarios in remote areas.
- The design obtained through the tool output must be tested under different input parameter scenarios.

In this thesis, 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. This thesis aims to give a solid foundation for researchers who wish to develop integrated design methods for hybrid system sizing and operation control.

1.4.1 Overview of thesis chapters

The body of this thesis has five chapters followed by a chapter of conclusions and several appendices. In these chapters the design tool is developed that makes use of genetic algorithms. The design algorithm is constructed as a practical tool for the integrated design of hybrid system sizing and operation control.

Chapter 2 characterises the components of a hybrid energy system. From the description of the energy sources and the challenges when they are operated in a single-source system, the advantages of operating the energy sources in a hybrid system configuration become apparent.

Chapter 3 models the costing involved for a hybrid system design using a financial analysis. It defines initial costs and operation costs of system components and component operation based on data derived from mainly South African applications. The issue of assigning benefits to covering demand or penalty to not covering demand is discussed and the inclusion of a benefit/penalty description in the cost function is explained.

Chapter 4 outlines the hybrid system model, which represents the component input-output relations mathematically and then combines their interaction in an integrated modelling effort. Thereby the control decisions at every time instant of hybrid system operation are made dependent on control settings which can be implemented in the field. In this way, it is not required to optimise the control decisions at every time instant and only the general, time-independent settings have to be optimised.

Chapter 5 applies the genetic algorithms in the developed software tool to the sizing and operation control problem of a hybrid system and shows results for a rural farming case study located in South Africa.

Chapter 6 draws conclusions about the use of genetic algorithms in the integrated optimisation tool and proposes directions for future work.

A list of references is then given and a number of appendices, containing results of the simulated case scenarios, weather data for the simulated regions and a comparative simulation with the system performance tool HYBRID2.

Chapter 2

System Components and their Operation in a Hybrid System

2.1 Introduction

The following sections will describe the different components a hybrid system can consist of and how their interaction can be set up and controlled. The aim is to give an understanding of the complex component interaction in a hybrid system. A hybrid system design is only as good as is the accuracy of its underlying component and operation characteristics. As will be seen in later chapters, the developed algorithm has captured many of the actual characteristics of the hybrid system components and their operation as explained in this chapter.

It needs to be noted that apart from the component operation, load management and efficient use of any surplus energy are also an important consideration in operating a hybrid system.

2.2 Photovoltaic panels

2.2.1 PV electricity

A PV cell converts sunlight into DC electricity. The PV generated electricity is ‘silent’, low in maintenance and does not need fuel or oil supplies. However, PV energy is only available when enough irradiation is accessible. PV panels are available in wide variety of ratings up to 100 Wp. In some cases, panels up to 300 W_p each are manufactured. Developments are under way to produce AC PV panels by including an inverter into the panel set-up to enable easy and modular AC bus connections ([Schmid-97], [Haas et al-97], [Engler et al-97], [Stoer et al-97]). A slight economy of scale can often be noted for the different panel sizes up to 100 W_p, however after that size the costs will increase circa linearly with size. The main disadvantage of PV is its high capital costs even though it is hoped that panel costs might come down in future. PV can become cost-effective for small power requirements in areas remote from the existing electricity grid. PV panels last depending on their type over 10 - 20 years.

2.2.2 General workings

A PV cell is a semiconductor device that can convert solar energy into DC electricity through the photovoltaic effect. A PV panel consists of several connected PV cells. The power rating of a panel is specified at standard test conditions (STC) which include a defined cell junction temperature (usually 25°C) and irradiance (usually 1000W/m^2) and is the maximum power output in this state expressed in peak Watts (W_p). The power rating of a panel depends on its cell area and efficiency.

2.2.3 Operating issues

PV panels have a specific voltage-current relationship, which is depicted in an IV-curve. The maximum power point (MPP) operation is where the maximum panel output power is obtained with given irradiation and temperature levels.

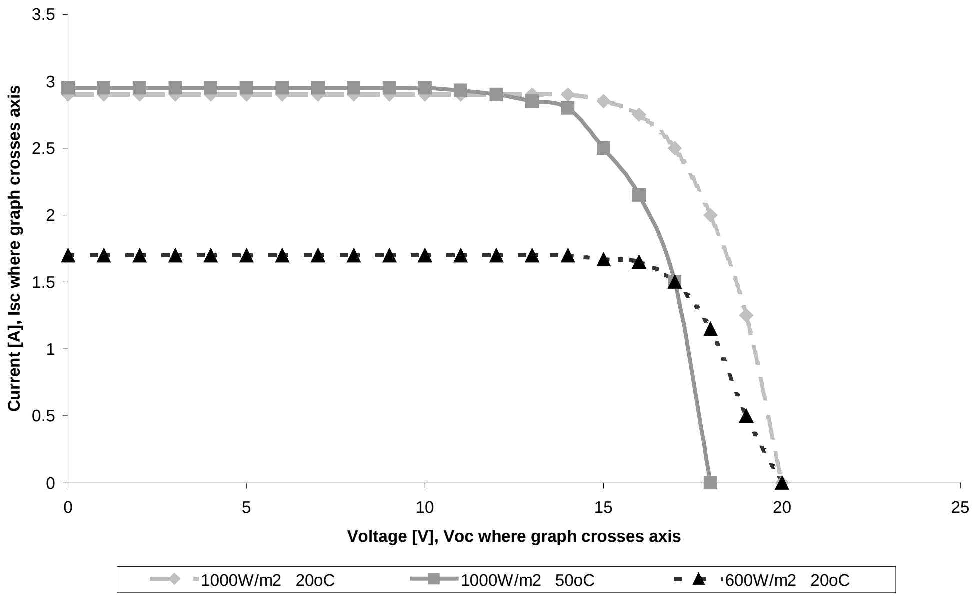


Figure 14: I-V curves showing the effects of solar insolation and temperature on PV panel performance. ([Duffie,Beckman-91], [Manwell et al-96])

Manufacturers typically provide IV curve specifications at different levels of irradiance keeping other variables such as temperature and wind speed constant (Figure 14). The PV panel generates at constant irradiation levels a roughly constant current from the short circuit current to just before the current values near the open circuit voltage. If irradiance increases, the PV panel output current increases nearly linearly. The maximum power point voltage stays nearly unaffected by the level of irradiance, and the open circuit voltage changes only slightly [Jimenez-98].

To account for the effects of panel temperature, manufacturers will usually give IV curves for various temperatures keeping irradiance levels constant (Figure 14). The open circuit voltage (current is zero) decreases with increasing temperature, while the short circuit current (voltage is zero) increases only slightly, leading to decreased power production of the panel [Jimenez-98]. The electrical and thermal PV model is given in the [Schuhmacher-93]. It takes into account the ambient temperature and the wind speed.

A correction can be made if the panel does not necessarily operate at its maximum power voltage, which can be the case if no maximum power point tracker is installed. The desired correction is achieved through multiplying the energy output by the ratio of the output at nominal battery voltage and the maximum power output, both at STC, and by the ratio of actual battery voltage versus nominal battery voltage [Dijk-96].

2.2.4 PV system design

Due to the variable nature of the energy source, one of the most expensive aspects of a PV power system is the necessity to build in system autonomy to provide reliable power during periods of adverse weather or increased demands. This is accomplished by over-sizing the PV array and enlarging the battery storage, the two most costly system components. It is also necessary to consider the fraction of the array output required to offset losses and to provide the necessary periodic “equalising charges” which usually take the form of a measured overcharge.

Batteries can store PV energy for later use but this energy storage is associated with efficiency losses during the charging/discharging process.

Most PV panels have appropriate maximum power points for charging batteries. For some applications, such as when the panel is directly connected to a water pump, a maximum point power tracker (MPPT) may be necessary. A MPPT adjusts the impedance seen by the panels so that it matches the optimum point on the I-V curve [Slabbert,Seeling-Hochmuth-97].

2.2.5 PV installation

The tilt angle of a PV array can be adjusted to optimise various system objectives, such as maximising annual, summer or winter energy production. Using adjustable fixed mounts and adjusting the tilt angle periodically through the year can further increase energy production [Jimenez-98]. Fixed mounts are lower in cost than tracking mounts.

When installing PV panels the racks are mounted on a roof or a pole and then the panels are mounted on the racks. Care must be taken to ensure the panels will not be shaded during the day as even partial shading of a panel will often reduce its power output to near zero. The PV array can then be connected to DC loads, directly or via batteries and/or regulators [Jimenez-98]. DC appliances can be slightly more expensive than AC appliances for which also a DC/AC inverter needs to be installed.

When the PV modules are installed in parallel they can be segregated into separate sets to fine-tune the battery charging current. However, this is only feasible for big systems.

Because one PV module that is not working properly any more can take out a whole string, PV panels need to be kept clean, free of overshadowing, and the electrical connections need periodic inspection for loose connections and corrosion [Jimenez-98].

2.2.6 PV in hybrid systems

Improved system usage and operation may be more easily achieved with a hybrid system than with a single-source application.

Hybridising a PV system often reduces the need for over-sizing the PV array to achieve system autonomy especially when complementarity of different energy sources can be used effectively. In a hybrid system the PV array may be used as a slow-rate battery charger for the upper end of the charge cycle where the battery is topped up with a trickle current.

Voltage mismatches between PV array and system DC voltage can be generally kept to a minimum in hybrid systems and maximum power point trackers are often not required. This consideration is subject to the installer's preference, and it is found that some prefer a low-cost approach (without an MPPT) while others adopt a best-possible system approach (including a MPPT).

2.3 Wind generator

2.3.1 Wind turbine electricity

Wind turbines convert the kinetic energy of moving air into mechanical or electrical energy. Wind turbines need somewhat more maintenance than a PV array but with moderate wind speeds will often produce more energy than a similarly priced array of PV panels [Jimenez-98]. Several wind turbines can be installed in parallel to produce more energy.

Wind turbines exist in many different types in terms of manufacturing process and materials used. Correspondingly prices vary widely. Wind speeds are highly irregular, therefore wind turbine energy production becomes highly variable. This can reduce wind turbine cost effectiveness. If a turbine is mounted higher up it catches higher wind speeds and produce more energy [Jimenez-98].

2.3.2 General workings

The blades, using aerodynamic lift, capture the energy from the wind in order to turn the shaft. In small wind turbines the shaft usually drives the generator directly. The generator converts rotational mechanical energy into electricity. The shaft power causes coils to spin past alternate poles of magnets allowing electric current to flow. If a permanent magnet device is being used the opposite occurs: current flows as magnets spin past coil windings. Most small wind turbines use a permanent magnet alternator. Larger wind turbines usually use either an induction generator or a synchronous generator. In addition, in larger wind turbines the shaft is connected to the generator via a gearbox that steps up the rotational speed for the generator [Jimenez-98], [Slabbert,Seeling-Hochmuth-97].

In off-grid applications it is difficult to keep the frequency of the resulting current constant, as it depends on wind speed which is highly variable. Therefore the current is usually rectified to give DC.

Most wind turbines have two or three blades. Two bladed machines are somewhat less expensive. Three bladed machines suffer less mechanical stress and are less vulnerable to fatigue problems. The yaw bearing allows a wind turbine to rotate in order to face the wind from any direction. A tower supports the wind turbine and places it above any obstructions [Jimenez-98].

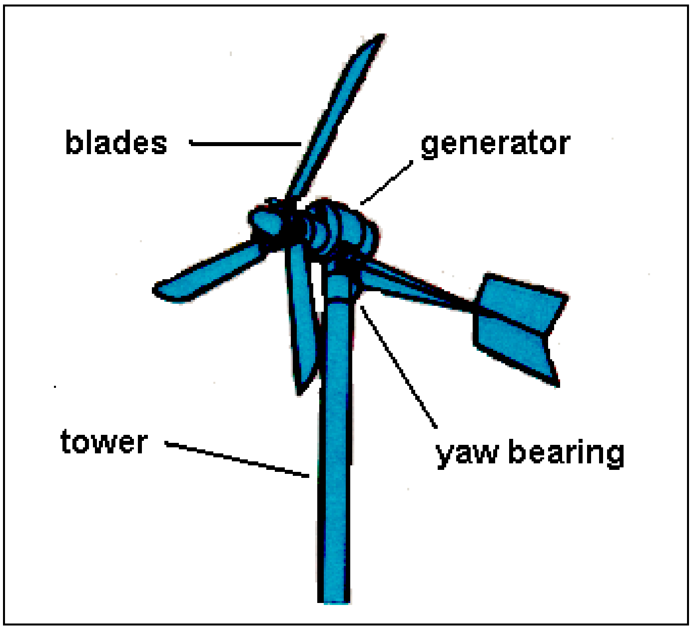


Figure 15: Typical wind turbine components ([Rural and Remote Area Power Supplies for Australia-93])

2.3.3 Operating issues

The power extracted by a wind turbine will have a mean value during a specific time interval with variations about the mean due to fluctuations in wind speed. A power curve is typically used to reflect the performance of a wind turbine and is the relationship between wind speed (at the hub height) and average output power (during the averaging time interval). Generally the output of a wind turbine is assumed to be proportional to the cube of the wind speed. The manufacturer will usually specify a cut-in wind speed at which the turbine starts to generate power, a rated wind speed at which it starts to generate rated power and a cut-out wind speed at which it shuts down for safety (Figure 16) [Slabbert,Seeling-Hochmuth-97].

Most small turbines cut out by tilting the rotor out of the wind. Larger turbines change the blade pitch to destroy the aerodynamic lift on the blades. After cut out, the power output of small wind turbines usually doesn't go all the way to zero, but the output of the larger turbines, in contrast, usually does [Jimenez-98].

The power rating of wind turbines in W_p can be misleading as the optimum wind generator and rotor combination depends on the wind regime. Nothing says more about a wind turbine than rotor diameter [Gipe-93]. Wind turbines are best compared by the area which is swept over by the rotor: the larger the swept area, the more energy the turbine can generate [Jimenez-98].

It is important to note that the choice of wind turbine type should suit the weather regime of the proposed area of application. Areas that are more suitable for wind turbine use (those with high average annual wind speeds) are often coastal areas where appropriate protection should be taken against rusting of the wind turbine structure. In strong gust areas, the construction should be able to cope with this weather condition. Other special areas of concern can include protection against extremely cold weather conditions by means of appropriate coatings [Slabbert,Seeling-Hochmuth-97].

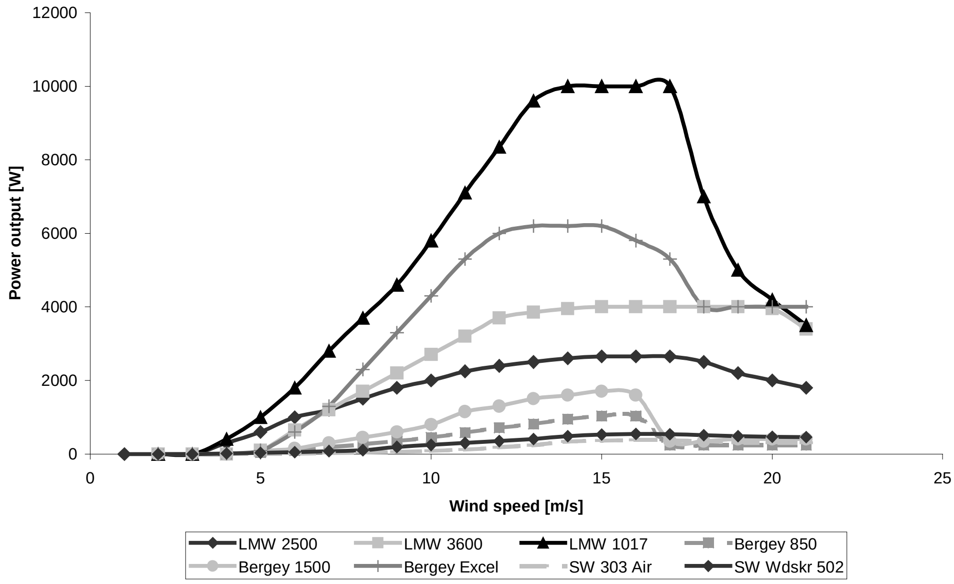


Figure 16: Selected wind turbine power curves (Manufacturer data sheets-LMW, Bergey, SW [Jimenez-98])

2.3.4 Wind system design

If the generator is undersized, the turbine will reach peak power at relatively low wind speeds and stay there until the cut out wind speed is reached. If the turbine is oversized, then the power will increase until the cut out speed is reached [Jimenez-98].

The energy output of a wind turbine can be calculated by determining the frequency distribution of local wind speeds and then computing the expected range of power outputs for each wind speed by using the wind turbine power curve.

The wind turbine load and hence speed are governed electrically by a voltage controller and mechanically by counterweights which reduce the pitch of the blades in the event of excess speed. Problems concern the number of shutdowns of the wind generator due to excess wind speed or energy production. The shut down problems can be solved partial by using a dump load [Jimenez-98].

2.3.5 Wind turbine installation

The AC output of the wind turbines can supply DC loads if an AC/DC rectifier is built in. This rectifier is sometimes already installed in the wind turbine. The wind turbine output is well suited to contribute to the battery charging process in the battery’s low-charging regime.

A direct connection of the wind turbine to the DC bus may impose additional requirements to the battery storage to ensure that wind energy variations do not cause voltage fluctuations that exceed inverter input voltage limits. For reactive power management the inverter output needs to be adjusted [Slabbert,Seeling-Hochmuth-97].

Most small wind turbines require very little preventive maintenance, however periodic inspections are recommended [Jimenez-98].

2.3.6 Wind turbines in hybrid systems

Wind turbine single-source systems tend to produce highly variable and therefore unreliable power supply due to the irregular wind speeds. If the wind turbine is combined with other sources in a hybrid system the produced energy can become more regular improving system performance and cost effectiveness. In some regions wind speeds and radiation levels complement each other.

2.4 Micro-Hydro power

2.4.1 Hydro-electricity

The hydropower usually refers to the generation of shaft power from falling water. The power is then used for direct mechanical purposes or, more frequently, for generating electricity.

Micro-hydro power systems are widely used for a number of applications such as irrigating crops. Micro-hydro installations can last over 50 years if properly maintained. Difficulties, especially with larger systems constitute environmental impacts, silting of dams, corrosion of turbines in certain water conditions, and the relatively high capital costs.

The installation may require different civil works depending on location that may be more costly than for other technologies, but at appropriate sites micro-hydro can be very low in operation costs. Much of the maintenance consists of regular inspections of the water channel and penstock to keep them free of debris [Jimenez-98].

A micro-hydro installation can produce power continuously thereby generating larger amounts of energy than PV or wind turbines of similar size, except in adverse weather conditions such as droughts or freezing temperatures [Jimenez-98].

2.4.2 General workings

Different types of turbines are available, depending on the head and flow rate available at the site. Impulse turbines, such as the Pelton wheel, cross-flow turbine or Turgo turbine have one or more jets of water impinging on the turbine, which spins in the air. The kinetic energy is extracted from the flow. These types of turbines are most used in medium and high head sites. Reaction turbines, such as the Francis, Kaplan and axial turbines are fully immersed in water. They extract kinetic energy and pressure energy from the flow. They are used more in low head sites [Jimenez-98].

The turbine is connected to a generator that produces electricity. Both AC and DC generators are available. Governors and control equipment are used to ensure frequency control on AC systems and dump excess electricity [Jimenez-98], [Slabbert,Seeling-Hochmuth-97].

2.4.3 Operating issues

The power output of a micro-hydro is proportional to the product of fluid density, falling water volume per second, the acceleration due to gravity and the vertical component of the water path [Jimenez-98]. This can be expressed as a function of the product of the pressure (head) and flow rate of the water going through the turbine.

2.4.4 Micro-hydro in a hybrid system

Running a micro-hydro system together with a wind turbine and a pump can feed water back into the reservoir and increase the micro-hydro output. Energy that would have been dumped by the wind turbine otherwise can thereby be utilised efficiently. It must be remembered that there are large seasonal fluctuations in water flow so micro-hydro systems should be used with complementary energy sources to cater for poor flow months [Slabbert,Seeling-Hochmuth-97].

2.5 Diesel generator

2.5.1 Engine generator electricity

Generators run on a variety of fuels, including diesel, petrol, propane and bio fuels. Compared to renewable energy installations, generators have low capital costs and produce power on demand. Disadvantages of generator operation include fuel dependence, transport and storage costs, high maintenance costs, and exposure to fumes and noise.

Diesel generators are the most common generators in a large number of small and remote power systems throughout the world. By and large they provide a dependable AC output, but diesel fuel at these locations can often be very expensive due to the additional transport costs involved [Jimenez-98]. Diesel generators are available in sizes ranging from under 1kW to over a megawatt. Compared to gasoline generators, diesel generators are more expensive, longer lived, cheaper to maintain, and consume less fuel. A typical lifetime for diesel generators is 25.000-30.000 operating hours. Large diesels may be overhauled quite often [Jimenez-98].

The fuel efficiency of a diesel generator is generally 2.5kWh/litre-3.5kWh/litre at high load levels. Fuel efficiency drops substantially at low load levels. Petrol generators are available in very small sizes and are most suitable when loads are small and only seldom powered [Jimenez-98].

2.5.2 General workings

Generators consist of an engine driving an electric generator. These generators are often run at low load with poor efficiencies, which can lead to increased engine maintenance requirements. Thus a major characteristic of the motor generator is its fuel consumption which may vary from generator to generator. Figure 17 shows the specific fuel consumption curve for a commonly available water-cooled diesel generator [Slabbert,Seeling-Hochmuth-97]:

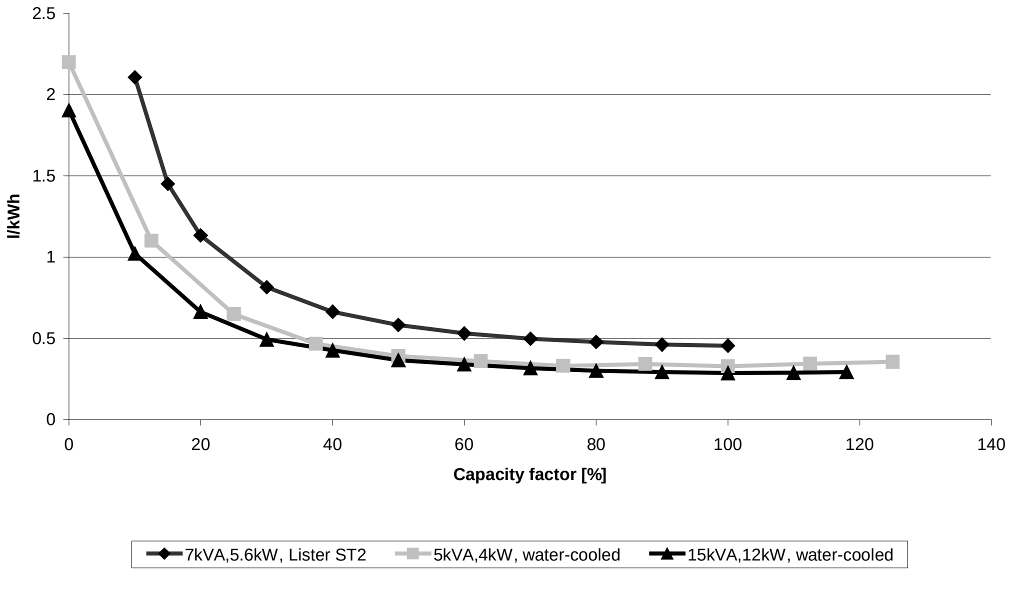


Figure 17: Diesel fuel use as function of the capacity factor for a 15kVA generator [Remmer & Dymond 1991], a 5kVA generator [Jennings-96] and a 7kVA generator [Morris-88]

2.5.3 Operating issues

A generator should be run at high load levels to maximise fuel efficiency. Low load operation results in increased cylinder glazing, high frictional losses, increased oil viscosity, low combustion temperatures and fuel deposition which in turn lead to greater maintenance costs and lowered fuel efficiency.

Frequent start-ups increase wear because oil films have drained away at stand still, and increasing cylinder pressures promote wear at contact points. It is common practise to install dump loads which deliberately dissipate energy when useful demand is low, to protect the diesel engines [Jimenez-98],[Slabbert,Seeling-Hochmuth-97]. Improvements to diesel operation would be aiding engine warming up, lessening peak pressures at start-up and avoiding partial load conditions.

2.5.3.1 Diesel start-stops

The diesel will have to be utilised also during the renewable intensive months, as it should not be turned off for extended periods of time, for example like 3 months in a row. More starts seem to mean more maintenance even though that is being debated. In [Seeling-Hochmuth-96] a diesel start once or twice a day as rule of thumb is mentioned, other research work states that up to 8 diesel starts per day are alright. It was also stated that the diesel should be started at high loads, but early enough so that the inverter does not get overloaded. The diesel should be allowed to warm up for 20-30 seconds, unless the load increases dramatically.

The diesel cools down within an hour. Keeping the diesel warm for future starts is expensive even though it allows a quick start of the diesel with minimum wear. This seems good practice for multiple diesel systems in which one diesel is always on. If the outside temperature is very cold, it can be wise to start the diesel every few hours. In case of a warm start the wear is equivalent to 2-4 minutes running time. A failure to start the diesel can occur each starting time (failure around every 100 starts) [Seeling-Hochmuth-96]. The view is expressed in [Seeling-Hochmuth-96] that wear and tear is not the main problem concerning diesel starts, but the likelihood of a failure to start.

2.5.3.2 Diesel maintenance

The experiences shared in [Seeling-Hochmuth-96] were that the number of maintenance intervals per year depends on the customer level of confidence. One participant said that some automated systems will have 2-4 maintenance intervals per year and one maintenance interval would not be sufficient. An example was mentioned of the South African Lister diesel generator, which needs every 500 hours running time a standard maintenance service and every 15,000 hours a complete overhaul. The amount of diesel maintenance also depends on how big the accumulated oil sump is. An oil change is needed ca. every 250 hours of diesel running time. Therefore to reduce the frequency of maintenance shorter runtime and more oil changes were recommended.

2.5.4 Design

A diesel generator should be designed such that it meets the load reliably but also runs on average at very high load levels.

If a battery for short-term storage is installed in the diesel generator system it can help to overcome peak loads and thereby reduce the design capacity of the diesel generator, and system costs, if the inverter is sized accordingly. The diesel generator is charging the battery via a battery charger that converts the AC energy into DC energy. The battery allows the diesel engine to operate close to its rated power and it can help reduce the start/stop cycles of the generator resulting in a decrease in fuel consumption and maintenance costs.

A drawback is that a generator when operated at peak output is a very high-rate charging source for the battery. The batteries, however, require lower charging rates close to full state of charge, in order to prevent the deleterious effects of severe overcharging.

A battery charger can be installed that can taper the current output of the diesel generator. Thereby some energy is lost. Therefore, in general, any diesel generator energy allocated for charging is primarily used for high-rate battery charging after the batteries have been sufficiently discharged. This is achieved by operating the generator only when the batteries are deeply discharged and need large amounts of current, allowing the generator to run at full efficiency.

2.5.5 Diesel generator in a hybrid system

The integration of renewable energy sources into a diesel system is far from straightforward, especially where the renewable energy sources are expected to have a large contribution. Depending on the specific control strategy, problems can include:

- Unacceptably high numbers of generator stop-start cycles if it is operated as a back-up generator. This is due to the variability of the renewable energy sources and the consumer load.
- Prolonged low running of the diesel generator, which will lead to, increased wear and maintenance together with a reduction in working lifetime. This is the case if the diesel generator is over-sized and/or the renewable/battery sources are designed as back-up sources and are not sufficient to cover the load over some time periods.
- An increase in the specific fuel consumption of the diesel at low load conditions which results from the last two points.

Criteria should thus be set such that the diesel is run favourably and these can include next to the ones recommended generally for diesel generator operation:

- **Starting criteria –** Diesels are started for one of two reasons: firstly if the renewable energies and the battery cannot meet the load and secondly if the battery state of charge has fallen below a specified value.
- **Shut off criteria** – Generally diesels may be shut off if there is sufficient power available from the renewable energies and the battery to supply the load or if the battery has attained a respectable state of charge [Slabbert,Seeling-Hochmuth-97].

Many of these points can be achieved in a well-designed hybrid system as opposed to a single-source system. In a hybrid system the diesel generator is often not used all the time but only in certain instances (such as battery charging, covering peak loads) where it can run at a high loading levels thus reducing wear and maintenance on the generator. It can be easier to have the diesel shut-off during required times (e.g. at night), as other energy sources and storage means are available. Setting minimum run-times, where the diesel is forced to stay on for some defined period of time, is more appropriate in a hybrid system as there is often a destination for excess energy (battery charging, dump loads).

A diesel generator in a renewable hybrid system often eliminates the need to build in system autonomy and adds to the system reliability. In addition, the design capacity of hybrid system component can often be reduced as compared to their required sizing in single source systems.

2.6 Energy storage

2.6.1 Battery electricity

Batteries are electro-chemical devices that store energy in chemical form. They are used to store excess energy for later use. Most batteries used in hybrid systems are of the deep-cycle lead-acid type. There are several other appropriate types (nickel-cadmium, nickel-iron, iron-air and sodium-sulphur) but these are generally either too expensive or too unreliable for practical application as most of them are still in the experimental stage. The lead-acid battery is widely used and, although complex, is well known. Its major limitation is that it must be operated within strict boundaries as it is susceptible to damage under certain conditions – such as overcharging, undercharging and remaining for long periods in a low state of charge [Jimenez-98], [Slabbert,Seeling-Hochmuth-97]. Battery costs can form a minor part of the system initial costs but, under adverse conditions, battery maintenance and replacement can become a significant portion of system lifecycle costs and can prove to be expensive in the long run. If the operating conditions are favourable, however, these batteries can last up till 15 years in an autonomous application. Individual batteries used in renewable energy and hybrid systems are available in capacities ranging from 50 amp hours at 12 volts to thousands of amp hours at two volts (i.e. from 0.5 kWh to several kWh) [Jimenez-98].

2.6.2 General workings

Batteries consist of one or more 2V-cells wired in series. Each cell consists of plates that are immersed in an electrolyte. When discharging a chemical reaction between the plates and the electrolyte produces electricity. This chemical reaction is reversed when the battery is charged.

The thickness of the battery's plates determines the maximum depth of discharge beyond which the battery suffers damage. Shallow cycle batteries, such as car batteries, have thin plates and are designed to produce large currents for short periods of time. These should not be deeper discharged than 10% - 20% depth of discharge after which the battery is ruined easily [Jimenez-98]. Shallow cycle batteries are usually not suited for hybrid and renewable systems but are often used anyway in small home systems in developing countries due to lack of any alternatives. Deep cycle batteries have thick, often tubular plates and can often be discharged up to 70%-80%. However, this type of battery cannot be quickly charged and discharged [Jimenez-98].

2.6.2.1 Storage capacity

The storage capacity of the battery is generally given in amp hours or after multiplication with the battery's nominal voltage in kWh. The value for the storage capacity depends on its operation, age and treatment. The storage capacity is increased when the battery charging and discharging rates are slow. Most battery manufacturers give the storage capacity for a given discharge time, usually 20 or 100 hours [Jimenez-98]. Some of the energy used to charge a battery is lost which is accounted for by the round trip efficiency (typically 50%-80%).

2.6.2.2 Battery modelling

Validated battery modelling is essential for accurate predictions of the ability of the renewable system to meet the load demand, especially in the autonomous case. A common technique is to estimate the state of charge (SOC) of a battery in Ampere hours or a percentage to express its condition. A battery is said to have a certain capacity in Ah (100% SOC) and the amount of charge taken from it under operation (% depth of discharge) will leave it at a new % SOC [Slabbert,Seeling-Hochmuth-97].

Unfortunately a quantity such as SOC is not directly measurable. As an alternative approach the battery state of voltage can be used to give an indication of the SOC in order to judge the condition of a battery. Battery SOC levels correspond to different voltages depending on the operation (e.g. charging, discharging) such that a battery might be at 100% SOC at 13.4V at the beginning of discharge and the battery might be charged to as much as 14.1V (SOC = 100%) before gassing commences. A means of relating the voltage and SOC is suggested by the Shephard equations [Shephard-65] and as described in [Schuhmacher-93]. Battery modelling is further discussed in [Schuhmacher-93] whose model is used in this thesis, [Manwell,McGowan-93], [Protogeropoulos-94], and [Stoll-92] who modelled battery behaviour with the help of neural networks. An example of the format for discharge curves can be seen in Figure 18:

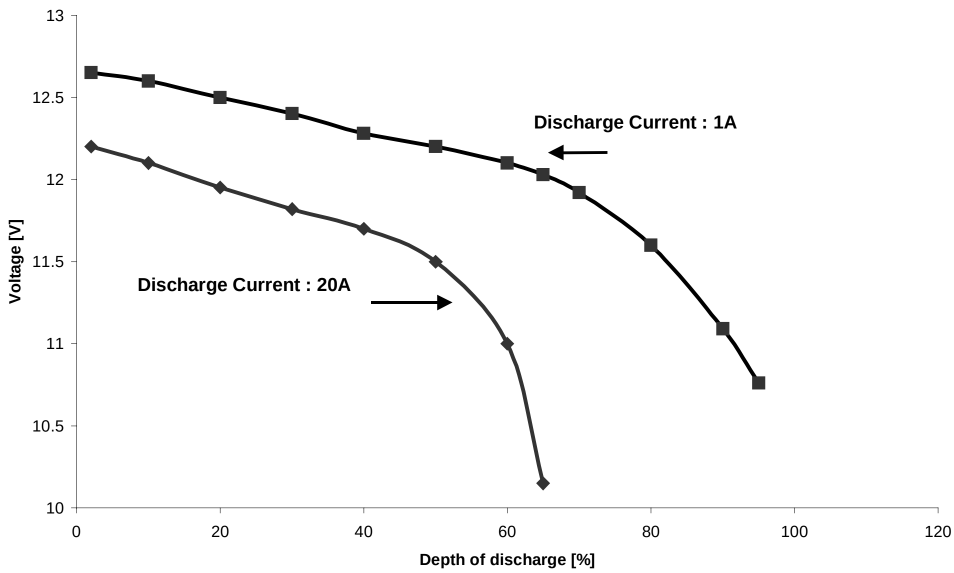


Figure 18: Battery discharge curves, 90Ah, 12V Battery [Purcell-91]

Although it is useful in a practical sense to use voltage as a representation of SOC, this has some drawbacks. The ageing of batteries has an impact on the voltage-SOC determination such that at a certain voltage (e.g. 13.4V) a new battery may be at 100% SOC whereas an older battery may be only at 85% SOC. In order to cater for this, some modern battery regulators incorporate Ampere hour counters to provide a more accurate means of regulation [Slabbert,Seeling-Hochmuth-97].

2.6.2.3 Lifetime

Battery lifetime is measured both in terms of energy taken out of the battery and by float life. A battery is dead when all available energy has been taken out or when the average battery capacity has been reduced to 80% of its original value.

The main factors affecting battery lifetime are grid corrosion, buckling of plates, sulfation, and stratification of the electrolytes. These factors are causing loss of active material and internal short circuits. If less active material is available the ratio of the reaction components is becoming non-optimal resulting in a drop of capacity and the charging efficiency is reduced. Internal short circuit leads to harmful deep discharge of the concerned cell and hence ruins the whole battery [Piller-97].

For many batteries, especially the lead acid types, as long as the battery state of charge is kept within the manufacturer's recommended limits, the lifetime cumulative energy flow is roughly independent of how the battery is cycled. Depending upon the brand and model, battery lifetime cumulative energy flows vary widely [Jimenez-98].

Typical float lives for good quality lead acid batteries range between 5 and 10 years at 20°C. High ambient temperatures will severely shorten a battery's float life. A rule of thumb is that every 10°C increase in average ambient temperature will halve the battery float life [Jimenez-98].

2.6.3 Operation

Battery operation in an off-grid system is different to laboratory conditions, as batteries are cycled irregularly, often at partial discharge, and the recharge is usually not completed to float-charge conditions.

The state of charge of the battery depends on the charging rate, temperature and charging history. Experiences reported in [Seeling-Hochmuth-96] state that batteries function better if not charged with slow changing currents. That might explain some of the good battery performance in wind systems according to [Seeling-Hochmuth-96].

For best performance batteries should not spend long periods of time at a low state of charge. Long periods (over ~2 weeks) at a low state of charge and partial cycling makes batteries susceptible to sulphation (a type of corrosion on the plates) and stratification of the electrolyte, both of which reduce battery life and capacity.

Electrolyte stratification is likely to occur during prolonged operation at partial discharge without stirring the electrolytes. In general, degradation of the positive active material is caused by mechanical stress through transformation, in volume and mass, of active material ($PbO_2 \Leftrightarrow PbSO_4$) during cycling. The volumetric changes give rise to cracking of the corrosion layer and loss of electrical contact. Furthermore, electrolyte stratification can contribute to uneven active material use and concentration differences forming in the electrolyte. Stratification losses may not be reversible in the long term and result in the cell working unevenly. The net result is corrosion and slow $PbSO_4$ formation which are likely to cause premature failure of the cell and can increase the internal resistance [Piller-97], [Slabbert,Seeling-Hochmuth-97].

Sulphation of the negative electrode occurs during prolonged cycling with deep discharges and high temperatures. It causes fine PbSO4 crystals becoming coarse-grained, leading to thickening of the grid, and adversely affecting the operation of the battery through loss of contact with the conducting grid. Irrecoverable sulphation may result if the batteries are not recharged [Piller-97], [Slabbert,Seeling-Hochmuth-97].

Overcharging and operation at high temperatures can cause a phenomenon known as gassing where excessive amounts of H2 and O2 gases are formed. This can decrease the life of the cell by increasing the rate of active material shedding and can also enhance the rate at which the positive grid is corroded (transformation of metallic lead into PbOx). Consequences of this can include an increase in internal resistance, water losses leading to sulphation and short-circuiting, and capacity and cycle life reduction. In addition the H2/O2 mix is explosive, which can be dangerous [Piller-97], [Slabbert,Seeling-Hochmuth-97].

Batteries should, however, be equalised roughly once per month. Equalisation is the controlled overcharge of the batteries. Valve regulated batteries are less susceptible to the bad effects of spending prolonged periods of time at a low state of charge. These types of batteries should thus receive serious consideration for cases where regular boost charging and equalisation may be difficult such as in systems with no diesel back up [Jimenez-98].

2.6.4 Design

When selecting a battery type, usually lead acid type batteries are chosen. In general lead acid batteries are more cost effective than Nicad batteries, but the latter may be the better choice if greater battery raggedness is an important consideration [Jimenez-98].

Selection of battery voltage depends on inverter and generation controller equipment generally available. They come in specific voltages from 12, 24, 48 up to 120 and 240 VDC and thus batteries must be selected and combined in series to meet this voltage requirement. The number of battery strings that can be connected in parallel is limited to about five without rigorous monitoring and higher maintenance costs. This means that once the general battery bank capacity has been selected the size of the individual battery type must be chosen accordingly [Jimenez-98].

When designing the system depth of discharge (DOD) a trade-off must be made between a low DOD where the battery will be less affected by sulphation, but may face frequent load interruption and will be cycled more often; and a high DOD where although the supply may be more reliable and the cycling reduced, the battery lifetime may be shortened due to increased sulphation [Slabbert,Seeling-Hochmuth-97].

2.6.5 Installation

Voltage set-points can then be set for battery levels such as: minimum state of charge, maximum state of charge, boost charge interval, etc, and these can be applied via a battery charge regulator which is discussed in more detail later.

Batteries should be installed in a vented, enclosed area. Batteries may be connected in series to increase the battery bank voltage and in parallel to increase the capacity. The batteries in a bank should all be of the same brand, model and age [Jimenez-98].

2.6.6 Batteries in a hybrid system

Battery operation in a hybrid system as opposed to a single-source application may result in certain advantages with respect to battery lifetime optimisation. This can be attributed to the fact that there is often more sophisticated control installed in a hybrid system due to the interaction of many components. This requires better regulation of components and will result in better treatment of the battery. Moreover, there are more energy sources available resulting in the battery not being utilised to as high a degree as in single-source systems. Reduced cycling leads to increased lifetime and more time (and sources) available for recharging and boost charging [Slabbert,Seeling-Hochmuth-97]. Batteries are costly and can often be sized smaller in a hybrid system than in a single-source system.

2.6.7 Flywheel storage

Flywheel storage is used for very short-term energy storage of milli-seconds to seconds, predominantly in wind/diesel systems. When the diesel generator is separated from the synchronous generator via a clutch and a flywheel is connected to it, then the flywheel/generator’s rotating inertia compensates for the wind turbine’s power fluctuations, which can be used to start the diesel when it is needed.

2.7 Loads

Most common loads are 12V or 24V DC appliances or 220/230V or 380V AC appliances. DC devices can be slightly more expensive than similar AC appliances. DC supply to AC loads needs inverters with the corresponding power range and efficiencies for the expected load factors. However, inverters are very costly and system expenses are greatly reduced if inverters can be avoided. But most home appliances will be only available in AC versions.

Similarly AC supply to DC loads will make use of rectifiers which have to be sized with the right power and efficiency range, too.

Surplus energy is used for heating (e.g. of water) or shed to a dump load. Dump loads may be needed if the system contains wind turbines, micro-hydro or generators. A dump load consists of essentially one or more big resistors that dissipate electricity by converting it to heat. Available dump loads are either water or air-cooled. Dump loads are sometimes used to control the frequency of the AC output of a system [Jimenez-98], [Slabbert,Seeling-Hochmuth-97].

2.8 Conversion devices

Power converters are used to convert DC power, e.g. from PV panels, batteries and smaller battery charging wind turbines, to AC power, which is required by most electrical appliances, and vice versa. Engine generators typically produce AC power which can be converted to DC power with the help of a rectifying battery charger in order to be used to charge batteries. The most common power conversion devices are electronic and include inverters (DC to AC), rectifiers (AC to DC) and bi-directional converters (both directions) [Jimenez-98], [Slabbert,Seeling-Hochmuth-97].

2.8.1 Inverter

When AC appliances are used, an inverter is required between them and the battery/DC supply subsystem [Nayar et al-93]. The inverter is normally only single phase for small power ratings. Three phase inverters are more costly than one-phase inverters. A consideration when selecting a three-phase inverter is its ability to serve unbalanced loads. In a DC/AC bus system with renewable and battery back-up sources one could select a small inexpensive inverter to operate light household equipment [Jimenez-98]. Larger appliances are in some systems operated solely by a generator. In case that the renewable energy sources are sized to a large percentage of required energy, possibly integrated with a generator that might be used as back-up source, the inverter might have to power higher loads including peak loads, so a more powerful and sophisticated inverter is needed.

2.8.1.1 General working

The harmonic distortion of inverters is an important issue especially when powering components like computers and refrigerators and is an indication as to what extent the inverter output waveform is non-sinusoidal. Inverter output waveforms can be square wave, modified sine wave or sine wave. Square-wave and quasi-square inverters will introduce distortion as compared with a 50 Hz sine wave, but are less expensive than a sine wave inverter [Jimenez-98]. They can suitably power resistive loads such as resistance heaters or incandescent lights. Modified sine wave inverters produce a staircase square wave that more closely approximates a sine wave. They can supply most AC electronic devices and motors. However, some sensitive electronics may require sine wave inverters. These inverters can produce utility grade power but cost more than the other types of inverters [Jimenez-98].

Inverters used in off-grid applications are electronic devices based on high frequency switching. In sine wave inverters, an internally generated sine wave is digitally produced at 50Hz as a reference and this is used to create a train of pulse-width modulated voltages. This train controls the switching of transistors such that the DC source is connected and disconnected accordingly. This is amplified across a transformer and filtered to get a sine wave voltage on the output at 50Hz with the magnitude set by the transformer (usually about 230V). Sometimes simple square wave or stepped-square (quasi-sine) inverters can be used as these exhibit better efficiency and are much cheaper although not always applicable [Slabbert,Seeling-Hochmuth-97].

Normally an inverter will shut down as soon as its output upper limit is exceeded but modern inverters have been designed such that they can handle power surges for a limited duration. This is possible by dynamically limiting the output in order to minimise the heat build-up in switches and transformer. Typically heat-limited inverters can supply in excess of their rated capacity for 30 minutes. This is especially important for such applications as starting induction motors where up to six times the normal power output is needed for starting [Jimenez-98, Slabbert,Seeling-Hochmuth-97].

2.8.1.2 Operating issues

Inverter efficiency is generally low at low power levels and good (80%->90%) at high power levels depending on the inverter type. Figure 19 shows an example inverter efficiency curves. The curves vary for different types of inverters. The inverter consumes always some power at no load condition so it should be switched off during that time.

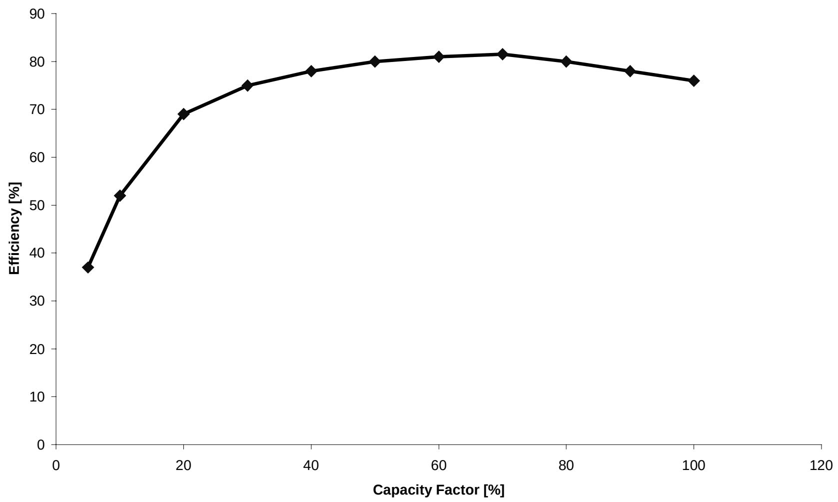


Figure 19: Example of inverter efficiency versus capacity factor

A way of alleviating the problem of low efficiency at low capacity factors is to operate the inverters only at preferred levels of output. Other specialised inverters try and solve this problem – for example, inverters have been produced with a high efficiency in the low power region with the higher region designed to cover power surges.

Paralleling of inverters is sometimes viable where the load is extremely variable. In this case only the inverters required will operate while the others will wait in standby mode. Only specialised inverters can run in parallel, as much synchronisation is required.

A so-called parallel inverter can supply power to a load simultaneously with a diesel generator. With a switched inverter, either the inverter or the generator, but not both at the same time, supply power to the load. A tri-mode inverter allows operation in parallel with a conventional diesel/alternator set and can be used simultaneously as a battery charger.

In grid-connected systems, a line-commutated inverter uses the 50Hz/60Hz signal from the grid to regulate the frequency of its output. Such units are not for use in stand-alone systems unless it is planned to keep a diesel on continuously. A self-commutated inverter doesn't need the grid for frequency regulation. Related considerations are how tightly the inverter can regulate frequency and voltage and its ability to supply reactive power [Jimenez-98].

2.8.1.3 Design

Inverters are usually sized according to the maximum required continuous power output. Most inverters are capable of handling three to six times more power than their rated size for short periods of time in order to accommodate surge currents which occur when starting a motor.

2.8.2 Rotary Converters

An alternative to inverters is the rotary converter consisting of an alternator on the AC bus and a generator on the DC bus, and both are connected via a shaft. The rotary converter is not that widely used and is most suitable for larger installations. Rotary converters are less efficient than solid state converters but offer lower costs and higher reliability [Jimenez-98].

2.8.3 Rectifiers

2.8.3.1 General workings

Rectification usually takes the form of battery charging from an AC power source. Rectifiers are relatively simple and inexpensive devices. Sometimes rectifiers are encompassed in a more complex battery charger unit performing such tasks as load-sensing and charge rate control to allow acid agitation and prevent stratification and plate sulfation at high SOC. Other functions may include boost voltages from time to time and soft-start characteristics. Some inverters already contain built in battery chargers or can have one added as an option. Also, many generators can produce DC power directly for charging batteries [Jimenez-98, Slabbert,Seeling-Hochmuth-97].

2.8.3.2 Operation issues

Chargers' efficiency characteristics tend to drop off slightly due to transformer losses if the charging current is high. A more important issue with chargers is their power factor capabilities, which are usually quite poor as current is drawn only at small portions of the AC voltage curve. This sporadic drawing of power is undesirable from a supply point of view as generators have to produce power in short bursts whereas they prefer to have a more constant output. Power factors tend to improve as the output increases although the efficiency tends to drop off slightly [Jimenez-98], [Slabbert, Seeling-Hochmuth-97].

2.8.4 MPPT

2.8.4.1 General workings

Maximum power point trackers are usually high-frequency DC-DC converters used to force the output of PV arrays to their maximum instantaneous power. They can improve system energy efficiency. They can be coupled to battery regulators, directly to DC water pumps or to AC water pumps via an inverter. Best results are achieved with direct DC pumps coupling where potentially the biggest operating mismatches occur. Smaller improvements are realised with battery coupling as the natural battery/array operating point is usually close to the array MPP [Jimenez-98], [Slabbert, Seeling-Hochmuth-97].

2.8.4.2 Operating issues

Energy conversion efficiencies are high over a narrow operating range. If the output voltage requirements vary significantly then the loss due to conversion inefficiencies should be checked against the change in array power to see the net effect [Jimenez-98], [Slabbert, Seeling-Hochmuth-97].

Generally in a hybrid system if a MPPT is installed, voltage mismatches are low and losses due to conversion are kept to a minimum. However, the inclusion of MPPTs is installer dependent and can improve operation even though costs are increased through the MPPT purchase.

2.9 Controllers

Controllers regulate the flow of energy through the system components to the load. The complexity of the controls depends upon the size and complexity of the system and the needs and preferences of the user.

2.9.1 Battery regulators

2.9.1.1 General workings

Battery regulators are used to control the operation of batteries used in an off-grid/hybrid system and thus protect them from unfavourable conditions. The main functions are top-of-charge regulation to prevent overcharging and load-disconnection to prevent excessive discharging. Additionally they may indicate the status of the system and may also give a boost charge from time to time to avoid stratification of the battery.

Regulators measure voltage levels as an approximation to state of charge but this may vary with charge/discharge currents, temperature and the prior history of the battery. For this reason more sophisticated regulators may use temperature compensation and Ampere hour counting to determine state of charge more accurately. Set-points are selected for such situations as [Slabbert,Seeling-Hochmuth-97]:

- Voltage at which loads are disconnected due to battery reaching maximum depth of discharge;
- Voltage at which loads are reconnected;
- Voltage at which charging of battery should cease to prevent gassing;

- Voltage at which charging should recommence;
- Voltage at which charging rate should taper off (at near full SOC).

It is important to note that these set points will differ with battery type and according to the history of the battery.

2.9.1.2 Operating issues

On low voltage systems voltage drops due to the regulator can have significant effects on system performance including array/battery mismatching. On such systems the power consumption of regulators can be significant and proper selection of relays can improve power efficiency. Reliability of regulators is another important issue as they can fail under certain conditions like lightning, surges and overheating. Voltages can be affected by temperature fluctuations and thus temperature compensation of set points is desirable in circumstances where battery temperature varies substantially.

2.9.2 Controller integration

In many cases, controls are integrated into the inverter. Each of the renewable generators can have its own controller whose settings are determined by the battery bank voltage which regulates the charging and discharging of the battery bank, and generator operation, insuring that the generator is started if the battery charge level is below specified parameters. Some larger inverters, up to 30 kW, have been designed with integrated system controls but above that range, supervisory controls are used [Jimenez-98]. Controls usually consume a certain amount of power which needs to be taken into account when designing a system.

Supervisory controllers are usually based on PLC, programmable logic controllers, which can be purchased commercially. These devices take input from either separate component controllers or other centres and, using a programmed logic, decide which devices should be operational. The supervisory controller sends out the appropriate signals to other devices, relays or controllers. Supervisory controllers are the most complex and expensive but also allow much more detailed system manipulation and optimisation than standard integrated controllers [Jimenez-98].

Some of the functions of the supervisory controller can include monitoring and data logging, the switching on and off of components so as not to require user intervention and the diversion of energy to a dump [Jimenez-98].

2.9.3 Remote control

Remote supervision possible e.g. via phone alleviates the problems connected with maintenance in remote areas. In addition fault monitoring and indication, and acquisition of operational data are of interest. The system controller and transmission equipment will consume some power as well.

2.10 Balance of System (BOS)

BOS components include all the remaining items that are needed to field a functioning system [Jimenez-98].

Chapter 3

Hybrid System Costing Model

3.1 Introduction

The modelling of the hybrid system costing together with the system performance modelling in Chapter 4 make up the overall hybrid system model. It is the aim of this thesis to derive a solution for the hybrid system design problem. The solution is optimal only with respect to the accuracy of the model being employed. The model depicts the real system mathematically so that the model, rather than the physical system, can be manipulated. All models are necessarily abstractions, however, and the optimal solution with respect to the model may not be the optimal solution for the real world problem. If the model is well formulated, however, it is reasonable to expect that the resulting solution will be a good approximation to the actual problem. Therefore emphasis has been placed on formulating the different ingredients of the hybrid system model as accurately as possible while trying to ensure that the model is still suitable to the solution finding process.

The solution finding to the model typically employs an algorithm. An algorithm is a set of procedures or rules that is followed in a step-by-step, or iterative, manner that provides or converges to the best solution for a given model. Such an optimisation algorithm is usually programmed on a computer, which can then perform the calculations within the iterative process.

It is important to note that a particular algorithm has a specific set of rules that apply to a specific problem formulation and thus a large number of algorithms are in existence.

The underlying optimisation model has an objective function that is optimised (minimised or maximised) subject to constraints that utilise decision variables (i.e. the unknowns of the model) and parameters. The optimised set of decision variables prescribes the course of action that the decision maker/controller should select to achieve the defined objective.

The quantitative model used for describing the hybrid system contains the following elements:

Objective function. The objective function changes value as a result of changes in the values of its variables, the so-called the decision variables. The objective function measures the desirability of the consequences of a decision. In this approach, the objective function describes the net present costing value of a hybrid system design in terms of a) initial equipment costs, and b) fuel and other operating costs discounted over the project planning period according to cost/benefit calculations (Marrison and Seeling-Hochmuth, 1997).

Model. Based on the values of the decision variables the hybrid system model calculates the values of the

- Component sizes

at the beginning of each iteration and at each time instant the values of

- Component outputs
- Transformation losses
- DC and AC bus inputs and outputs and the
- Supply to the loads.

The resulting hybrid system performance over the simulation time period of, say, a year is extrapolated to the project life. Then the amount of load met as well as required fuel purchase, maintenance, overhaul and component replacements can be determined during the project life. This performance data yields the required operational costing data and penalty/benefit data to calculate the resulting value of the objective cost function for a certain system and operation choice.

Decision variables. Decision variables are the unknowns that are to be determined by solving the model equations. A specific decision is made when decision variables take on specific values. Decision variables concern component sizes, component numbers and installation settings and operating decisions such as amount of battery charge or discharge current (x_{bat}), diesel output power (x_{diesel}), position of switches (x_{Si}) and routing decisions (x_{Ri}). The decision variables in the model are all labelled with an ‘x’ and an appropriate suffix. The above-mentioned operating decisions are time-dependent which can make a computer simulation very lengthy. If the time interval, over which the simulation is running, increases, then the number of operating decision variables is enlarged. Therefore, in this thesis a methodology is given that links the operating decisions at each time instant to time-independent control settings that are then optimised during the algorithm’s iterations.

Constraints. The constraints restrict the range of the decision variables as a result of technological, socio-economic, legal or physical constraints on the system. The constraints in the presented approach are given by technical characteristics of battery and diesel operation and by matching demand and supply. They can be incorporated in the model and in the objective function in form of a benefit description (benefit of meeting demand and other constraints) or in form of a penalty function (penalty on not meeting demand or other constraints).

In this design problem the requirement was to model the hybrid system with a high degree of accuracy while still being able to run an optimisation algorithm over the model. Therefore genetic algorithms were chosen as the optimisation tool. Genetic algorithms have the advantage of being able to optimise quite complex models, as they do not require the calculations of gradients. Their disadvantage is that they might require some time to converge depending on the specific problem case.

The following sections explain the derived objective function description in terms of net present value costing, the incorporation of the design constraints in form of benefit and penalty descriptions and the underlying system model with its decision variables. The shortcomings of rule-of-thumb or spreadsheet modelling in optimising a hybrid system design are highlighted and the characteristics of the developed optimisation algorithm for the hybrid system design are described.

3.2 Hybrid system life cycle costs and net present value analysis

When designing a hybrid off-grid electricity supply system, the analysis comprises the comparison of mutually exclusive alternatives for the choice of system design that produce a similar techno-economic and social benefit for the chosen remote application. The evaluation of different hybrid and other off-grid design choices determines what type of system to use for a given application. This may also be done by comparing a hybrid system with electrification by grid extension, a local diesel generator, a SHS project, a central battery charging station or other options. Whichever technical solution is chosen, the benefits need to be determined. Such benefits can describe the technical reliability of the electricity supply or can also address socio-economic improvements induced through the provision of electricity service. The developed optimisation model is formulated such that after the optimisation algorithm’s iterations the type of system is recommended that offers the best combination of least-cost design and highest benefit choice.

In counting the cost of a project, it is customary to use Net Present Value (NPV) analysis [Gowan-85], [Marrison,Seeling-Hochmuth-97]. The concept of Net Present Value analysis is an extension to the principle of life cycle costing. In both cases the discounting of future costs is an important concept.

The present value of an asset/liability of value C held/incurred in n years from the present, where the value of C escalates by esc, is described as

$$PV = C \cdot R$$

Equation 4: Present value of an asset after n years

$$R = \frac{(1+esc)^n}{(1+r)^n}$$

Equation 5: Discount factor after n years

where *r* is the discount rate. The present value of a cost C incurred every year for the next n years with a real escalation of esc per annum, is described as

$$PV = C \cdot R_{yearly}$$

Equation 6: Present value of a cost incurred every year for n years

$$R_{yearly} = (\frac{1+esc}{r-esc}) \cdot (1-(\frac{1+esc}{1+r})^n)$$

Equation 7: Discount factor for a cost incurred every year for n years

The discount rate *r* represents an appropriate opportunity cost, with which future costs and benefits are discounted to their present value.

The opportunity cost of a scarce resource is defined as the benefit foregone by using the resource for one purpose instead of in its best possible alternative. The basis is that most resources have several potential uses. The direct opportunity cost of a person-day labour used for a rural electrification project is what this labourer would have produced, for example by working on agricultural land had she not been taken away from her usual occupation to be employed in the rural electrification project.

In this analysis inflation is not included in any of the cashflows. *r* is therefore the real discount rate. It is generally difficult to obtain the theoretically correct value of *r* because it depends on the riskiness of the cashflows [Marrison,Seeling-Hochmuth-97]. [Davis,Horvei-95] suggests that 8% is the appropriate rate to use for this type of project in the South African context and is used for the base case in this thesis.

In life cycle costing equipment and operation costs are compiled and discounted over the assumed project life. The hybrid system life cycle costs are the added costs of initial investment costs and future discounted operation costs:

$$LCCs = InitialCosts + \sum_{i=1}^{NoOfComponents} Discounted\ OperationCosts_i$$

Equation 8: Life cycle cost equation

$$Discounted\ OperationCosts_i = \sum_{year\ n}^{ProjectLife} \frac{OperationCosts_i(n)}{(1+r)^n}$$

Equation 9: Discounting of operation costs

In Net Present Value analysis not only the cashflows for expenses are considered, but also the discounted cashflows for income or benefits arising from providing electricity over the project life.

$$NPV = InitCosts + \sum_{i=1}^{NoOfComponents} Discounted\ OperationCosts_i - \sum_{j=1}^{NoOfIncomeSources} Discounted\ Income_j$$

Equation 10: Net Present Value equation

$$Discounted\ Income_j = \sum_{year\ n}^{ProjectLife} \frac{Income_j(n)}{(1+r)^n}$$

Equation 11: Discounting income

There are three broad types of expenditure cashflows, initial capital costs, costs that depend on the passage of time, and costs that depend on usage [Marrison,Seeling-Hochmuth-97]. The initial costs for a given design are typically well known and for a small project they will occur at time t=0 with no discounting.

Costs that depend on the passage of time, for example monthly administration costs, are accumulated for a year or so and then discounted over the project life. Costs that depend on usage require information from the system performance, as can be estimated or more accurately simulated. Examples of costs that depend on usage are overhaul, diesel replacement, refuelling, and battery replacement. Figure 20 taken from [Marrison, Seeling-Hochmuth-97] illustrates capital, periodic, and usage cashflows. The initial peak represents the capital cost, the later large peaks represent diesel overhaul and replacement events.

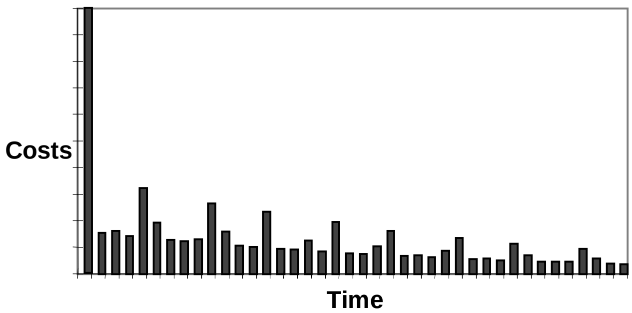


Figure 20: Illustration of discounted cashflows [Marrison,Seeling-Hochmuth-97]

The next sections develop the objective function formulation for the hybrid system design model in more detail. Thereby the component and system costs presented are based on references from [Helios-96], [Hochmuth-96], [RAPS manual-92], [Morris-94], [Davis,Horvei-95], [Schuhmacher-93]). The utilised parameters are also summarised in Table 7.

3.3 Initial hybrid system costs

3.3.1 General

The initial costs are the costs incurred through purchasing equipment, and hiring labour, in order to install a hybrid system. A component purchase might also generate certain associated fixed costs for the user. For example regardless what kind of component size is purchased a certain type of transport would always have to be paid for, or a certain sized container etc. When installing equipment certain costs arise due to installation, labour or required accessories. These costs depend on size and type of a component and are often given as a percentage of individual or overall equipment purchase costs. All contributing initial component costs are summed to give the overall initial costs (Equation 12, Equation 13).

$$InitialCosts = (\sum_{\forall components} InitCosts) + \%of \cdot (\sum_{\forall components} InitCosts) + FixedCosts$$

Equation 12: Initial component costing

$$InitCosts(component\ i) = f(x_{size,type,i}, x_{number,type,i})$$

Equation 13: Dependence of initial costs on size and type

In general, the initial purchase costs of a component bank will depend on the size and type of a component, and on how many components are bought. For example, differently sized wind turbines are available at varying costs due to different material and labour costs in producing a turbine. In addition, similarly sized wind turbines from different manufacturers might be priced differently due to the use of particular designs, materials, quality standards and mark-ups.

The component size and type are subject to optimising system design criteria. They are therefore selected as decision variables to be optimised in the developed hybrid system design model. The component initial cost is multiplied by the required number of components to be installed in the system in series ($n_{i,series}$) and in parallel ($x_{i,parallel}$). The number of components to be installed in series is often straightforward and determined by the nominal operating voltages of the system and the components. However, the number of components to be installed in parallel is subject to system design and its optimisation and is therefore labelled with an ‘x’, as is the size of a component type.

Therefore, in the initial cost modelling, the size and type of a component and the required number of parallel connected components are taken to be decision variables to be optimised in the developed hybrid system model.

In the following, the initial costs of different component types are discussed.

3.3.2 Initial costs of the PV array

PV panels are available in different sizes, with the size being characterised by their peak wattage (W_p) that stands for the maximum power a PV panel can produce under standard test conditions (STC; 1000W/m^2, AM of 1.5, 25 C and perpendicular insolation). Most common sizes are 40W_p-80W_p, 18W_p and 300W_p are more rare and used specifically for very low or very high PV power requirements respectively. An economy of scale in panel prices occurs at between 18W_p and 75W_p (see Figure 21), not considering increased installation costs for smaller panels.

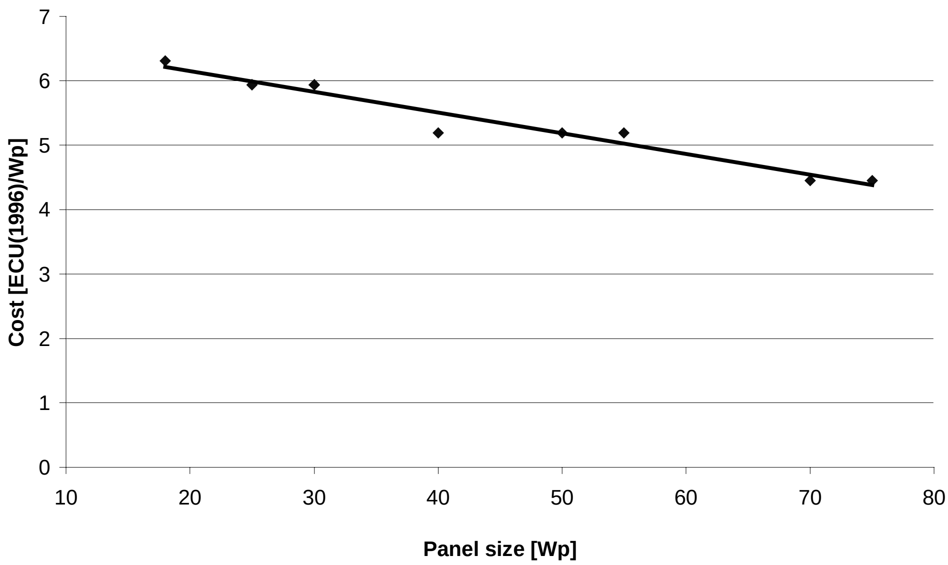


Figure 21: Initial PV panel costs in ECU_{1996}/W_p ([Helios-96])

The economy of scale in PV panel costs becomes apparent if different combinations of different panel sizes can be used to produce the required PV power. As a general rule, the designer will use the largest possible panel size. 350W, for example, can be made up of 7 panels of 50W_p for 1818 ECU_{1996} or 5 panels of 70W_p each for an overall 1558 ECU_{1996}. However, in some cases it might be more economic to consider a smaller panel size. For example, if a design was carried out for a certain site and the PV power requirement was calculated to be 6kW_p, then with a 48V nominal voltage bus and panel voltages of 12V, 120 panels of 50W_p are needed to meet the designed power requirement, amounting to 31.164 ECU_{1996}. Or alternatively 88 panels of 70W_p would be required, costing 31.995 ECU_{1996}, a difference of 831 ECU_{1996}. However, even though the costs would have increased for the system design using the 70Wp panel size, the installed kW_p would have been slightly increased namely to 6.16kW_p, higher than specified as required, but nevertheless available in case of slightly higher demand levels. As can be seen, design often involves considering the trade-offs of different possible design and cost solutions.

If PV panels with 24V nominal voltage are available on the market then the $70W_p$ panels would become cost-competitive to the $50W_p$ panel sizes in meeting the design requirement of $6kW_p$. Figure 22, Figure 23 illustrate for 12V and 24V PV panels that from a certain amount of required kW_p onwards, the most economic panel size to meet the power requirements is the largest available size with the highest possible panel voltage.

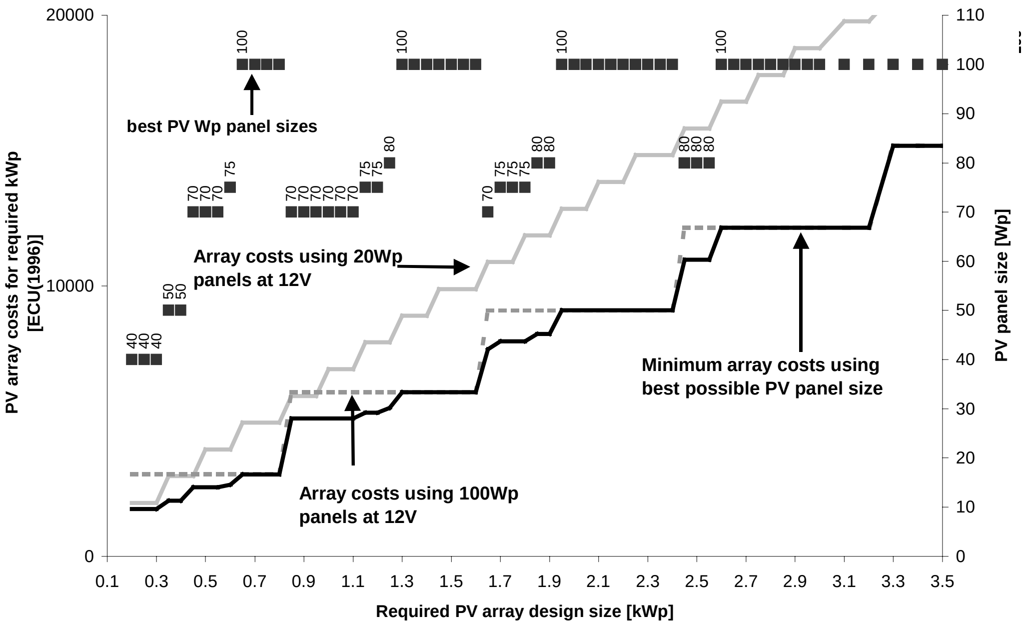


Figure 22: Best 12V PV panel size for lowest PV array costs

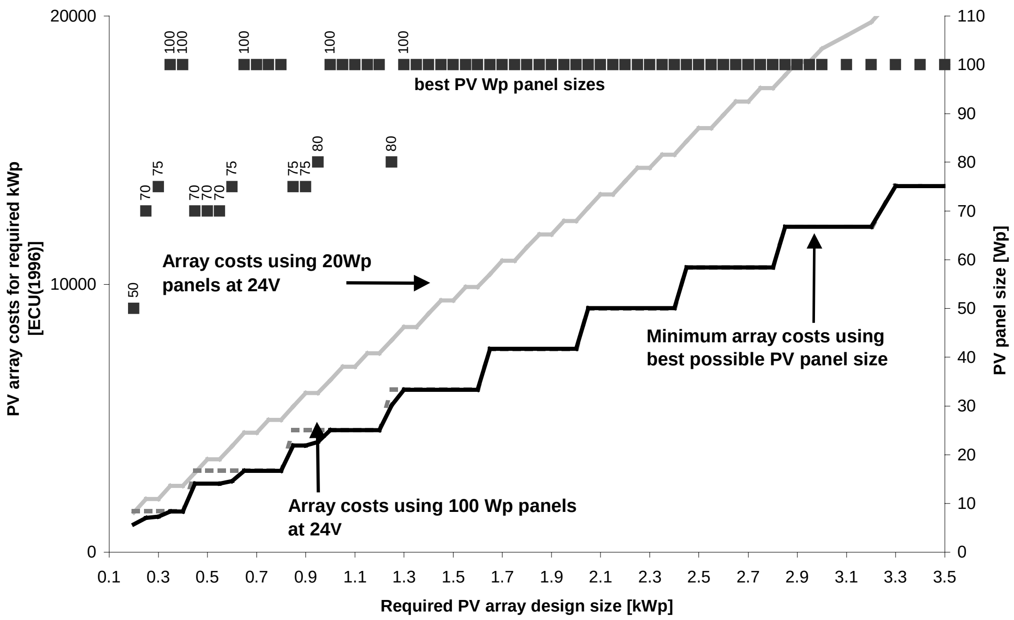


Figure 23: Best 24V PV panel size for lowest PV array costs

It can be seen that for PV power requirements of up to $2.6kW_p$, using 12V PV panels, the use of small PV panels (less than $100W_p$ or $75W_p$) can in some cases be more economical.

Using 24V PV panels, it is in some cases more economic to use small PV panels, in terms of W_p, for power requirements of up to $1.3kW_p$.

The prices per W_p vary with manufacturers and are also country-specific. Therefore Figure 21 gives only an indication of the price variations

The required number of panels to be installed in series in order to obtain the required nominal bus voltage is given as

$$n_{series,PV} = \frac{U_{DCbus,Nom}}{U_{PVpanel,Nom}}$$

Equation 14: Number of PV panels required in series connection

The number of PV panel strings required in parallel to produce the desired PV output energy, needs to be optimised. Some paper-based rule-of-thumb methods take the required system Ah current from the PV array, divided by the nominal PV panel current times the number of average sunshine hours to obtain this number. However, to obtain reliable design results the amount of energy desired from the PV array as percentage of overall system energy generation needs to be determined by a design or optimisation procedure such as the one presented in this thesis.

The values for installation costs, BOS costs and fixed costs can differ however, for different applications and projects. For example, [Davis,Horvei-95] indicate that the installation costs for PV systems ranged from 20% of PV array costs for a 400Wh/day domestic system and up to 55% to 67% of PV array costs for very small systems or very critical load systems. In some cases, the installation and BOS costs are added to the overall system equipment costs. In order to summarise all required equipment costs, namely PV, batteries and BOS parts, the installation costs would amount to 16% of capital costs for the domestic system, 30-35% for the small load systems, 20% for higher load systems, and 26% for the critical load system.

3.3.3 Wind turbine generator Initial costs of wind generators

The initial wind turbine generator costs vary profoundly (see Figure 24). This is partly due to the wide range of wind turbines designed for different applications and regions using diverse quality standards, materials, and production methods. Wind turbines require tower constructions and often difficult installation procedures. The costs of the tower and control equipment and the installation contribute a large percentage to the wind turbine capital costs. An advantage of wind turbines when compared to PV panels is that the nominal output voltages of the DC and AC wind turbines can often be adjusted to the corresponding bus voltages. Adding wind turbines is therefore achieved by connecting each additional turbine in parallel.

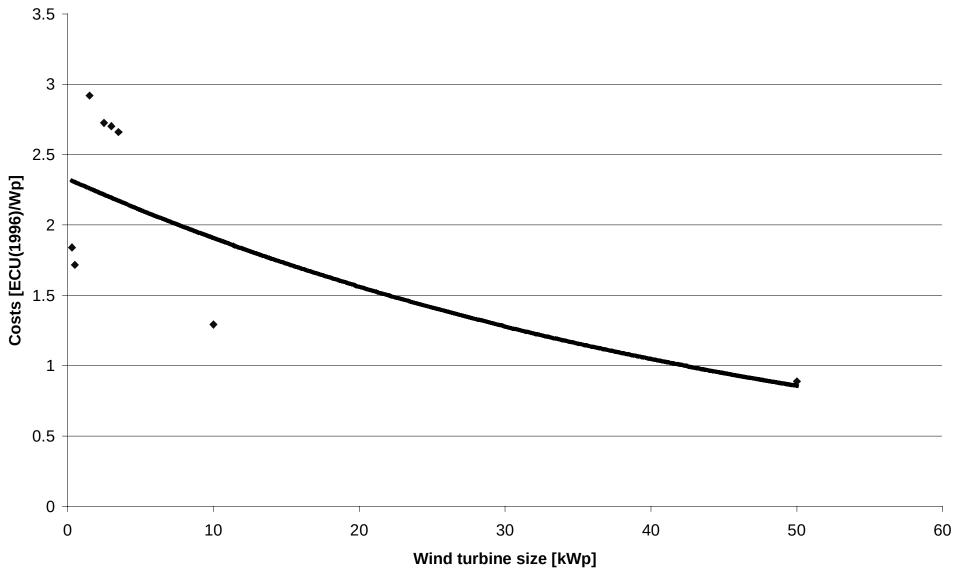


Figure 24: Wind turbine initial costs in ECU_{1996}/kWp

The balance-of-system costs are quite high for a wind turbine due to the tower and control equipment required. These costs are often expressed as a percentage of the wind turbine capital costs or the overall system equipment costs.

3.3.4 Initial costs of diesel generators

The diesel generator initial costs vary with size, model and design as can be seen in Figure 25.

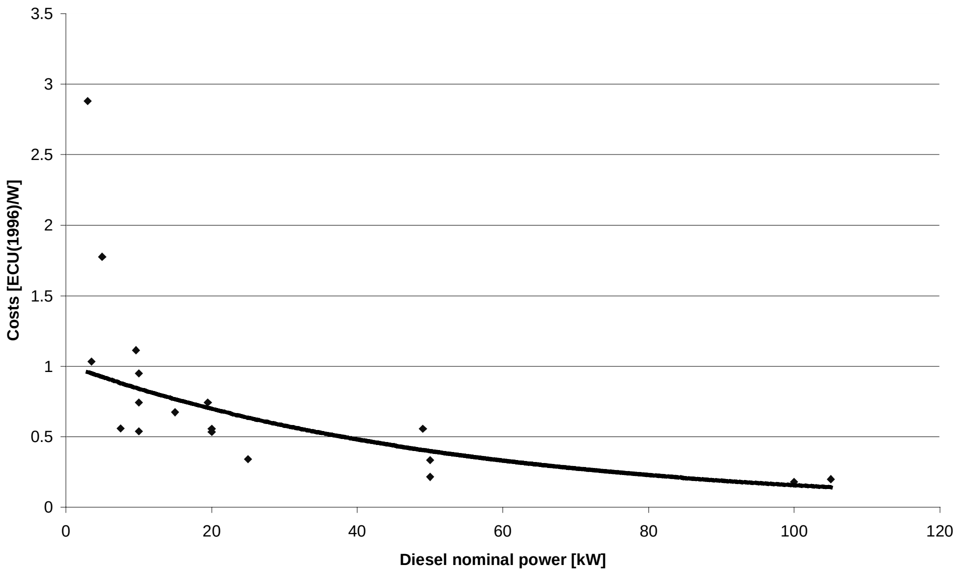


Figure 25: Diesel generator initial costs in ECU_{1996}/kW nominal capacity

Although diesel generators can come with AC or DC outputs, the AC diesel generator is the more common one. In general, the nominal output voltage will correspond with the bus voltage. Therefore each additional diesel generator can be connected to the system in parallel. Installation costs often include transport costs and intensive labour costs. A diesel generator will need a well-designed shelter with good ventilation. A tank is also needed to store the required fuel. These items can add to the installation and balance-of-system costs or are sometimes classified as fixed costs.

For the BOS costs and diesel generator installation costs as a percentage of diesel generator capital costs are given in Figure 26 and Figure 27 respectively [Davis, Horvei-95]. The share of labour costs in these expenditures is country-specific and might be higher for countries with higher labour costs.

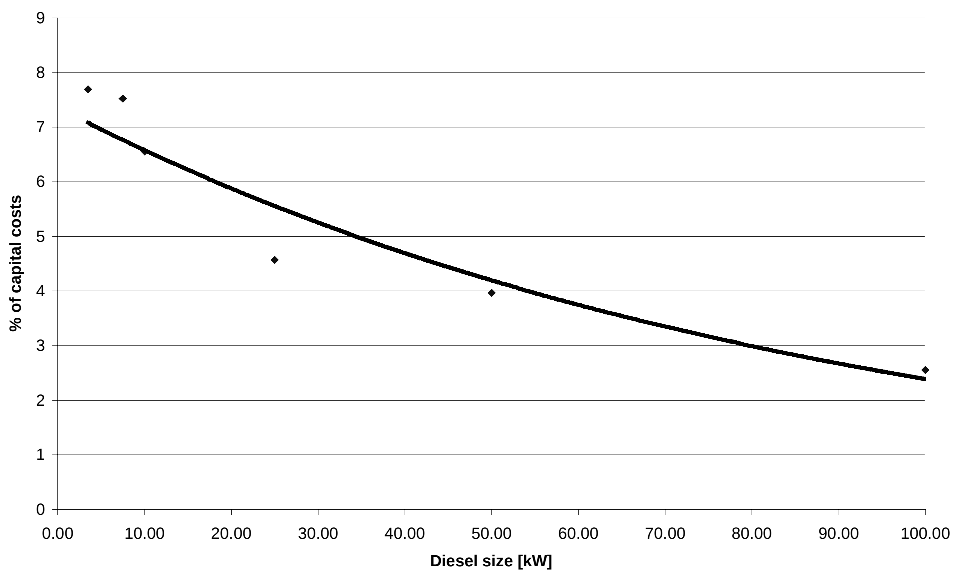


Figure 26: Diesel generator installation costs as percentage of diesel generator capital costs

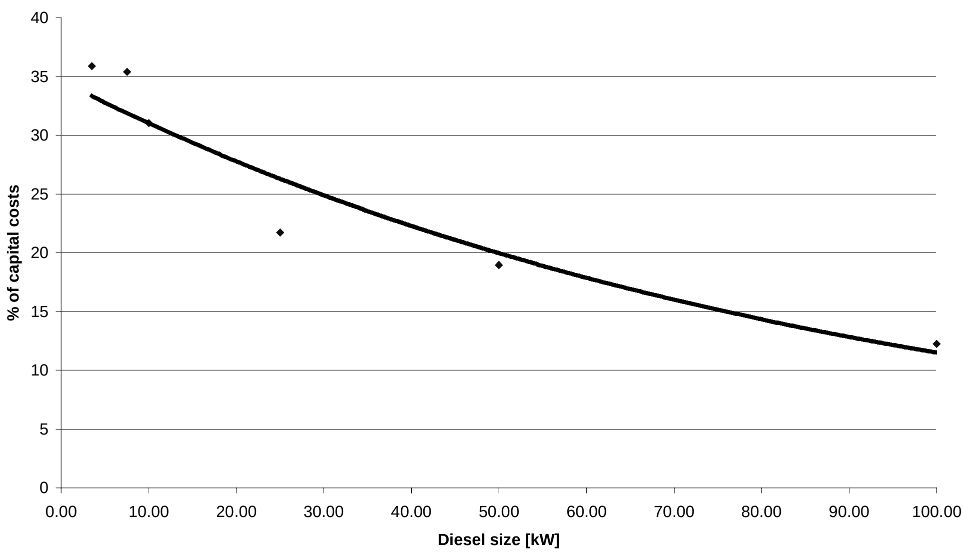


Figure 27: Diesel generator BOS costs as percentage of diesel generator capital costs

3.3.5 Initial costs of batteries

Various battery types exist, with different nominal voltage ratings. The most common ones in a hybrid system are the 2V cells with different Ah ratings. The initial costs of flat plate batteries are lower than those of tubular batteries, for example. However, flat plate batteries do not last as long as tubular batteries in terms of the estimated number of cycles during the battery's lifetime. Costs for lead-acid batteries are in most cases given as cost per Ampere hour rating with a rough estimate of around 0.56 ECU_{1996} per Ampere hour.

The batteries are connected in series to give the desired nominal DC operating voltage and are connected in parallel to yield a desired Ah system storage capacity. The batteries need a suitable battery shelter and a battery controller. The battery shelter can be accounted for in the fixed costs or the costs proportional to capital costs. Installation is often measured as a percentage of capital costs and the controller expense is often accounted for under BOS costs.

3.3.6 Balance of system (BOS) initial costs

The balance-of-system costs can include cost for components like system control, inverters, battery chargers, converters, wiring, etc and can in some cases be up to 30% - 35% of overall system investment costs.

3.3.7 Overall initial costing

The initial costs in the objective function description need to be determined carefully. Due to a variety of component types and cost figures and due to economies of scale, in general initial costs do not vary linearly with system size. Therefore already the initial system costing introduces non-linearity into the hybrid system design optimisation. As an example, in Figure 28 initial system costs have been calculated for different random system configurations each of whose components can adopt 4-5 different sizes. The systems are not optimised but only their initial costs are calculated as a means of an example. It needs to be noted that the initial costs are country-dependent and are likely to be less in South Africa than in Europe due to lower labor costs for installation and operation and lower manufacturing costs.

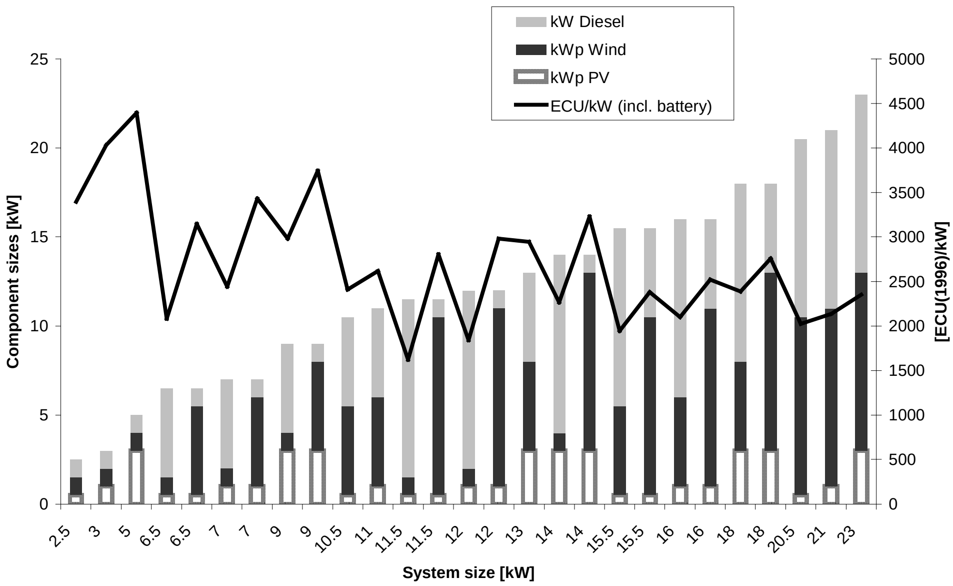


Figure 28: Initial costs of a PV/Wind/Diesel hybrid system versus system size in ECU_{1996}/kW

3.4 Hybrid system operation costs

3.4.1 General

The operation costs describe costs incurred after installation in order to run the system for a certain number of years, the so-called ‘project life’. The project life is an important parameter for system designers as it helps to benchmark different life cycle costs or net present value costs for different designs. The operation costs include expenses for fuel, maintenance, component overhaul and component replacement. As operation costs occur in the near and distant future and are only estimates, they are more difficult to determine than initial costs. It is also difficult to estimate component degradation as part of the replacement and maintenance costing. It is stated in the literature that the relationship of operation and component degradations has so far not been well understood.

In the developed model the predicted timing for maintenance, overhaul and replacements is based on the number of hours or operational cycles a component has been operating which is influenced by the system size and system operation.

Operation costs can be split into a number of contributing expenditures, mainly costs for maintenance, refuelling, component overhaul, component replacement, and administration. In many projects, a maintenance person is employed to look after a system or several systems. This person’s monthly salary or part of it will therefore occur in the maintenance costs. Often systems will need some kind of administrative support, and then monthly administrative costs will be included in the operation costs. The operation costs for either a component or the overall system can contain fixed costs and costs that are counted as a percentage of initial capital expenditure. Equation 15 summarises the different shares of operation costs.

$$OpCosts_i(\,year\ n\,) = no_{i,series} \cdot x_{i,parallel} \cdot$$
$$\begin{bmatrix} MaintenanceCosts_i(\,year\ n\,) + \%ofInitCostsOC_i(\,year\ n\,) + FixedOC_i\ (\,year\ n\,) + \\ + FuelCosts_i(\,year\ n\,) + HoursOn\_CyclingOC_i(\,year\ n\,) + Admin(\,year\ n\,) + \\ + ReplacementCosts(\,year\ n\,) + OverhaulCosts(\,year\ n\,) \end{bmatrix}$$

Equation 15: Operation costs in a hybrid system

As is implicitly reflected in Equation 15, component sizes impact on the operation costs. The operation costs are determined yearly or in any other suitable time interval and are then discounted for the project life. The annual operation costs are sometimes obtained differently for the different contributions. If a diesel generator is part of a hybrid system then the incurred fuel costs are summed up for a year and can then be easily discounted over the whole project life. Each occurrence of maintenance, overhaul and replacement of a component in every year during the project life is determined, costed and then discounted corresponding to the passed number of years from the beginning of the project.

Every contribution to the operation costs can have fixed costs such as transport or labour. For example, often maintenance costs per year are given as a percentage of the initial component or system capital costs (Equation 16).

$$MaintenanceCosts_i(\,year\ n\,) = FixedMaintCosts(\,year\ n\,) + \%ofInitCosts(\,year\ n\,) + \\ + CostHoursComponentOn(\,year\ n\,)$$

Equation 16: Maintenance cost components

In some cases, a certain estimated percentage of cost is added to the overall operation costs, for example 10% may account for oil costs, transport and labour [Morris-94]. The overall operation costs incurred over a project life are then given by Equation 17.

$$OperationCosts = \sum_{\forall i\ components} OpCosts_i + \%of_2 \cdot (\sum_{\forall i\ components} OpCosts_i)$$

Equation 17: Added operation cost margin

The following sections will describe operating costs of individual components.

3.4.2 PV operation costs

PV maintenance costs are often collected in monthly payments. These payments can cover system inspection by a maintenance person. The PV panels are in many cases assumed to have a lifetime of 20 years. So in this case, if a project life of up to 20 years is chosen, no PV panel replacement costs occur. Some of the factors influencing operating costs are reduced panel lifetimes (due to vandalism, corrosion, etc) and reduced panel output power (due to dusty panel surfaces, corrosion, shading by trees etc). Monthly maintenance costs in South Africa can range from 0.93 ECU_{1996} (SHS [Hochmuth-96]) – 27.8 ECU_{1996} per month (clinic, school systems) or more depending on system sizes [Davis,Horvei-95]. Some maintenance costs can be assumed to increase with the PV array size.

3.4.3 Wind turbine operation costs

Wind turbine operating costs comprise maintenance and replacement costs. The wind turbine life is often assumed to be more than 20 years, therefore in many life cycle costings no wind turbine replacement will take place. Maintenance is carried out after a certain amount of run time. Some larger wind turbines are inspected every 6 months. Maintenance costs for wind turbines can vary depending on the application, type of maintenance and wind turbine sizes. For smaller wind turbine sizes, they can sometimes be assumed to be roughly in the range of PV maintenance costs.

3.4.4 Diesel generator operation costs

The diesel generator operating costs comprise fuel costs, and maintenance, overhaul and replacement costs. The fuel costs occur whenever the fuel storage tanks are refilled. Overhaul is assumed half way through the diesel lifetime. Replacement occurs after a certain number of diesel generators run time hours. The effective lifetime of a diesel generator is defined by the time until a mechanical overhaul becomes uneconomic (i.e. when overhaul costs exceed 60% of the replacement costs). Factors that affect lifetime include the quality and regularity of maintenance, the average capacity factor and the number of start-ups. An air-cooled machine is likely to have a shorter life than a water-cooled unit that can keep the operating temperature down. Maintenance costs include a lube service around every 250 hours, an oil change and a tune-up every 500 hours, and a decoke service every 2000 hours. Maintenance costs depend partly on the diesel generator size. Figure 29 depicts a maintenance estimate per 500 hours of maintenance intervals, into which all other maintenance services have been averaged, for different diesel sizes.

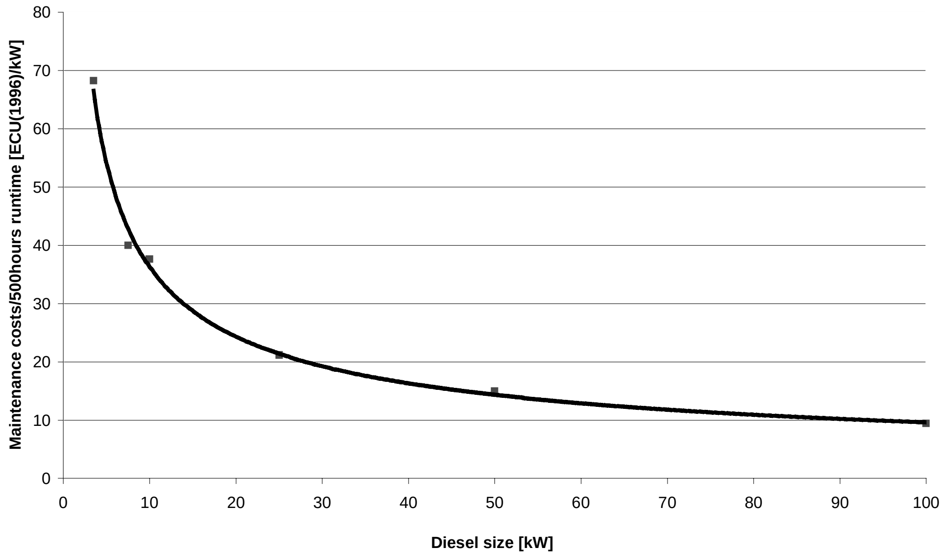


Figure 29: Diesel generator maintenance costs in ECU_{1996} per kW of nominal capacity and per 500 hours

The lifetime of a diesel varies between roughly 20.000 hours to 40.000 hours of run time. On average 30.000 hours can be assumed. Sometimes the total hours of run time are assumed to increase with larger diesel sizes [Davis,Horvei-95]. Some studies suggest that the diesel generator lifetime decreases with increased number of diesel generator cold starts, other findings suggest that this might not have a strong impact.

The diesel fuel consumption varies according to generator size and loading factor (Figure 17), and is non-linear.

3.4.5 Battery operation costs

Battery operation costs comprise expenses for maintenance and replacement. Maintenance includes checking the battery electrolyte levels, [Purcell-91]. Battery maintenance costs are often included in maintenance costs of the overall system or individual electricity generators.

Battery lifetime is rated on the basis of the charge-discharge cycles obtained during laboratory bench tests [Purcell-91]. Most conventions specify cycle life as the number of cycles a battery attains at the specified DoD before its capacity is reduced by wear and ageing to 80% of the rated value. Some manufactures, however, specify cycle life as the number of cycles to 50% loss of capacity. A typical battery life cycle curve is shown in Figure 30 as function of the average DoD assumed during system operation.

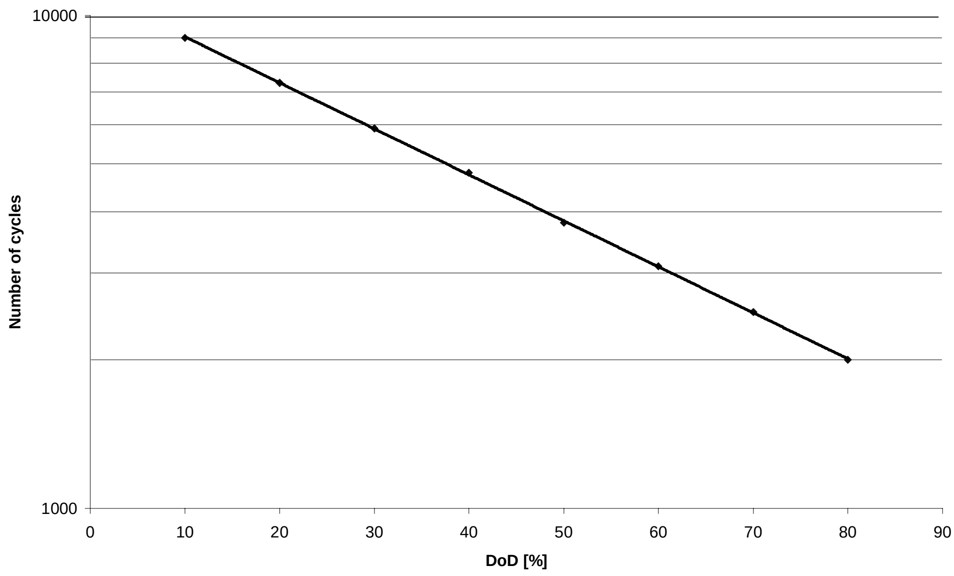


Figure 30: Typical diagram on number of battery full cycles during battery life time versus depth of discharge [Purcell-91]

Battery cycle life as a function of depth of cycling is most often portrayed as a straight line on a semi-logarithmic graph [Purcell-91]. Curves for various lead-acid types tend to conform to this assumption, as is shown in Figure 31 taken from [Barley et al-95]. The cycle life also depends on temperature (Figure 32).

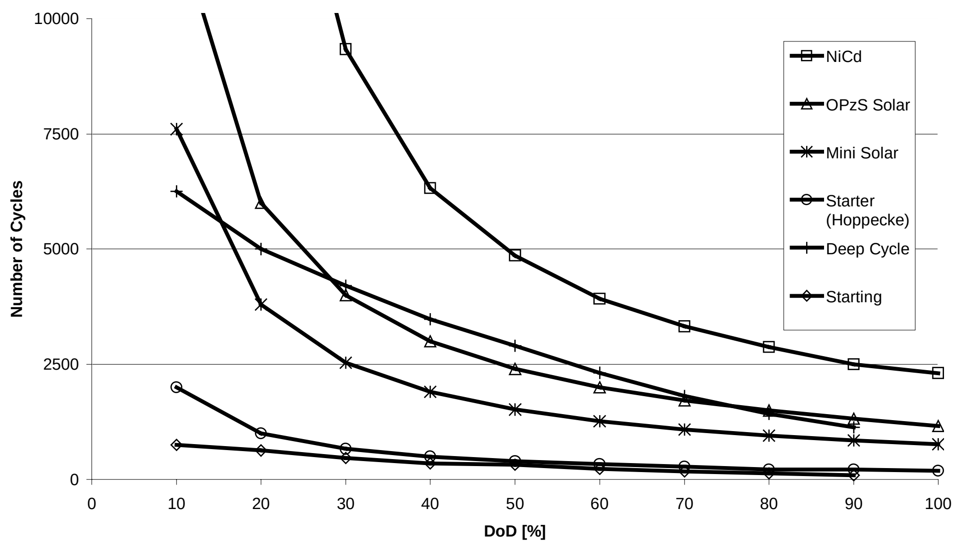


Figure 31: Number of full cycles versus depth of discharge for various battery types [Purcell-91]

The actual battery life may be longer or shorter than the laboratory tests due to operation conditions, which cannot be modelled with the laboratory test conditions. In laboratory tests the battery is usually operated for the whole of its lifetime such that it is fully charged and then fully discharged. During real system operations, batteries are to a large extent partially cycled.

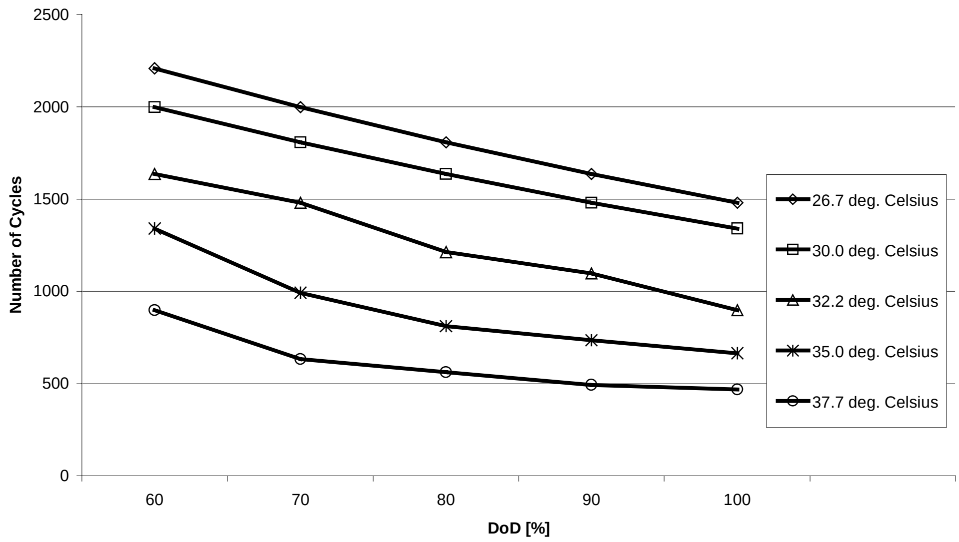


Figure 32: Effect of temperature on number of full battery cycles at a certain DoD [Purcell-91]

^{o}C It is difficult to account for the wear in partial cycling. [Purcell-91], describes that the incremental wear from partial cycling between DoD_1 and DoD_2 can be modelled as

$$\Delta W = \frac{(\frac{1}{L_{DoD,1}} + \frac{1}{L_{DoD,2}})}{2}$$

Equation 18: Estimate of wear in partial cycling

where $L_{dod,i}$ is the expected cycles life at a certain DoD. This approach accounts for both cycling wear and a penalty for partial SOC operation, though the weighting seems to be arbitrary [Purcell-91].

In general, estimating battery lifetime according to its operation is difficult. Some approaches attempt to construct the number of full battery cycles by adding the energy cycled during partial battery cycles. Here it is useful that on average the energy that can be taken out of the battery during its lifetime is almost constant and independent of the depth of discharge between 20% and 80% DoD. This can be seen in Figure 33 which shows the number of full energy cycles versus the depth of discharge.

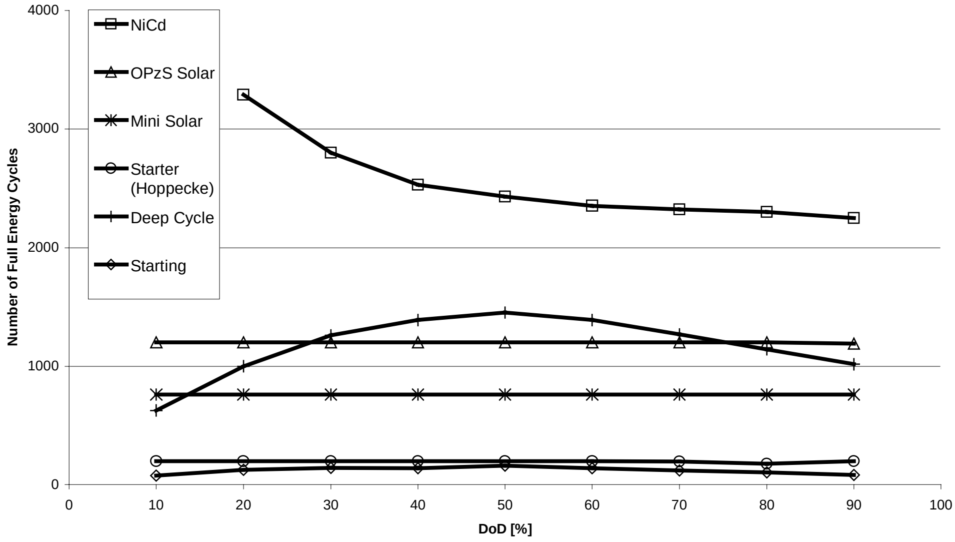


Figure 33: Full cycles of energy versus battery depth of discharge [Purcell-91]

Therefore the amount of Ah or Wh that can be stored and taken out of a battery during its lifetime is obtained by multiplying the averaged full cycles of energy with the nominal battery capacity rated in Ah or Wh (Equation 19).

$$Ah_{BatteryLife} = C_{nom} \cdot \overline{\sum_{i=20\%}^{80\%} DoD(i) \cdot NoCycles(i)}$$

Equation 19: Average battery energy that can be taken out during its lifetime

The advantage is that this expression is nearly independent of the system depth of discharge. This is useful as many different depths of discharge are encountered in hybrid system operation. However, the effect of partial cycling on the amount of energy that can be taken out during the battery's lifetime is not explicitly addressed.

If the discharge taken out of the battery over a year is equal or less than the charge put into the battery, then the battery life time in years is obtained as

$$BatteryLifeInYears = \frac{Ah_{BatteryLife}}{\sum_{1\ year} I_{discharge}(t) \cdot \quad t}$$

Equation 20: Battery life in years

Equation 20 calculates the number of times the required yearly discharge can be obtained out of the estimated energy available from the battery.

To ease the following calculations an abbreviation for the discharge and charge taken out of a battery over a year is introduced in Equation 21.

$$Discharge = \sum_{1\ year} I_{discharge}(t) \cdot \quad t$$

$$Charge = \sum_{1\ year} I_{charge}(t) \cdot \quad _{Bat,Charge}(t) \cdot \quad t$$

Equation 21: Charge and discharge during one year of battery operation

If the discharge taken out of the battery during a year of system operation is greater than the charge put into the battery, then this level of discharge can only be sustained for the number of years given by $BatteryLifeInYears_{Dh \geq Ch}$ in Equation 22. The calculation of $BatteryLifeInYears_{Dh \geq Ch}$ derives from the fact that the system design is based on unchanged PV, wind, and diesel energy contributions and unchanged demand requirements in following years. Therefore the system with its specified sizing and operation strategy relies on the yearly amount of battery discharge $\Sigma I_{Discharge}(t) \cdot \Delta t$. Otherwise the demand will not be met as it was in the initial year, and therefore the system reliability measure will be lower. Or the life cycle costing will change because more energy from other resources needs to be made available.

$$BatteryLifeInYears_{Dh \geq Ch} = \frac{SOC(t_0) - SOC_{\min}}{\sum_{1year} I_{Discharge}(t) \cdot \Delta t - \sum_{1year} I_{Charge}(t) \cdot \eta_{Bat,Charge}(t) \cdot \Delta t}$$

Equation 22: Battery life in years, if discharge greater than charge in one year and if battery not empty at beginning of year

Therefore Equation 22 equals number of years in which the full required discharges at the level $\Sigma I_{Discharge}(t) \cdot \Delta t$ are possible. Theoretically the battery needs to be replaced after $BatteryLifeInYears_{Dh \geq Ch}$, in order to cover the demand as in previous years, because the PV, wind, diesel resources will not be enough to cover it in a system design that was based on discharging the battery to this level. That means if Equation 20 and Equation 22 are implemented in an optimisation simulation, the resulting costs will be very high, and the corresponding solution might be a very bad one and will be thrown out when iterating the developed algorithm.

If the battery is not replaced in year $BatteryLifeInYears_{Dh \geq Ch}$, and the system energy sources and demand requirements stay the same, then the battery will last $BatteryLifeInYears_{Dh \geq Ch,Unreplaced}$, with the effect, however, that demand will be increasingly less met.

The year after BatteryLifeInYearsDh≥Ch the battery can only deliver part of the required discharge, namely

$$\begin{aligned} Discharge_{InBetween} &= [(BatteryLifeInYears_{Dh \geq Ch} - \lfloor BatteryLifeInYears_{Dh \geq Ch} \rfloor) \\ &\cdot (Discharge - Charge)] + Charge \end{aligned}$$

Equation 23: Discharge during the year in which the yearly discharge level cannot be met

After this, the battery discharges to the amount that it has been charged with as is described in Equation 24.

$$\begin{aligned} Discharge_{AfterThat} &= \sum_{1year} I_{Charge}(t) \cdot \quad _{Bat,Charge}(t) \cdot \quad t \\ &= Charge \end{aligned}$$

Equation 24: Discharge determined by charge levels

The overall discharge during the battery's lifetime will therefore be as given in Equation 25.

$$OverallDischargeDuringBatLife = BatteryLifeInYears_{Dh \geq Ch} \cdot Discharge +$$
$$+ Discharge_{InBetween} + y \cdot Discharge_{AfterThat}$$

Equation 25: Overall discharge during the battery life

Whereby y, the number of years the battery is discharged at its charging level before its lifetime ends, is determined by computing how many intervals it takes until the battery is depleted (Equation 26).

$$y = \frac{Ah_{BatteryLife} - (BatteryLifeInYears_{Dh \geq Ch} \cdot Discharge + Discharge_{InBetween})}{Charge}$$

Equation 26: Number of years discharge equals the charge level

Therefore in the case of continuing to use the battery in the hybrid system after $\text{BatteryLifeInYears}_{Dh \geq Ch}$ years, demand will not be satisfactorily met and replacement occurs after $\text{BatteryLifeInYear}_{Dh \geq Ch,Unreplaced}$ years (Equation 27).

$$BatteryLifeInYears_{Dh > Ch,Unreplaced} = BatteryLifeInYears_{Dh \geq Ch} + 1 + y$$

Equation 27: Battery lifetime in number of years if the yearly discharge is greater than the yearly charge and battery is used until its average available energy is used up

In case a shorter time horizon than one year is chosen in equations Equation 22 - Equation 27, say one winter month, adjustments can be made to account for increased charging during the summer months or when running the diesel generator a few extra times to charge the batteries

In [Piller-97], [Piller et al-97] it is attempted to trace the battery degradation in detail through attempting to describe the impacts of battery operation on degradation with fuzzy intervals and then superimposing the different fuzzyfied degradation contributions according to a collection of rules derived from collected battery operation experiences. Other models use a $/kWh cost description for energy taken out of the battery during system simulation and so avoiding the charge-discharge ratio problem.

3.4.6 Balance of system operation costs

Other operating costs such as tear and wear and replacement of inverter, battery chargers, controllers and other BOS parts should be taken into account as well. Some designers calculated hourly costs of these components based on the invested component costs. Others include these expenditures as fixed or proportional costs in the component costing or overall system costing.

3.4.7 Overall life cycle costs

The hybrid system operation costs are in general non-linear. As they depend on future operations, they can only be estimated roughly. The operation costs depend largely on component size and type, and the way the system is operated.

In order to demonstrate the high level of non-linearity of operation costs in general, which make an optimisation algorithm necessary, and the unwieldiness of spreadsheet methods, a few examples of overall life cycle costing of hybrid systems using specially created spreadsheet calculations are presented in Figure 34 and Figure 35. Thereby, operation costs had to be expressed through fitted equations that were specifically developed for that purpose. However, using the fitted equations does not give accurate operation costs for a component, as the fit might have been very bad for a particular component, or not all available component type are included making the estimated fit unreliable. Figure 34 and Figure 35 clearly show the impacts of non-linear initial and operation costs, which result in non-linear objective function (i.e. life cycle costing) shapes. The life cycle costs and estimated energy supply were calculated for nearly hundred different hybrid system component combinations based on three differently sized PV arrays, and four differently sized wind turbines and diesel generator. The example spreadsheet calculations were done for two sites, one site with very high renewable energy resources and therefore the diesel runtime was set low (Figure 34), and one site with average renewable energy resources and therefore a higher diesel runtime (Figure 35). The required battery storage was estimated based on these combined component sizes.

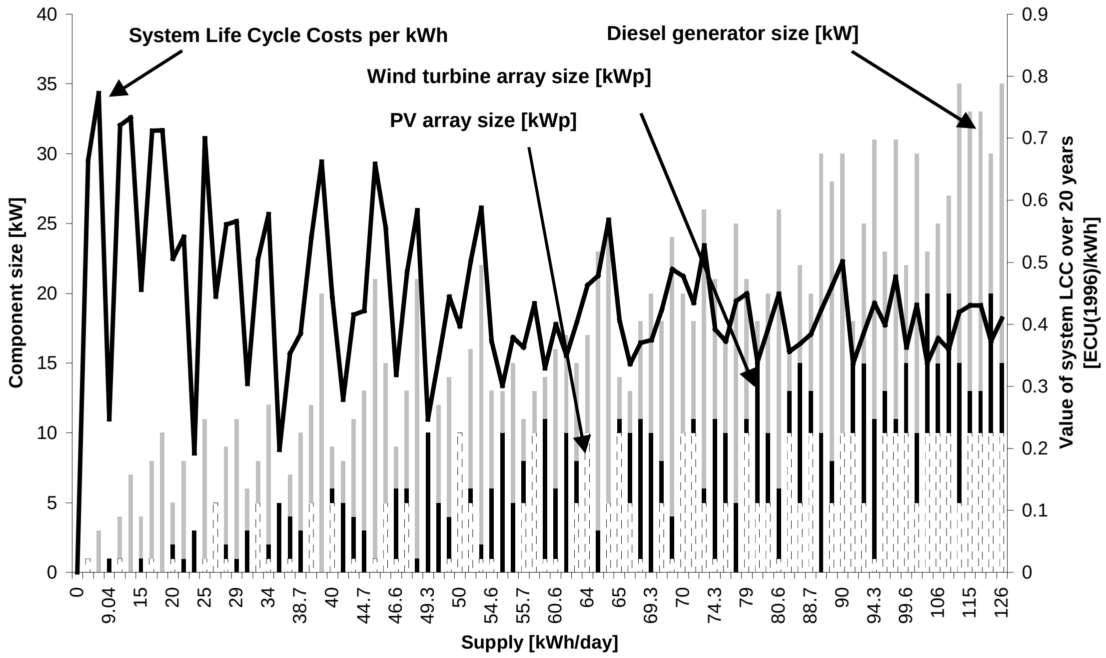


Figure 34: Life cycle costs of single source and hybrid systems, with an average diesel generator runtime of 2 hrs/day and high renewable energy resources (6 average sunshine hours per day, average wind speed 6m/s), average diesel capacity factor is 100%

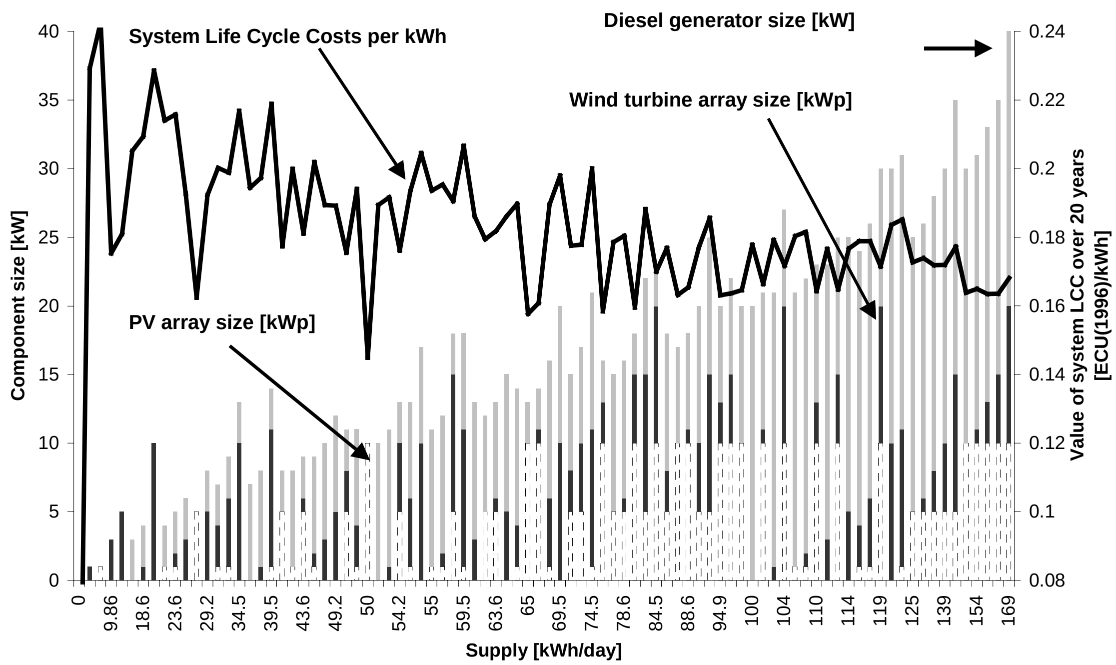


Figure 35: Life cycle costs of single source and hybrid systems, with an average diesel generator runtime of 5 hrs/day and low renewable energy resources (5 average sunshine hours per day, average wind speed 4m/s), average diesel capacity factor is 100%

The shortcomings of such spreadsheet methods are clearly highlighted through these examples:

- the spreadsheet calculations involve a large number of cell calculations, that can become difficult to track
- the different scenarios are calculated using weather and demand data for only one typical average day
- fixed estimates of diesel generator runtime hours per day are necessary
- the lifetime of the battery can only be estimated but not be made dependent on actual operation
- only an extremely limited number of combinations of weather conditions, component sizes, daily generator runtimes and average capacity factors can be analysed in the spreadsheet model due to the complexity involved in tracking calculations.

It can be seen that a computer-based optimisation algorithm is necessary to sufficiently investigate different sizing and operation design choices for a required energy supply. In the developed algorithm, a computer program carries out all the required iterative tasks and the component costs and their associated operation and maintenance costs are entered for each component specifically instead of using fitted equations. Thereby a component database is built up with specific characteristics for operation and costing of each entered component.

3.5 Quantification of benefits

A benefit can be defined in a number of different ways. It can range from purely technical quantification such as reliability of electricity supply, to detailed socio-economic descriptions such as how the introduction of electricity improves the degree of education and overall living standard.

Benefits in this design work are quantified as the percentage of demand covered by the electricity generated from the hybrid system. The benefits are an important tool enabling the evaluation of the trade-off between lowest cost against highest benefit designs [Marrison,Seeling-Hochmuth-97]. In this regard over-sizing a system ensures a low probability of loss-of-power but causes an excessive capital cost, while under-sizing a system minimises the capital cost but causes frequent loss-of-power. By quantifying benefits for the given application, it is possible to match the benefit of reliable power with the cost of avoiding a loss and thereby find the optimal design for each application.

As with costs, the total benefit can be defined in terms of a net present value

$$NPVBenefits = \sum_{i}^{NOofBenefitTypes} Discounted\ Benefit_i$$

Equation 28: Net Present Value of Benefits

$$Discounted \quad Benefit_i = \sum_{year\ n}^{ProjectLife} \frac{Benefit_i(n)}{(1+r)^n}$$

Equation 29: Discounting benefits

For commercial applications, such as telecommunications relay stations, or a refrigeration plant, the financial benefit of powering the application can be obtained by considering the resulting operating revenue. Similarly, loss of benefit caused by system failures can be quantified in terms of lost revenue, damage caused, or the cost of making alternative arrangements. In this case, an event in the simulation causing a loss-of-power will generate a change in cash flow in the NPV as given by Equation 10.

More complex functions can also be implemented. The loss of power at one time step, for example, may reduce revenues at all other time steps because an unreliable service is less valuable.

The benefits in domestic or non-revenue generating applications are more difficult to quantify. The reliability of the electricity supply for a domestic application and its value to the user cannot in most cases be measured in terms of revenues lost and costs incurred due to power losses.

One way to obtain a measure of supply reliability can be to introduce a weight in the cost function that is inversely proportional to the level of supply reliability. Therefore low reliability would have a high weight factor resulting in high costs and high reliability would have a low weight factor resulting in low costs. This weight function is often called “penalty function”, as it penalises undesirable outcomes and unmet conditions, such as constraints placed on the system, with high costs.

Figure 36 and Figure 37 show how the penalty function works for the two previously discussed spreadsheet examples (Figure 34 and Figure 35). The system configurations are displayed along the kWh supplied. In Figure 36 the average diesel generator runtime per day is much lower while the renewable energy sources are higher than in Figure 37. Therefore the same system is supplying different levels of kWh/day in Figure 36 and Figure 37. Assuming a daily design demand requirement of 40kWh/day for both examples, the penalty function has a very high value for every system that cannot supply at least 40kWh/day. The value of the penalty weight is often chosen very high as Figure 36 and Figure 37 in to ensure that only systems with satisfactory performance are selected for the optimisation process. When adding this penalty value to the life cycle costs of various systems representing numerous levels of supply, a design estimate can be obtained through minimisation of the combined penalty and life cycle cost function as shown in Figure 38 (see also next section). The penalty value is very high for system layouts that cannot cover the load, rendering these systems undesirable. It drops to zero as soon as the systems are covering the load, thereby leaving the life cycle costs of the system as the pure measure of design performance.

Again the drawbacks of using spreadsheet methods can be easily identified. In order to truly optimise the system design for a given demand requirement, it is necessary to analyse many more combinations of component sizes and operating possibilities, especially around the supply level that matches the demand requirement. This can only be achieved through simulations given the amount of combinations that can produce supply levels that match the required design demand, and therefore the amount of iterations involved.

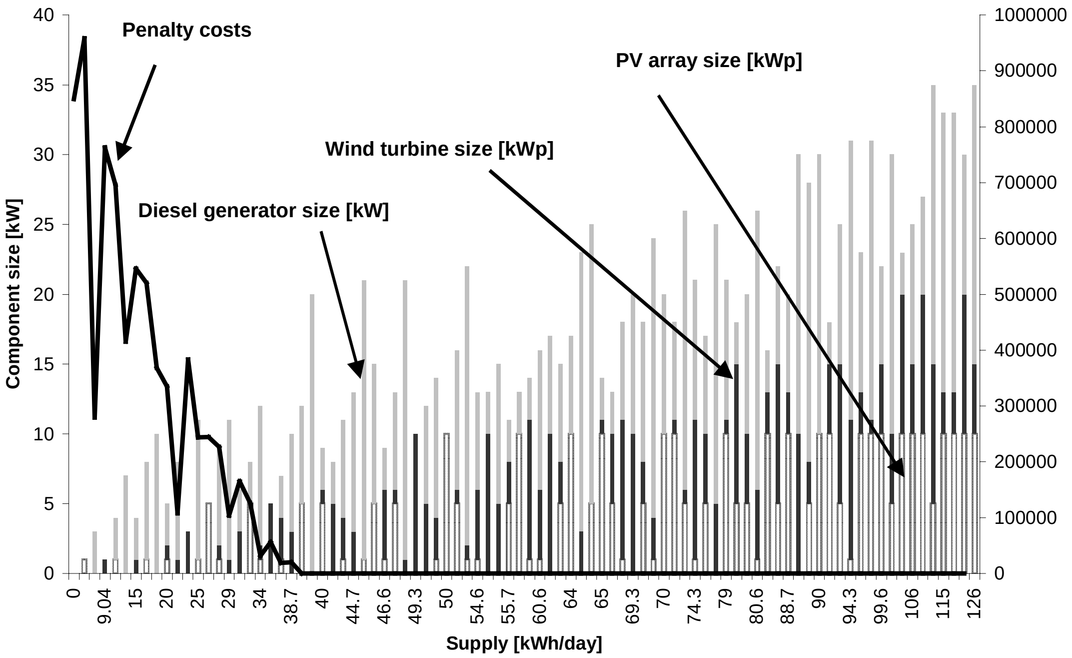


Figure 36: Penalty function for single source and hybrid systems, with an average diesel generator runtime of 2hrs/day and high renewable energy resources (6 average sunshine hours per day, average wind speed 6m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

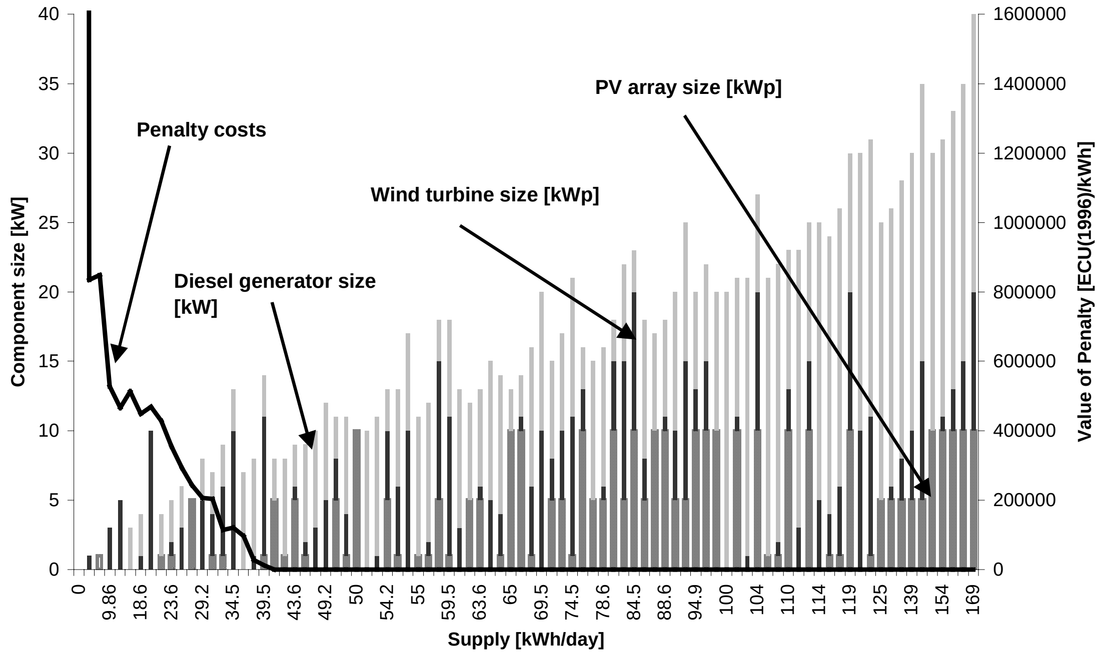


Figure 37: Penalty function for single source and hybrid systems, with an average diesel generator runtime of 5hrs/day and low renewable energy resources (5 average sunshine hours per day, average wind speed 4m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

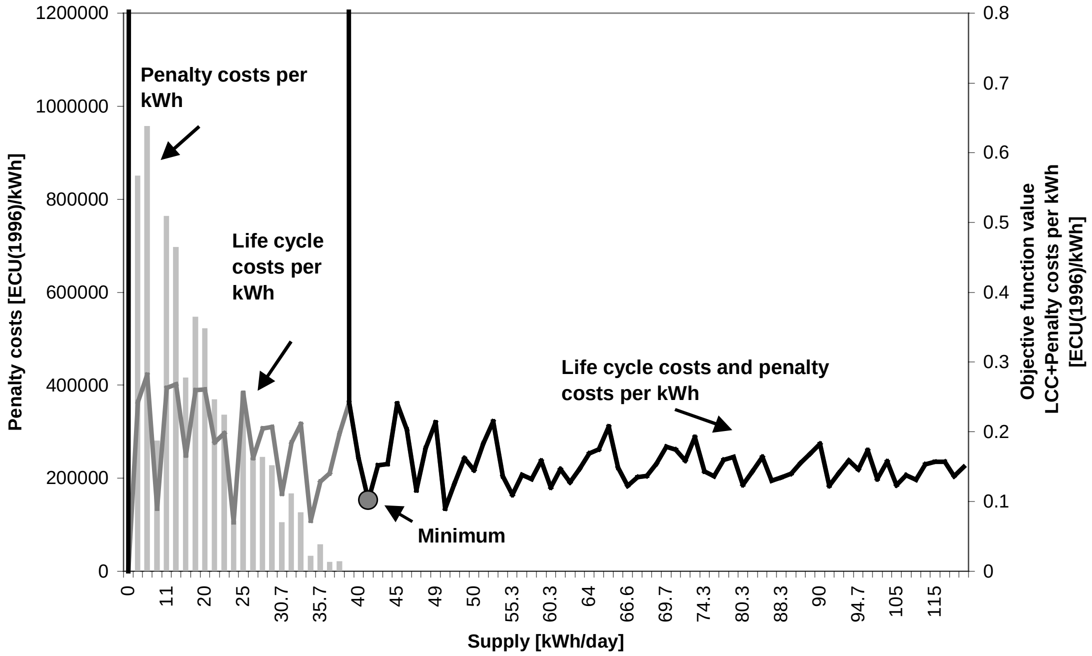


Figure 38: Penalty function scenario

In general, the penalty approach gives easily obtainable thresholds on the desirability of a design. However, it cannot readily be fine-tuned to account for more complex factors in the design, such as what the electricity is worth to a user, the environment, or the living standard of a community. These factors can be better accommodated in a more complex benefit analysis.

The benefit formulation is derived as follows. The marginal benefit of supplying power decreases as the supply increases because the initial supply is used for the most important services (e.g., lighting) and further supply is used for services that could also be supplied from using other sources (e.g., heating).

According to [Marrison,Seeling-Hochmuth-97], the marginal benefit of reliable supply can be approximated by Equation 30.

$$MarginalBenefit(t)_{Reliable} = BenefitperUnit \cdot Demand(t) \cdot \left(\frac{Supply(t)}{Demand\ (t)}\right)^{-W1}$$

Equation 30: Marginal benefit of meeting demand reliably

where BenefitperUnit is the marginal benefit per kWh supplied to the demand Demand(t). The variable BenefitperUnit can account purely for the technical reliability or also for the socio-economic worth of supplying a given demand. W_1 is a weight between zero and one. The total benefit of supply is the integral of Equation 30:

$$Benefit(t)_{Reliable} = BenefitperUnit \cdot Supply(t) \cdot \frac{1}{-W1} \cdot \left(\frac{Supply(t)}{Demand(t)}\right)^{-W1}$$

Equation 31: Benefit of reliable supply

Equation 31 quantifies the benefit derived from a reliable supply. If there is the possibility of a loss of power this benefit will be reduced due to the unmet demand or the inconvenience in using back-up sources. In the case of a gray-out, i.e., a supply less than demand, the following form can be considered

$$Benefit(t) = Benefit(t)_{Reliable} \cdot \left(\min\left[1, \frac{Supply(t)}{Demand(t)}\right]\right)^{W2}$$

Equation 32: Overall benefit formulation

W_2 is a weight greater than zero and dictates the seriousness of a power loss. The minimum formulation in Equation 32 guarantees that the oversupply of electricity will not be counted as a benefit.

A power loss can be annoying or catastrophic depending on the application. For some applications such as irrigation the hourly reliability is not important and the weight W_2 will be close to zero. For sensitive applications, such as a hospital, any power loss will be serious and W_2 will be large.

Figure 39 and Figure 40 clarify how the concept of benefit works. The figures show again the two case scenarios of Figure 36 and Figure 37, this time using benefit functions with different values for W_1 and W_2. Again, there are different average diesel generator runtimes per day and different weather conditions, but the same design demand requirement is assumed. It can be seen that the shape of the benefit function depends highly on the values of W_1 and W_2. The value of the benefit function is highest or stays the highest, depending on whether the system can supply the required demand level. In this example this is 40kWh/day.

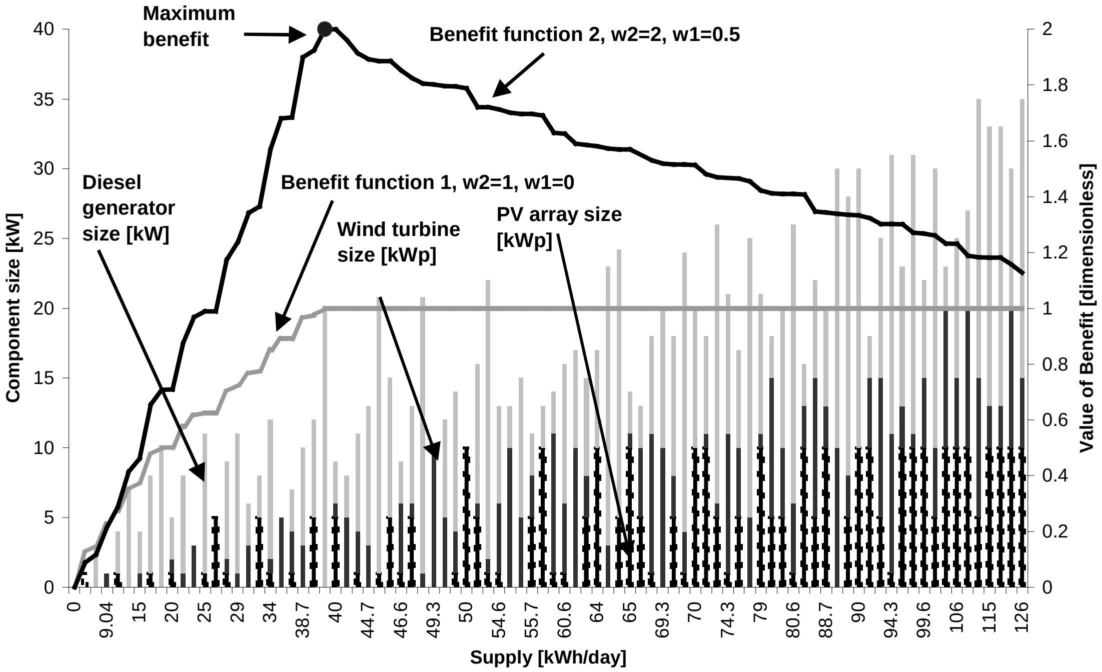


Figure 39: Benefit functions with different values for w_1 and w_2, for single source and hybrid systems, with an average diesel generator runtime of 2 hrs/day and high renewable energy resources (6 average sunshine hours per day, average wind speed 6m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

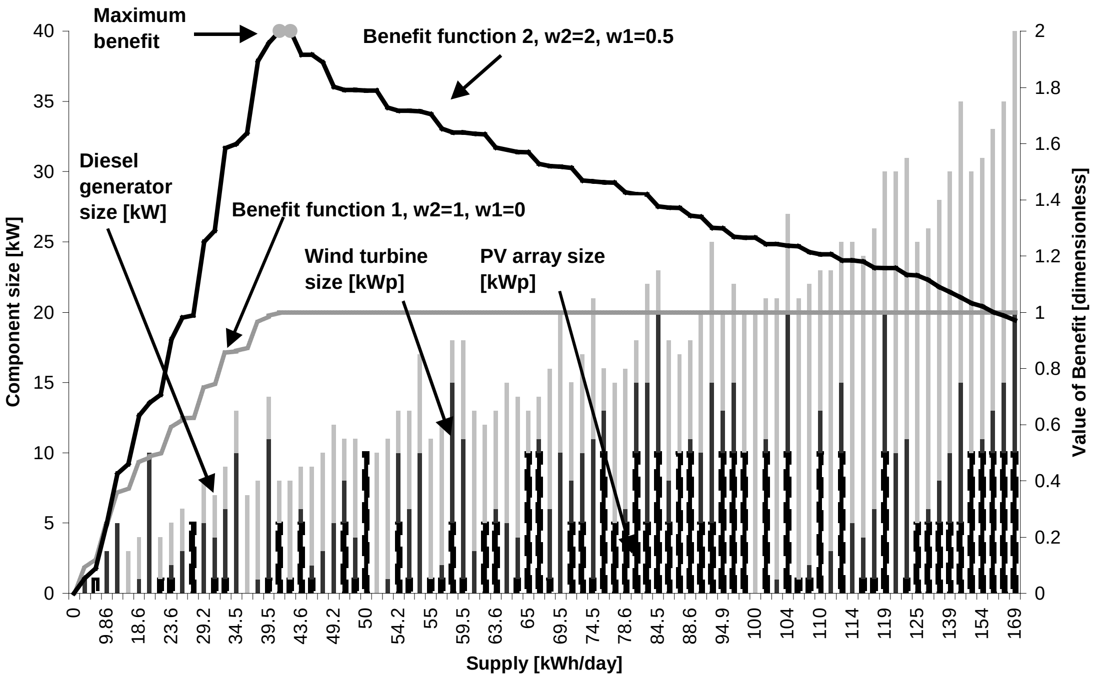


Figure 40: Benefit functions with different values for w_1 and w_2, for single source and hybrid systems, with an average diesel generator runtime of 5 hrs/day and low renewable energy resources (5 average sunshine hours per day, average wind speed 4m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

If the life cycle cost / benefit ratio is formed, the minimum of this function can indicate a recommendable system design (see also next section). Figure 41 and Figure 42 show such estimated design results for the examples depicted in Figure 39 and Figure 40, using benefit functions shaped by the values of 0.5 and 2 for W_1 and W_2 respectively. The design recommended in Figure 41 does not meet the demand requirements, whereas in Figure 42 it does. As can be seen the benefit function can be fine-tuned to potentially accommodate different conflicting needs in the design. For example, the benefit function could recommend a system that was under-sized as in Figure 41, not meeting the required demand, if another factor than meeting the load was more important.

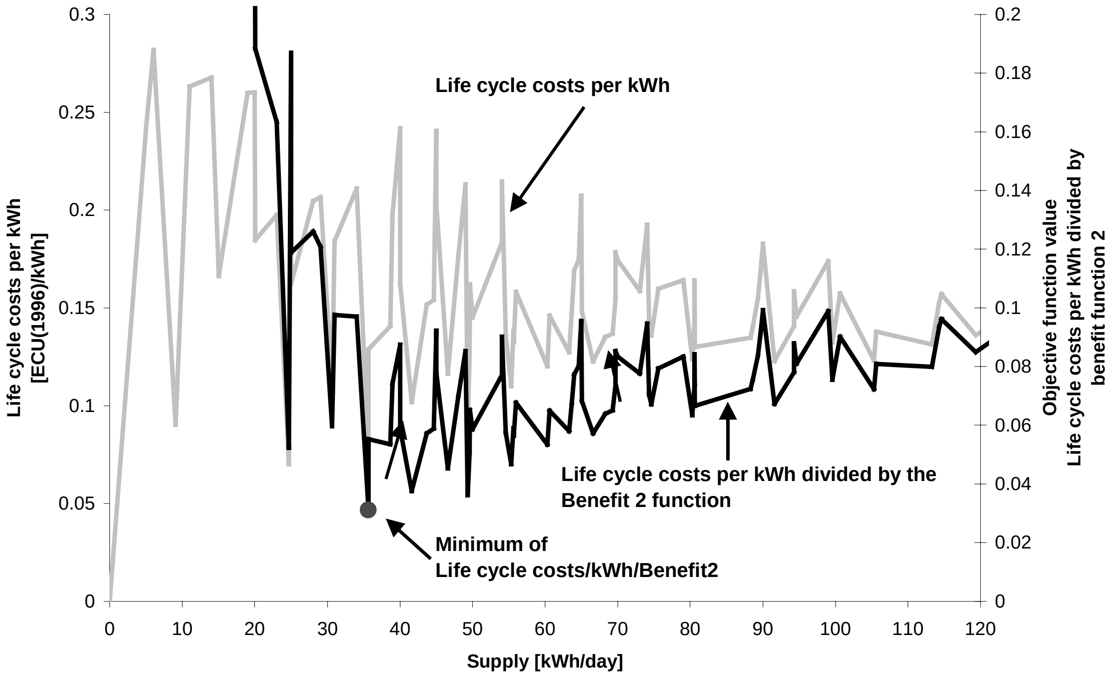


Figure 41: Life cycle cost plus benefit description (w_1=0.5 and w_2=2) for single source and hybrid systems, with an average diesel generator runtime of 2 hrs/day and high renewable energy resources (6 average sunshine hours per day, average wind speed 6m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

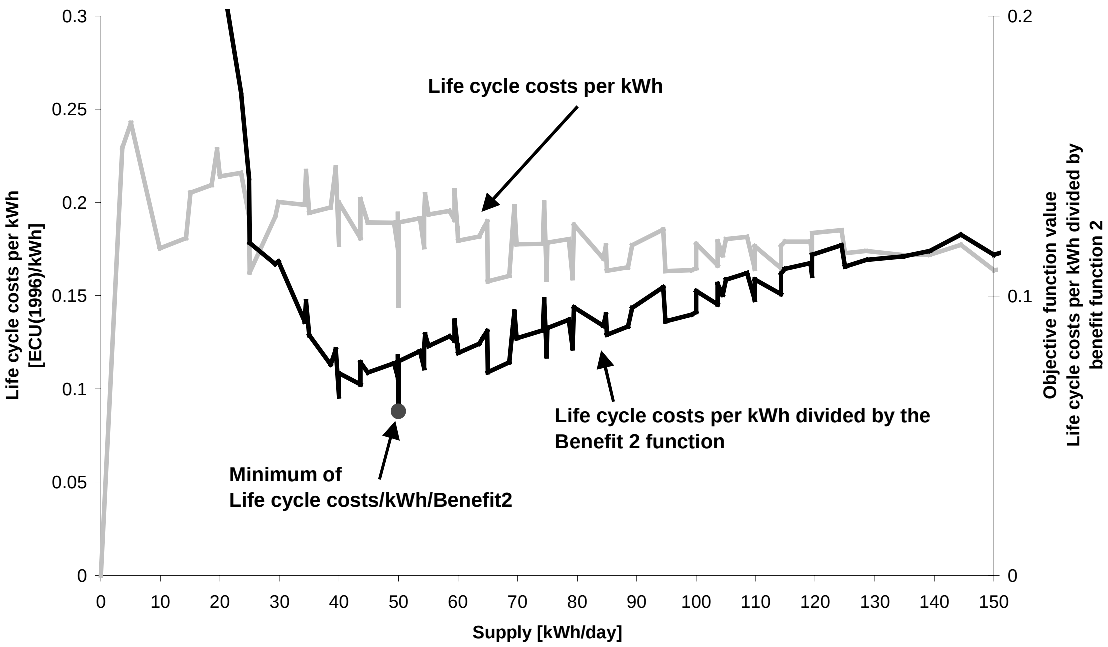


Figure 42: Life cycle cost-benefit description (w_1=0.5 and w_2=2), for single source and hybrid systems, with an average diesel generator runtime of 5 hrs/day and low renewable energy resources (5 average sunshine hours per day, average wind speed 4m/s), average diesel capacity factor is 100%, demand requirement is 40kWh/day

The developed algorithm uses the penalty function description to measure the reliability of electricity supply achieved with a hybrid system design. However, if more benefit measures are desired than just the technical reliability of the system, for example in assessing macro-economic and socio-economic impacts in an economic cost-benefit analysis, the described benefit methodology needs to be employed.

3.6 The objective function formulation

The objective function collects the different initial costs and discounted operation costs, which are incurred by a certain system design, in the system life cycle costs or LCC as in Equation 8. In case income is generated by the application, the discounted flow of income during the project life can be subtracted from the incurred LCC, giving the NPV in Equation 10. To note, the discounted costs can also be subtracted from the discounted income, thereby changing the sign of the NPV value.

As discussed in the previous section, a measure that indicates the reliability of supply and other socio-economic benefits needs to be introduced. This can be done using the benefits or penalties as described in the previous section.

The costing and penalty or benefit descriptions can be combined into a single measure of worth either by subtracting the benefits from the NPV (J_1) or dividing the NPV by the benefits (J_2), or by adding penalties to the NPV (J_3).

$$J_1 = NPV - NPVBenefits$$

Equation 33: Objective function formulation as difference between the NPV of design and NPV of corresponding benefits

$$J_2 = \frac{NPV}{NPVBenefits}$$

Equation 34: Objective function formulation as division of the NPV of the design by the NPV of corresponding benefits

$$J_3 = NPV + Penalty$$

Equation 35: Objective function formulation as adding a penalty description to the NPV of the design

The objective is to minimise the overall costs. If income is positive and expenditure is negative than the objective would be to maximise the overall objective function. [Davis,Horvei-95] points out that J_2 should be used if there are multiple projects under consideration. J_2 also has the advantage that only the relative shapes of the cost and benefit functions are important [Marrison,Seeling-Hochmuth-97]. When comparing two designs, the absolute value of the benefits is not important. This is a useful feature given the difficulty of accurately quantifying the benefits. Figure 41 and Figure 42show cost/benefit scenarios as obtained by using J_2.

The overall objective function for J_2 can be given as

$$J_2(size_{componts}, number_{components}, operation_{components}) = \frac{1}{\sum Supply(size_{comp}, operation_{comp}, weather_{site})} \cdot$$

$$\cdot \frac{\sum\limits_{\forall components\ i} (InitialCosts_i(size_{Comp\,i}) + OpCosts_i(size_{Comp\,i}, characterticts_{Comp\,i}, operation_{Comp\,i})) + \sum Income}{BenefitperUnit \cdot (\max[1, (\frac{\sum Demand}{\sum Supply(size_{comp}, operation_{comp}, weather_{site})})^{(W_1 - W_2)}])}$$

Equation 36: Full formulation of objective cost-benefit function J_2

The maximum formulation in Equation 36 again guarantees that the over-supply of electricity is not counted as a benefit. It is up to the designer to include this restriction on assigning a benefit to oversupply or not.

The penalty description in the objective function as in J_3 was demonstrated in Figure 38. J_3 is given as

$$
\begin{aligned}
&J_3(size_{componts}, number_{components}, operation_{components}) = \\
&\sum_{\forall components\ i} (InitialCosts_i(size_{Comp\,i}) + OpCosts_i(size_{Comp\,i}, characterticts_{Comp\,i}, operation_{Comp\,i}) - \\
&- \sum_{\forall incomesources\ j} Income_j + Penalty(unmet\ demand)
\end{aligned}
$$

Equation 37: Full formulation of cost-penalty function J_3

As mentioned before, J_3 will be employed in this approach as only the technical reliability and not additional socio-economic benefits are analysed. Therefore the cruder but more easily implementable penalty measure is used.

As can be seen the objective function, whether J_1, J_2 or J_3, depends, apart from demand and weather conditions, on the component sizes, the operation employed and the often intricate characteristics of the components.

The objective function is optimised if optimum values for the component sizing and operation strategy can be found that minimise the objective cost function without violating any system constraints.

This optimisation problem and the constraints placed on the system are in almost all cases non-linear. In addition, there is often the need to solve a sub-optimisation problem to find the right operating strategies for a chosen component configuration. Therefore the task of optimising the hybrid system design is difficult to solve and requires intensive computation. Chapter 4 will describe the developed hybrid system model on which the calculation of the values of the sizing and operation costs in the objective function is based.

3.7 Summary

The hybrid system costing section developed the net present value costing as an objective function description in dependence of decision variables to be optimised by an optimisation algorithm as developed in this thesis. The net present value formulation is highly non-linear and complex, and cannot satisfactorily be solved by spreadsheet evaluation methods. The optimisation is aimed to choose a least cost alternative with lowest present value of total financial or economic costs, when discounted at an appropriate opportunity cost, and greatest benefit design with the highest socio-economic impact.

The initial costs in the objective function description need to be determined carefully and a variety of component types and cost figures exist. It is important to notice that for the majority of components an economy of scale exists, not only for the capital component costs but also for costs of installation and accessories. The actual non-linear relationship between component sizes and their costing is difficult to determine and can only be approximated. Very different experiences, which are often country-dependent, complicate the costing of the expense of installation and system accessories.

Hybrid system operation costs are complex and highly non-linear, and can only be roughly estimated.

It has been shown that the operational costing of components depends largely on their size, their type and brand, and the way they are operated. Using the fitted equations will not give accurate operation costs for a component, as the fit might have been very bad for a particular component, or not all available component type are included making the estimated fit not universally reliable.

Therefore, in the developed algorithm, the component costs are entered for each component specifically instead of using fitted equations. A component database is thereby built up with specific characteristics for operation and costing of each entered component.

It can be seen that the diagrams derived from the rough spreadsheet analysis (Figures 10, 17-25) give some rough design and cost estimates.

The spreadsheet calculations are an improvement over rough rules-of–thumb methods, but will still be inaccurate due to

- Weather and demand estimates based on one typical day only
- Fixed “diesel-run-time” per day regardless of weather, needs, variations
- Assumption of one single average diesel capacity factor
- Assumption of average efficiencies of conversion elements and batteries
- Assumption of component replacement after a fixed number of years for the battery independent of actual use
- Only an extremely limited number of combinations of weather conditions, component sizes, daily generator runtimes and average capacity factors can be analysed in the spreadsheet model due to the complexity involved in tracking calculations.

In addition, the spreadsheet analysis is cumbersome and can get out of control due to the high number of parameters that can be varied in the design.

The optimisation algorithm as developed and described in this thesis improves this situation. This is due to the fact that:

- The demand requirements and local weather can be simulated for a period of time
- Components operate at various capacity levels to meet the demand based on 10 minutes to 1-hour intervals
- The different component efficiencies encountered in inverter losses, battery charging losses, fuel efficiency, renewable energy production are taken into account during the simulation
- Component maintenance, overhaul and replacement needs can be determined more accurately based on actual operation
- The impact of different control strategies can be evaluated
- The overall life cycle costing is more accurate.

In addition to the life cycle costing equations described in this chapter, Chapter 4 explains the hybrid system performance model. Following that in Chapter 5, case scenarios are simulated with the developed algorithm and its simulation results are presented and evaluated.

Chapter 4

Hybrid System Performance Modelling

4.1 General

The hybrid system model to be described in the next sections is the core of the simulation. Apart from correct costing and optimisation, the quality and accuracy of the model and its implementation in the algorithm, greatly determines the usefulness of the simulation results.

The system model is based on a description of current flows through the system which depend on the system design decision variables to be optimised and include efficiency losses and other descriptive design parameters (see Figure 43).

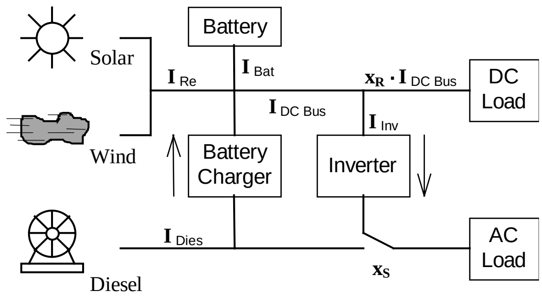


Figure 43: Basic hybrid system set-up

The decision variables are component sizes, number of components, and operation control settings which then determine the amount of diesel output power and amount of battery output. The decision variables are optimised by the algorithm in such a way that minimum life-cycle costs are achieved subject to satisfying demand.

The estimated power consumption of the appliances utilised should be given in one hour to 15 minutes intervals, for the length of a year, possibly with estimations of likely demand changes.

4.2 System component models

4.2.1 Renewable energy components

The simulation determines how many renewable energy components are needed in parallel and in series, their current outputs and power outputs as well as the component initial, operation and replacement costs.

With weather data from the site, component output characteristics and installation details like angle and height, the energy output can be calculated based on the models explained in [Schuhmacher-93] and [Dijk-96].

4.2.2 PV module model

The model of the PV module consists of two parts: an electrical model and a thermal model based on an energy balance. The model is described in detail in [Schuhmacher-93].

Manufacturers give the characteristic curves for their PV modules as I-U curves with irradiation and temperature as parameter, and for wind turbines as power output versus wind speed respectively. In the design tool the energy output and current output of each renewable component for each time instant is then computed based on the local weather conditions.

4.2.2.1 PV sizing variables

The PV sizing variables to be optimised are the size of a PV panel and the number of strings in a PV array.

The necessary number of PV panels to be connected in series is derived by the number of panels needed to match the bus operating voltage ($U_{Bus,Nom}$). In most cases DC PV panels will be used, therefore the operating voltage will be the one of the DC bus.[2]

$$n_{PV,series} = U_{Bus,nom} / U_{panel,nom}$$

Equation 38: Number of required PV panels in series

where $U_{Panel,Nom}$ is the PV panel voltage and $n_{PV,series}$ is the number of PV panels in series.

The number of PV panels to be installed in series is therefore not subject to optimisation but is a straightforward calculation.

When matching the current requirements of the system, several PV strings, each consisting of $n_{PV,series}$ panels connected in series, need to be installed in parallel. The number of parallel PV strings is a design variable that needs optimisation.

In the simulation the number of parallel PV strings is therefore handled as a variable, $x_{PV,parallel}$, to be found through iterating the optimisation algorithm. By changing the value of $x_{PV,parallel}$ in the simulation, the amount of available output current from the overall PV array changes. Through simulating the system with a certain value for $x_{PV,parallel}$ (and also certain values for other design variables) the quality of a system design can be assessed. The current output of a PV array at time t, $I_{PV,Array}(t)$, is related to the number of parallel strings as follows:

$$I_{PV,Array}(t) = I_{PVpanel}(t, x_{Size,Type,PV}) \cdot x_{PV,parallel} \cdot f_{MM}$$

Equation 39: PV array current output

where $x_{Size,Type,PV}$ is PV panel size of a certain PV panel type, $I_{PV,panel}(t,x_{Size,Type,PV})$ is the PV panel current output at time t depending on panel type, and f_{MM} is a mismatch factor for different PV panel current outputs if required.

$x_{PV,parallel}$ is to be optimised in order to cover the system energy requirements. The value of $x_{PV,parallel}$ can range from 0 to the highest amount of parallel PV strings needed when a PV stand-alone system were used to cover the energy requirements. For a PV stand-alone system, the number of PV strings in parallel is roughly given as the average daily energy requirements in Wh/day, $Demand_{Wh/day}$, divided by: energy losses through cables and inverter; the expected Wattage of a PV string based on local irradiation conditions; and the average number of sunshine per day.

$$x_{PV,parallel} \in [0, \overline{Demand_{Wh/day}} / (\eta_{losses} \cdot W_{expected,PVpanel}(x_{Size,Type,PV}) \cdot n_{PV,series} \cdot \overline{Hours_{sunshine/day}})]$$

Equation 40: Boundaries on the PV array sizing

where η_{losses} are efficiency losses due to conversion losses, wire losses, battery cycling losses, $W_{expected,PVpanel}$ is the expected PV panel output power, and $Hours_{sunshine/day}$ is the average number of estimated sunshine hours per day.

The current output of a PV panel, $I_{PV}(t)$, is determined by the external irradiation and temperature. The power output of the PV array, $Power_{PV,Array(t)}$, is calculated by multiplying the panel Wattage with the number of panels in series and the number of PV strings (Equation 41).

[2] There are also AC PV panels, i.e. DC PV panels with integrated inverters [Schmid-97]

$$Power_{PV,Array}(t) = I_{PV,panel}(t, x_{Size,Type,PV}) \cdot U_{PVpanel,nom} \cdot n_{PV,series} \cdot x_{PV,parallel} \cdot f_{MM}$$

Equation 41: PV array power output

The energy produced by the array is obtained through multiplying the array output power with the time interval over which the power is produced.

4.2.2.2 PV costing variables

The initial costs of the PV array, $InitCost_{PV}$, are

$$InitCost_{PV} = n_{PV,series} \cdot x_{PV,parallel} \cdot Cost_{PV}(x_{Size,Type,PV}) \cdot (1 + \%ofCC_{PV}) + FixedCosts_{PV}$$

Equation 42: Initial costs of the PV array

where $Cost_{PV}$,$\%ofCC_{PV}$, $FixedCosts_{PV}$ are the PV panel costs according to the size of the PV panel type, the percentage of capital costs added for installation and BOS parts, and added fixed costs accounting for installation and BOS parts respectively.

Operation and maintenance of PV arrays can be described with monthly fixed costs and yearly costs as a percentage of capital costs (Equation 43). Replacement events of PV arrays are assumed to occur after every 20 years, so for a project life of 20 years or less, there will be no PV replacement costs (Equation 44).

$$OP\cos t_{PV}(n\ years) = (FixedCosts_{perYear,PV} + OPas\%ofCC_{perYear,PV}) \cdot R_{yearly}(n\ years)$$

Equation 43: PV operation costs after n years

where $Opcost_{PV}(n)$ are the overall PV operation costs after n years, $FixedCosts_{perYear,PV}$ are the fixed operation costs arising during PV operation each year, $Opas\%ofCC_{perYear}$,PV is the percentage of capital costs arising as PV operation cost each year, and R(n) is the discount factor for the same yearly expenditure which occurs for n years (see Chapter 3).

R_{yearly} (Equation 7) is the discount factor for maintenance and operation costs, which occur regularly every year, and r is the discount rate assumed for the project life.

$$replacement\cos ts_{PV} = InitCost_{PV} \cdot \frac{1}{(1+r)^{Re\,placement\ year,PV}}$$

Equation 44: PV replacement costs

where $replacementcosts_{PV}$ are overall PV replacement costs, $InitCost_{PV}$ are PV initial costs, and $Replacement_{year,PV}$ is the lifetime of the PV panels in number of years.

4.2.2.3 Wind turbine sizing variables

A similar listing of relations as for the PV array can be obtained for wind turbine components. Manufacturers give the characteristic curves for wind turbines as power output versus wind speed at the hub height. In the design tool the energy output and current output of wind turbine components for each time instant is then computed based on the local weather conditions and actual installation height of the turbines.

Wind turbines are usually only connected in parallel, not in series. Therefore the number of wind turbines in series, $n_{Wtseries}$, will be equal to one. Several wind turbines can be connected in parallel to match the system current requirements. This can be done with parallel strings of the same wind turbine type or with strings of a different wind turbine type. It is assumed here that at most two different turbine types are used at the same time in one system. The current output of the wind turbine array of an AC or DC bus k, $I_{WT,Array,Bus,k}$, is then obtained as follows

$$I_{WT,Array,Bus,k}(t) = \sum_{i=1}^{NOofWTtypes} I_{WT,i,k}(t, x_{Size,Type,WT,i,k}) \cdot x_{WT,i,parallel,k} \qquad , NOofWTtypes \leq 2$$

Equation 45: Wind turbine array current output

where NOofWTtypes is the number of different wind turbine types available for the optimisation from a pool of wind turbines. $x_{Size,Type,WT,i,k}$ is the size of wind turbine type i on bus k. $x_{WTi,parallel}$ is the number of strings in parallel for wind turbine type i and $I_{WT,i}$ is the wind turbine current output of wind turbine type i. $I_{WT,i}$ depends mainly on the local wind speed. Again, $x_{WTi,parallel}$ and the type of wind turbines used in the design are design variables to be optimised by iterating the developed algorithm.

$$x_{WT,i,parallel} \in [0, \text{WT\_kWrating} = \text{f(Rotordiameter)}],$$

$$\text{Rotordiameter} = \sqrt{\frac{Demand_{kWh/year,Av}}{\eta_{\text{WTEnergyConversion}} \cdot \text{hrs/year} \cdot \text{PowerDensity}(WindSpeed_{\text{yearlyAv}}, location, heigth) \cdot \pi \cdot \frac{1}{4}}}\,]$$

Equation 46: Defining Wind turbine sizing boundaries

$\eta_{WTEnergyConversion}$ is wind turbine's energy conversion efficiency as given by the manufacturer. The power output of the wind turbine array at time t, $P_{WT,Array}(t)$, is then:

$$Power_{WT,Array}(t) = \sum_{i=1}^{NOofWTtypes} I_{WT,i}(t, x_{Size,Type,WT,,i}) \cdot U_{WT,i,nom} \cdot x_{WT,i,parallel}$$

Equation 47: Wind turbine array power output, DC or AC

where $U_{WT,i,Nom}$ is the nominal voltage of wind turbine type i, and NOofWTtypes is the number of different wind turbine types available for the optimisation from a pool of wind turbines.

4.2.2.4 Wind turbine costing variables

The initial costs of the wind turbine array, $InitCost_{WT}$, are similarly derived as for the PV array:

$$InitCost_{WT} = \sum_{i=1}^{NOofWTtypes} x_{WT,i,parallel} \cdot Cost_{WT}(x_{Size,Type,WT,i}) \cdot (1 + \%ofCC_{WT,type,i}) + FixedCosts_{WT,type,i}$$

Equation 48: Initial costs of wind turbine array, DC or AC

where $Cost_{WT}$ is the wind turbine cost according to the size of the wind turbine type, $\%ofCC_{WT}$ is the percentage of capital costs added for installation and BOS parts, and $FixedCosts_{WT}$ are the corresponding added fixed costs.

The overall wind turbine operation costs after n years, $Opcost_{WT}(n)$, are

$$OP\cos t_{WT}(n\ years) = \sum_{i=}^{NOofWTtypes} (FixedCosts_{perYear,WT,i} + OPas\%ofCC_{perYear,WT,i}) \cdot R(n\ years)$$

Equation 49: Wind turbine operation costs

where $Opas\%ofCC_{perYear,WT,i}$ is the percentage of capital costs arising as operation costs of wind turbine type i, $FixedCosts_{perYear,WT,i}$ are the fixed operation costs arising during operation of wind turbine i each year.

The overall wind turbine replacement costs, $replacementcosts_{WT}$, are given by Equation 50.

$$replacement\cos ts_{WT} = \sum_{i=1}^{NOofWTtyps} InitCost_{WT,type,i} \cdot \frac{1}{(1+r)^{\mathrm{Re}\,placement\ yearWT,i}}$$

Equation 50: Wind turbine replacement costs

where $InitCost_{WT,type,i}$ are the initial costs of wind turbine type i, and $Replacement_{year,WT,i}$ is the lifetime of the wind turbine type i in number of years.

For both PV and wind turbines, arising installation costs and balance of system costs are included in the %of CC (percentage of component capital costs) and the fixed costs (FixedCosts).

4.2.2.5 Overall renewable costing and output

Other energy sources and their performance, such as micro-hydro generators, AC wind turbines, PV panels with AC output etc., can be modelled and included. The costs and output currents are calculated similarly to the calculated costs and current outputs of the DC PV array and the DC wind turbine array. The additional outputs are added to the DC and AC bus current and power equations.

The overall renewable DC current output, $I_{RE-DC}(t)$, is then given as:

$$I_{RE-DC}(t) = I_{PV,Array-DC}(t) + I_{WT,Array-DC}(t) + I_{Other\,\mathrm{Re}\,Sources-DC}(t)$$

Equation 51: DC renewable current

where $I_{PV,Array-DC}(t)$ is the DC output current from the PV array at time t, $I_{WT,Array-DC}(t)$ is the DC output current from the wind turbine array at time t, and $I_{OtherRESources-DC}(t)$ is the DC output current from other renewable energy sources at time t.

The AC renewable current, $I_{RE-AC}(t)$, then becomes

$$I_{RE-AC}(t) = I_{PV,Array-AC}(t) + I_{WT,Array-AC}(t) + I_{Other\,\mathrm{Re}\,Sources-AC}(t)$$

Equation 52: AC wind turbine array current output

where $I_{PV,Array-AC}(t)$ is the AC output current from the PV array at time t, $I_{WT,Array-AC}(t)$ is the AC output current from the wind turbine array at time t, and $I_{OtherRESources-AC}(t)$ is the AC output current from other renewable energy sources at time t.

4.2.3 Diesel generator

4.2.3.1 Diesel generator sizing and operation variables

The nominal voltage of the diesel generator in most cases matches the AC bus or DC bus nominal voltage. Several diesel generators can run in parallel, so as to be able to output different load levels at good capacity factors. It is assumed here that the number of diesels in parallel does not exceed 5 which is a reasonable assumption.

The diesel output current at each time instant is an operation decision variable. Therefore it is modelled as the product of the maximum nominal diesel current $I_{dieselmax}$ and the diesel output decision variable $x_{Diesel}(t)$, which can be a number between 0 (no diesel output current) and 1 (maximum diesel output current), at each time instant:

$$x_{Diesel},i \in [0,1]$$

Equation 53: Limits of the diesel generator output decision variable where $x_{Diesel,i}(t)$ is the output of diesel generator type i at time t as percentage of maximum possible nominal output power in W.

The maximum nominal diesel output current depends on the size of the diesel generator, x_{sizeD} , used in the system:

$$x_{sizeD,i} = I_{Diesel\,max,i} \cdot U_{Bus,Nom}$$

Equation 54: Diesel nominal power sizes

where $x_{sizeD,i}$ is the nominal output power in W of diesel generator type i, and $I_{Dieselmax,i}$ is the maximum possible output current of diesel generator type i.

The $x_{sizeD,i}$ are optimised through iterating the design algorithm. The size of the diesel generator is limited between 0 (no diesel generator) and the size for a diesel single source system to cover the given application reliably, that is PeakDemandPower, the maximum demand in W.

Therefore

$$x_{sizeD,i} \in [0,\text{PeakDemandPower}]$$

Equation 55: Boundaries on diesel generator sizing

It follows that the diesel output current of the diesel generator array, $I_{Diesel,Array,Bus,k}(t)$, is obtained as follows:

$$I_{Diesel,Array,Bus,k}(t) = \sum_{i=1}^{NOofDieselTypes} I_{Diesel\,max,i,Bus,k} \cdot x_{Diesel,i,parallel} \cdot x_{Diesel,i}(t) \qquad , NOofDieselTypes \leq 5$$

$$I_{Diesel,Array,Bus,k}(t) = \sum_{i=1}^{NOofDieselTypes} \frac{x_{sizeD,i}}{U_{Bus,k,Nom}} \cdot x_{Diesel,i,parallel} \cdot x_{Diesel,i}(t) \qquad , NOofDieselTypes \leq 5$$

Equation 56: Diesel current contributions from different diesel generators at time t

where $x_{Diesel,i,parallel}$ is the number of diesel generators of type i installed in parallel. $x_{Diesel,i}(t)$ is the output of diesel generator type i at time t as percentage of maximum possible nominal output power in W. NoofDieselTypes is the number of different diesel generator types available for the optimisation from the diesel generator pool. And $I_{Dieselmax,i,Bus,k}$ is the maximum possible output current of diesel generator type i. Thereby k is an index indicating to which bus the diesel generator is connected. The bus can be DC or AC. If diesel generators with DC outputs are used, then their outputs and costs are similarly calculated and their output needs to be added onto the DC bus.

The diesel output current at each time instant depends on the size of the diesel and the operation decision about the output level of the diesel generator at that time instant. The sizing variable $x_{sizeD,i}$ and the types of diesel generators used are optimised directly in the design algorithm. The operation decision variables contained in $x_{Diesel,i}(t)$ are arrived at through optimising the system operational control settings. The found control settings then form an operation strategy.

4.2.3.2 Fuel consumption and fuel costs

The fuel consumption of a diesel generator is related in general non-linearly to the diesel output power and the diesel run time length [Morris-88]. Fuel consumption levels versus power running level of the diesel generator can be entered by the user as data points for each diesel generator type. The arising fuel consumption costs during operation are calculated as follows:

$$FuelCosts = {Fuel\ Cost}/{Litre} \cdot LitresUsed$$
$$= {Fuel\ Cost}/{Litre} \cdot \sum_{k=1}^{NOofBusTypes} \sum_{t=t_0}^{T} Litres(I_{Diesel,Array,Bus,k}(t) \cdot U_{Bus,k,Nom}) \cdot corr_{Factor}$$
$$= {Fuel\ Cost}/{Litre} \cdot \sum_{i=1}^{NOofDieselTypes} \sum_{t=t_0}^{T} Litres(x_{sizeD,i} \cdot x_{Diesel,i,parallel} \cdot x_{Diesel,i}(t)) \cdot corr_{Factor}$$

Equation 57: Overall fuel consumption and fuel costs

where NOofBusTypes is the number of different DC and AC busses in the system, Fuel Cost/ Litre is the cost of fuel in ECU/litre and LitresUsed is the fuel used during the simulation time interval T. Litres(:) is a function relating the diesel generator output power to its fuel consumption. $corr_{Factor}$ is a correction factor accounting for increases in fuel needs during start-up.

$corr_{Factor}$ accounts for increases in fuel needs during start-up. Running the diesel with a low capacity factor increases relative fuel consumption and wear. The fuel consumption is higher than normal during a cold start of the diesel, especially under low capacity factors. Many such cold-start periods in a short time contribute to increased diesel wear. In case the diesel is running at no loading a certain amount of fuel will still be consumed.

4.2.3.3 Diesel generator costing variables

The initial costs of the diesel gensets, $InitCost_{Diesel}$, are

$$InitCost_{Diesel} = \sum_{i=1}^{NOofDiesTypes} n_{Diesel,i,series} \cdot x_{Diesel,i,parallel} \cdot Cost_{Dies}(x_{sizeD,i}) \cdot (1 + \%ofCC_{D,size,i}) + FixedCosts_{Diesel,type,i}$$
$$NOofDiesTypes \leq 5$$

Equation 58: Initial equipment costs of the diesel generator

where $Cost_{Dies}$ is the diesel generator cost according to the size of the diesel generator type. $\%ofCC_{D,size,i}$ is the percentage of capital costs added for installation and BOS parts for diesel generator type i and $FixedCosts_{Diesel,type,i}$ are the corresponding added fixed costs.

The overall diesel generator operation costs after n years, $Opcost_{Diesel}(n)$, are calculated according to Equation 59.

$$OPcost_{Diesel}(n\ years) = [\sum_{i=1}^{NOofDieselTypes} (FixedCosts_{perYear,Dies,i} + OPas\%ofCC_{perYear,Dies,i} + $$
$$+ OPcostPerRunTime_{PerYear,Dies,i}) + FuelCosts(T = 1\ year)] \cdot R(n\ years)$$

Equation 59: Operation costs of the diesel generator

where $Opas\%ofCC_{perYear,Dies,i}$ is the percentage of capital costs arising as diesel generator operation.

The overall diesel generator replacement costs, $Replacementcosts_{Diesel}$, are calculated as described in Equation 60.

$$Replacementcosts_{Diesel} = \sum_{i=1}^{NOofDieselTypes} \sum_{j=1}^{NOofReplDiesType,i} InitCost_{Diesel,type,i} \cdot \frac{1}{(1+r)^{j \cdot (Repl\ yearDies,i)}}$$

Equation 60: Diesel generator replacement costs where $Repl_{year,Dies,i}$ is the lifetime of the diesel generator type i in number of years.

The installation costs, balance of system costs, fuel tank and shelter costs are included in the fixed costs or as a percentage of initial costs. The lifetime of the diesel generator in number of years is usually obtained through noting when the operating hours of the diesel generator in the system reach the number of hours given as the diesel generator operating lifetime by the manufacturers.

4.2.4 Battery

4.2.4.1 Battery design variables

The battery model described by [Schuhmacher-93] and according to [Shephard-65] is explained in detail in appendix A2.

Batteries in a hybrid system are connected in series to yield the appropriate nominal bus voltage. Therefore the number of batteries connected in series for the same type of battery in a battery bank is

$$n_{Bat,series,Bank,k} = U_{Bus,Nom} / U_{Bat,Nom,Bank,k}$$

Equation 61: Number of batteries required in series

The hybrid system can have several battery banks, which typically consist of different battery types. For example, the second battery bank can consist of batteries which are smaller in sizes than the ones of the first battery bank, so as to produce better battery cycling patterns in case of very diverse demand levels.

Each battery bank therefore has a certain number of batteries of the corresponding battery type connected in series to match the bus nominal operating voltage. In addition, each battery bank may have several strings of serial connected batteries so as to increase the Ampere hours available to the system.

It is assumed here that the number of battery banks (Figure 44) is limited to two which is a realistic presumption.

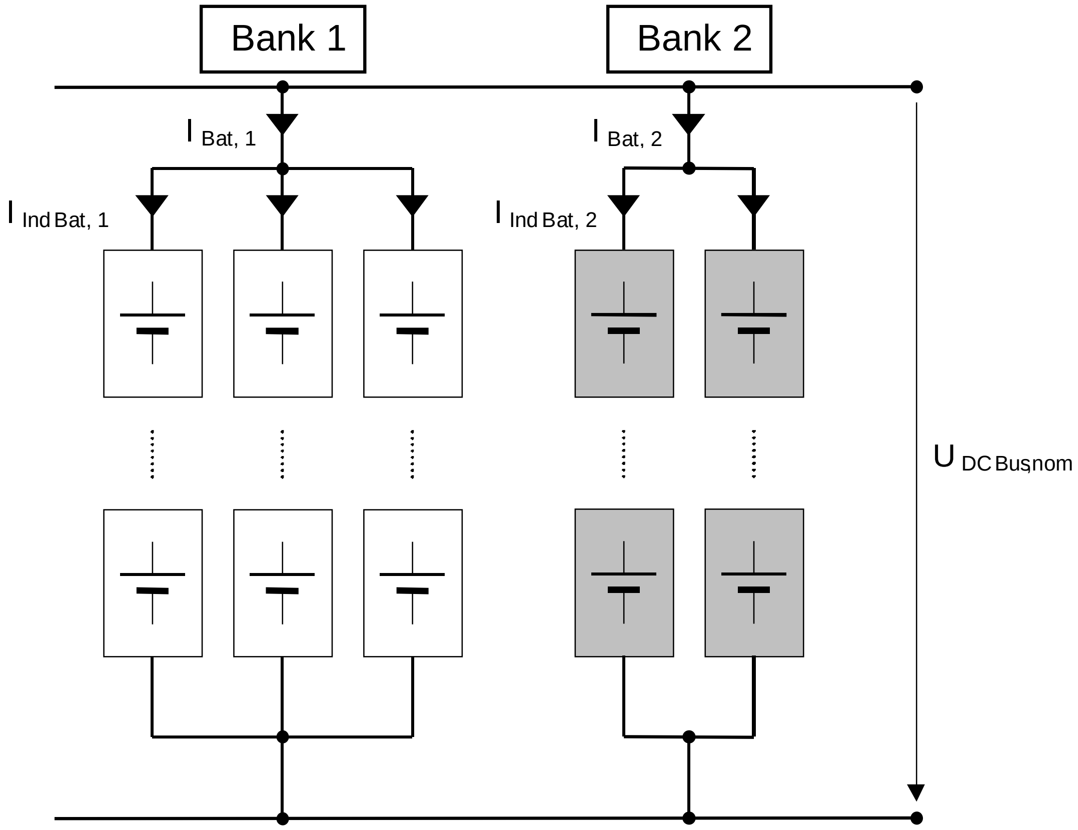


Figure 44: Several battery banks

It follows that the system battery state of charge, SOC_{Nom}, in Ah, is compiled by adding the SOC available from each battery bank i, $SOC_{Nom,Bank,i}$. The size of the individual batteries, $x_{size,Bat,Bank,i}$ in each battery bank i is a design variable to be optimised by the algorithm. This size corresponds to the nominal battery capacity in Ah.

$$
\begin{aligned}
SOC_{Nom} &= \sum_{i=1}^{NOofBatBanks} SOC_{Nom,Bank,i} = \\
&= \sum_{i=1}^{NOofBatBanks} SOC_{Nom,Bat,Bank,i} \cdot x_{Bat,parallel,Bank,i} \\
&= \sum_{i=1}^{NOofBatBanks} x_{size,Bat,Bank,i} \cdot x_{Bat,parallel,Bank,i}
\end{aligned}
$$

Equation 62: Battery nominal capacities

$x_{Bat,parallel,Bank,i}$ is the number of parallel battery strings in a battery bank i.

The system battery state of charge, SOC_{Nom} is limited to a value between 0 (no batteries used) and 5 days of storage which is a big enough size for many even single-source systems requiring typical system reliability.

$$
\begin{aligned}
&\mathrm{SOC}_{\mathrm{Nom}} \in \; [0;5\,\text{days of storage in Ah}] \\
\Leftrightarrow \; &SOC_{Nom} \in \; [0;5\,\text{days} \cdot \sum_{t=1h}^{24h} I_{Demand,Daily}(t) \cdot \Delta t]
\end{aligned}
$$

Equation 63: Battery sizing boundaries

The battery's state of charge is limited between maximum and minimum state of charge (SOC_{max} and SOC_{min}). The minimum state of charge is often set to 50% nominal capacity, even 20% nominal capacity, depending on the following factors: type of battery used, outside temperature, battery age and battery condition. The maximum state of charge is often set to 100% nominal capacity.

The system maximum or minimum state of charge $SOC_{Max(Min)}$ is obtained by adding the maximum and minimum state of charge of each battery bank, which are made up of the maximum (minimum) state of charge of the individual battery times the number of parallel strings in a battery bank i. The maximum (minimum) state of charge of a battery is often expressed as percentage of the nominal capacity of the battery.

$$
\begin{aligned}
SOC_{Max(Min)} &= \sum_{i=1}^{NOofBatBanks} SOC_{Max(Min),Bank,i} = \\
&= \sum_{i=1}^{NOofBatBanks} SOC_{Max(Min),Bat,Bank,i} \cdot x_{Bat,parallel,Bank,i} \\
&= \sum_{i=1}^{NOofBatBanks} \%_{Max(Min)} \cdot x_{size,Bat,Bank,i} \cdot x_{Bat,parallel,Bank,i}
\end{aligned}
$$

Equation 64: Maximum and minimum battery state of charge

The battery state of charge of a battery bank at time t is calculated based on adding the charge current (positive sign) or discharge current (negative sign) to the battery bank state of charge at the previous time instant. When adding the battery current to the battery state of charge, self discharge losses and battery charging losses (see [Schuhmacher-93]) need to be taken into account.

$$
\begin{aligned}
SOC(t+1) &= \sum_{i=1}^{NOofBatBanks} SOC_{Bank,i}(t+1) \\
&= \sum_{i=1}^{NOofBatBanks} SOC_{Bank,i}(t) \cdot \sigma_i + I_{Bat,Bank,i}(t) \cdot \Delta t \cdot \eta_i(I_{Bat,Bank,i}(t)) \\
&= \sum_{i=1}^{NOofBatBanks} [SOC_{IndBat,i}(t) \cdot \sigma_i + I_{IndBat,i}(t) \cdot \Delta t \cdot \eta_i(I_{IndBat,i}(t))] \cdot x_{Bat,parallel,i}
\end{aligned}
$$

Equation 65: System battery state of charge at time t

σ is the self-discharge rate, η the charging efficiency and I_{bat} the charge/discharge current. During discharge, η is assumed to be 1. The charging efficiency can be entered by the user or can be calculated by the battery model [Schuhmacher-93] using the Wood parameters. According to the model in [Schuhmacher-93], when charging, η is 0.85 to 0.65, depending on the charging current. When gassing starts at a critical state of charge $SOC_{crit}(I_{bat})$, η drops to 0.3 to 0.01. The battery efficiency also depends on the battery cycling and its history [Degner et al-94].

The maximum charge current that the battery can receive from the system is determined by the amount the battery banks can accept for charge. This amount is proportional to SOC_{max} - SOC(t). However, the amount the battery can accept for charge at any one time instant cannot exceed the maximum allowed charging rate of an individual battery given by the manufacturer, $I_{Max,Ch,IndBat}$.

The maximum discharge current the system can obtain from the battery is determined by the amount the battery banks can deliver as discharge, which is proportional to SOC(t) - SOC_{min}. However, the amount the battery can deliver as discharge at any one time instant cannot exceed the maximum allowed discharging rate of an individual battery given by the manufacturer, $I_{Max,Dh,IndBat}$.

The maximum possible overall battery charging (discharging) current $I_{bat,max}(t)$ at time t consists of the sum of the maximum possible battery bank currents at time t. The maximum battery bank current in turn is composed of the maximum current of the individual bank battery multiplied by the number of strings in the corresponding battery bank i.

$$I_{Bat,max}(t) = \sum_{i=1}^{NOofBatBanks} I_{Bat,max,i}(t) = \sum_{i=1}^{NOofBatBanks} I_{Bat,max,IndBat,i}(t) \cdot x_{Bat,parallel,i}$$

$$= \sum_{i=1}^{NOofBatBanks} Max[0, Min[c_i \cdot I_{Max,Ch,i} + (1-c_i) \cdot I_{Max,Dh,i}, \frac{c_i \cdot (SOC_{Max,i} - SOC_i(t)) + (1-c_i) \cdot (SOC_i(t) - SOC_{Min,i})}{t}]]$$

$$= \sum_{i=1}^{NOofBatBanks} Max[0, Min[(c_i \cdot I_{Max,Ch,IndBat,i} + (1-c_i) \cdot I_{Max,Dh,IndBat,i}) \cdot x_{Bat,parallel,i}, \frac{c_i \cdot (SOC_{Max,IndBat,i} - SOC_{IndBat,i}(t)) + (1-c_i) \cdot (SOC_{IndBat,i}(t) - SOC_{Min,IndBat,i})}{t} \cdot x_{Bat,parallel,i}]]$$

$$= \sum_{i=1}^{NOofBatBanks} Max[0, Min[(c_i \cdot I_{Max,Ch,IndBat,i} + (1-c_i) \cdot I_{Max,Dh,IndBat,i}) \cdot x_{Bat,parallel,i}, \ x_{Bat,parallel,i} \cdot \cdot \frac{c_i \cdot (\%_{Max,IndBat,i} \cdot x_{size,Bat,Bank,i} - SOC_{IndBat,i}(t)) + (1-c_i) \cdot (SOC_{IndBat,i}(t) - \%_{Min,IndBat,i} \cdot x_{size,Bat,Bank,i})}{t}]]$$

Equation 66: Maximum possible DC battery current at time t

Therefore the amount of the maximum, time-dependent battery current the battery banks can discharge to the system or charge from the system, $I_{Bat,max}(t)$, depends on the system battery state of charge at each time instant and the maximum allowed battery charging/discharging rates by the manufacturer. The maximum charge (discharge) rate, $I_{maxCh(Dh)} \cdot \delta t$ is often given by manufacturers as around 20%·of the value of nominal capacity. c, the charge/discharge indicator, is zero during discharge and 1 during charge.

The battery current is an operation decision variable to be optimised by the algorithm as part of the overall system operation strategy.

The actual battery current at time t, $I_{Bat}(t)$, is a percentage of the maximum possible battery current, $I_{Bat,max,}$ at that time instant. This percentage, x_{bat}, is determined by the optimisation algorithm, where $x_{bat}(t) \in [0,1]$.

$$I_{Bat}(t) = I_{Bat,max}(t) \cdot x_{Bat}(t)$$

Equation 67: Actual battery current at time t

The system battery current is the sum of the individual battery bank currents which in turn are composed of the individual battery currents multiplied by the number of battery strings in a battery bank i. The individual battery currents of battery bank i, $I_{IndBat,i}$, are determined by the percentage, $x_{Bat,i}$, of the maximum possible charge or discharge current, $I_{Bat,max,IndBat,i}$, which can be utilised at time instant t in battery bank i.

$$I_{Bat}(t) = \sum_{i=1}^{NOofBatBanks} I_{Bat,i}(t) = \sum_{i=1}^{NOofBatBanks} I_{IndBat,i}(t) \cdot x_{Bat,parallel,i}$$
$$= \sum_{i=1}^{NOofBatBanks} I_{Bat,max,IndBat,i}(t) \cdot x_{Bat,i}(t) \cdot x_{Bat,parallel,i} \qquad ,I \leq 2$$

Equation 68: Battery current contributions from different batteries

The derived equations in this chapter are implemented in the developed design optimisation algorithm. Before executing the developed algorithm, as is described in Chapter 5, the initial battery state of charge needs to be known. The initial state of charge of a battery bank at time 0 will be a percentage of $SOC_{nom,bank,i}$. The user of the algorithm also enters the maximum charge and discharge current rates, maximum/minimum possible battery state of charge, the battery efficiency versus state of charge, and the number of cycles a battery lasts versus the average depth of discharge. The latter are important to determine the battery operational costs (see Chapter 3).

4.2.4.2 Battery costing variables

The initial battery costs are

$$InitCost_{Bat} = \sum_{i=1}^{NOofBatBanks} n_{Bat,i,series} \cdot x_{Bat,i,parallel} \cdot Cost_{Bat}(x_{sizeBat,i}) \cdot (1 + \%ofCC_{Bat,i}) + FixedCosts_{Bat,Bank,i}$$
$$NOofBatBanks \leq 2$$

Equation 69: Initial battery costs

Installation costs and balance of system costs will be accounted for in the fixed costs or as a percentage of initial battery capital costs.

The battery operation costs depend on the battery cycling during system operation and also include fixed costs and costs at regular intervals such as maintenance costs.

$$OP\cos t_{Bat}(n\ years) = \sum_{i=1}^{NOofBatBanks} (FixedCosts_{perYear,Bat,i} + OPas\%ofCC_{perYear,Bat,i} +$$
$$+ OP\cos tPerCycling_{PerYear,Bat,i}) \cdot R(n\ years)$$

Equation 70: Battery operation costs

Replacement costs occur whenever the battery needs to be exchanged with a new or newer one.

$$Re\ placement\ cos\ ts_{Battery} = \sum_{i=1}^{NOofBatBanks} \sum_{j=1}^{NOof\ Re\ plBatType,i} InitCost_{Bat,Bank,i} \cdot \frac{1}{(1+r)^{j \cdot (Re\ pl\ yearBat,i)}}$$

Equation 71: Battery replacement costs

For the calculation of the battery replacement year see Chapter 3.

4.2.5 Inverter

4.2.5.1 Inverter design variables

The size of the inverter can be defined in terms of its AC output power.

$$x_{size,Inv} = P_{Inv-o/p}$$

Equation 72: Inverter power rating as sizing decision variable

The inverter size can be optimised by the design algorithm or can be determined according to some rule of thumbs, for example by choosing the inverter size in the range of the peak power demand, or below, depending on the technical design.

The inverter DC to AC power transformation is accompanied by conversion losses that depend on the inverter characteristics. The influence of these losses on the power flow from the energy sources to the load needs to be taken account of when determining how to best match demand and supply.

The inverter characteristics can be described by the inverter input-output relationship. Some of the power going into the inverter will be lost due to transformation losses. This is accounted for by the inverter efficiency losses, named eff_{Inv}.

$$P_{Inv-i/p} \cdot eff_{Inv} = P_{Inv-o/p} \quad , \qquad eff_{Inv} = f(P_{Inv-o/p})$$

Equation 73: Inverter power transformation equation

$$I_{Inv-i/p} \cdot eff_{Inv} \cdot U_{DCBus,Nom} = I_{Inv-o/p} \cdot U_{ACBus,Nom}$$

Equation 74: Inverter current transformation equation

Manufacturers give the inverter efficiency eff_{inv} over the inverter output power. The characteristic inverter curves are usually non-linear, i.e. the efficiency of the power transformation is non-linearly related to the obtained inverter output power. If the inverter is a parallel inverter, then efficiency losses also occur when transforming AC power back into DC power. This transformation can have higher losses and be less efficient than the other way round due to internal power electronics.

In some cases more than one inverter is installed in a hybrid system. Sometimes the second inverter is used as a back up in case the main inverter fails. In other cases, several inverters can be used to transform different DC bus power levels more efficiently into AC power using the inverter with the best conversion rate for a particular power demand level. In this case the DC bus input current to the set of parallel-connected inverters is split and/or routed through the most appropriate inverter or set of inverters (Figure 45). It is assumed that the number of parallel-connected inverters does not exceed 3 which is a realistic assumption.

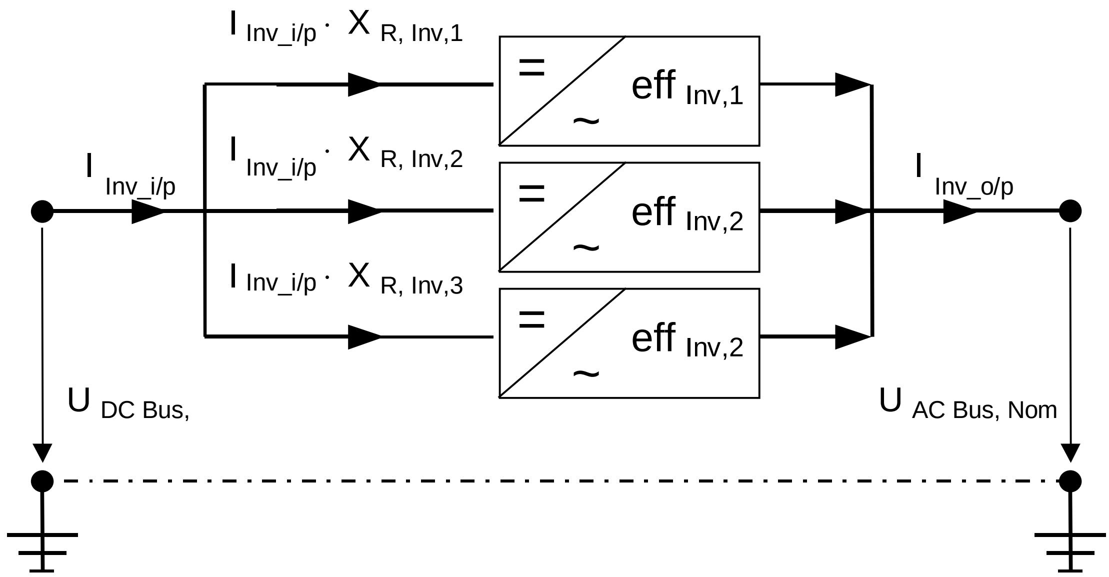


Figure 45: Current and efficiency relations for several parallel inverters

The percentage of current routed through inverter number i, $x_{R,Inv,i}$, is an operation decision variable to be optimised by the design algorithm.

$$I_{Inv-i/p} = \sum_{j=1}^{NOofInv} I_{Inv-i/p,j} = I_{Inv-i/p} \cdot \sum_{j=1}^{NOofInv} x_{R,Inv,j} \quad , \sum_{j=1}^{NOofInv} x_{R,Inv,j} = 1 \text{ , } NOofInv \leq 3$$

Equation 75: Inverter current contributions

The inverter input-output relationship for the case of several inverters becomes:

$$\begin{aligned}
& I_{Inv-i/p} \cdot eff_{Inv} \cdot U_{DCBus,Nom} = I_{Inv-o/p} \cdot U_{ACBus,Nom} \\
\Leftrightarrow \quad & \sum_{j=1}^{NOof\ Im v} I_{Inv-i/p,j} \cdot eff_{Inv,j} \cdot U_{DCBus,Nom} = I_{Inv-o/p} \cdot U_{ACBus,Nom} \\
\Leftrightarrow \quad & I_{Inv-i/p} \cdot \sum_{j=1}^{NOof\ Im v} x_{R,Inv,j} \cdot eff_{Inv,j} \cdot U_{DCBus,Nom} = I_{Inv-o/p} \cdot U_{ACBus,Nom} \\
\Rightarrow \quad & eff_{Inv} = \sum_{j=1}^{NOof\ Im v} x_{R,Inv,j} \cdot eff_{Inv,j}
\end{aligned}$$

Equation 76: Inverter efficiency relationship for several parallel inverters

The overall transformation efficiency is then the weighted sum of the efficiencies of the individual inverter power transformations.

4.2.5.2 Inverter costing variables

The initial inverter costs are:

$$\begin{aligned}
& InitCost_{Inv} = \sum_{i=1}^{NOofInv} n_{Inv,i,series} \cdot x_{Inv,i,parallel} \cdot Cost_{Inv}(x_{sizeInv,i}) \cdot (1 + \%ofCC_{Inv,i}) + FixedCosts_{Inv,i} \\
& \qquad NOofInv \leq 3
\end{aligned}$$

Equation 77: Initial costs inverters

Operation costs of the inverter can be included in overall system maintenance or operation costs.

The discounted replacement costs depend on the inverter lifetime and the number of its replacements during the assumed project life.

$$Re\ placement\ cos\ ts_{Inv} = \sum_{i=1}^{NOofInv} \sum_{j=1}^{NOof\ Re\ plInv,i} InitCost_{Inv,i} \cdot \frac{1}{(1+r)^{j \cdot (Re\ pl\ yearInv,i)}}$$

Equation 78: Inverter replacement costs

Usually the inverter lifetime is as long or longer than the assumed project lifetime.

4.2.6 Battery Charger

4.2.6.1 Battery charger design variables

The size of the battery charger can be defined in terms of its DC output power.

$$x_{size,BC} = P_{BC-o/p}$$

Equation 79: Battery charger rating as sizing variable

This battery charger size can be optimised by the design algorithm or can be determined according to some rules of thumb. For example, to choose the battery charger size in the range of the peak power diesel output power or the maximum allowed or required battery charging current.

It is necessary to describe the inverter AC to DC power transformation equation since the battery charger characteristics influence the decision how to best match demand and supply.

The battery charger characteristics can be described by the battery charger input-output relationship. Some of the power going through the battery charger will be lost due to transformation losses. This is accounted for by the battery charger efficiency eff_{BC}.

$$P_{BC-i/p} \cdot eff_{BC} = P_{BC-o/p} \quad , \qquad eff_{BC} = f(P_{BC-o/p})$$

Equation 80: Battery charger power transformation equation

The power transformation equation can also be expressed in terms of the input and output current and bus voltage descriptions:

$$I_{BC-i/p} \cdot eff_{BC} \cdot U_{ACBus,Nom} = I_{BC-o/p} \cdot U_{DCBus,Nom}$$

Equation 81: Battery charger current transformation equation

The output power $P_{o/p}$ of the battery charger equals the input power $P_{i/p}$ multiplied with the efficiency losses eff_{BC} during the energy conversion.

Manufacturers give the characteristic curves of battery chargers as efficiency losses eff_{BC} versus output power. In such a curve eff_{BC} depends non-linearly on the DC output power, and therefore non-linearly on the DC output current of the battery charger $I_{BC-o/p}$. Again, the user of the developed design optimisation algorithm can enter the data points of the characteristic curve.

Sometimes the battery charger function can be incorporated in a so-called tri-mode inverter which can also operate in parallel with a diesel generator, and can in addition function in reverse as a battery charger.

In some cases more than one battery charger could be installed in a hybrid system. The different battery chargers can be used to transform different AC bus power levels more efficiently into DC power using the battery charger with the best conversion rate, for example for a certain diesel generator output power level to be converted into DC power. In this case the AC bus input current to the set of parallel-connected battery chargers is split and/or routed through the most appropriate battery charger or set of battery chargers (Figure 46). It is assumed that the number of parallel-connected battery chargers does not exceed 3 which is a realistic assumption.

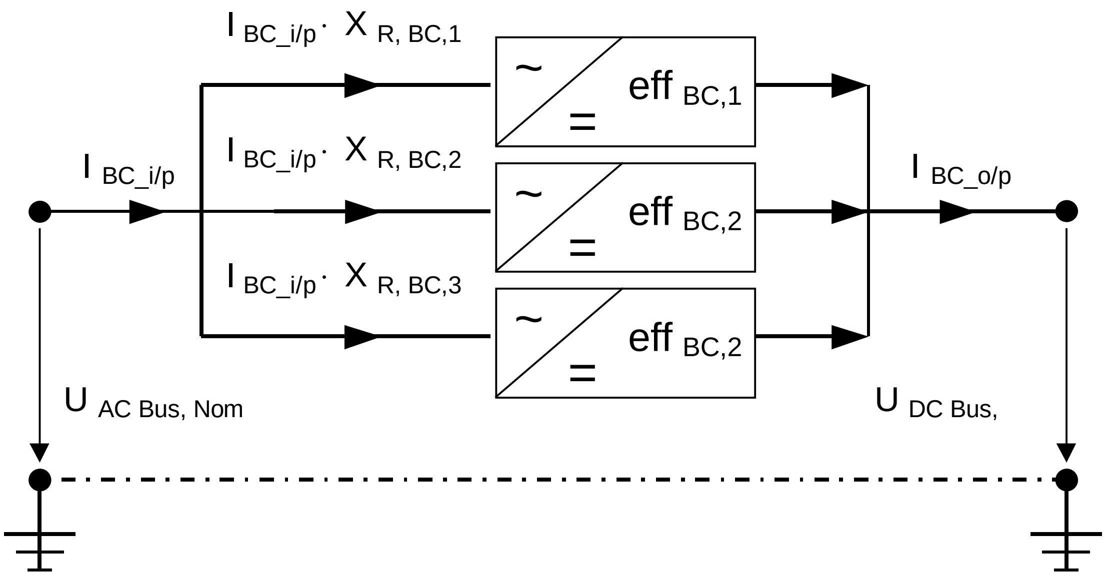


Figure 46: Current and efficiency relations for several parallel battery chargers

The percentage of current routed through battery charger number i, $x_{RBC,i}$, is an operation decision variable to be optimised by the design algorithm.

$$I_{BC-i/p} = \sum_{j=1}^{NOofBC} I_{BC-i/p,j} = I_{BC-i/p} \cdot \sum_{j=1}^{NOofBC} x_{R,BC,j} \quad , \sum_{j=1}^{NOofBC} x_{R,BC,j} = 1 \; , NOofBC \leq 3$$

Equation 82: Battery charger current contributions

The battery charger input-output relationship for the case of several battery chargers becomes:

$$\begin{aligned} & I_{BC-i/p} \cdot eff_{BC} \cdot U_{ACBus,Nom} = I_{BC-o/p} \cdot U_{DCBus,Nom} \\ \Leftrightarrow \quad & \sum_{j=1}^{NOofBC} I_{BC-i/p,j} \cdot eff_{BC,j} \cdot U_{ACBus,Nom} = I_{BC-o/p} \cdot U_{DCBus,Nom} \\ \Leftrightarrow \quad & I_{BC-i/p} \cdot \sum_{j=1}^{NOofBC} x_{R,BC,j} \cdot eff_{BC,j} \cdot U_{ACBus,Nom} = I_{BC-o/p} \cdot U_{DCBus,Nom} \\ \Rightarrow \quad & eff_{BC} = \sum_{j=1}^{NOofBC} x_{R,BC,j} \cdot eff_{BC,j} \end{aligned}$$

Equation 83: Battery charger efficiency for several parallel battery chargers

The overall transformation efficiency is then the weighted sum of the efficiencies of the individual inverter power transformations. The operation decision variables $x_{R,BC,j}$ are the percentage of current routed through battery charger number i.

4.2.6.2 Battery charger costing variables

The initial battery charger costs are:

$$InitCost_{BC} = \sum_{i=1}^{NOofBC} n_{BC,i,series} \cdot x_{BC,i,parallel} \cdot Cost_{BC}(x_{sizeBC,i}) \cdot (1 + \%ofCC_{BC,i}) + FixedCosts_{BC,i}$$
$$NOofBC \leq 3$$

Equation 84: Initial costs battery charger

Operation costs of the battery charger can be included in overall system maintenance or operation costs.

The replacement costs depend on the battery charger lifetime and the number of its replacements during the assumed project life.

$$Re\ placement\ cos\ ts_{BC} = \sum_{i=1}^{NOofBC} \sum_{j=1}^{NOof\ Re\ plBC,i} InitCost_{BC,i} \cdot \frac{1}{(1+r)^{j \cdot (Re\ pl\ yearBC,i)}}$$

Equation 85: Battery charger replacement costs

In general, the battery charger will last as long or longer as the assumed project life.

4.2.7 Transfer Switches

The transfer switch is located between the inverter output and the diesel generator output. In many hybrid systems the functions of this switch are implemented electronically. In quite a few hybrid systems, the functions of the transfer switch are carried out manually by the hybrid system operator, switching the diesel on and off when deemed necessary. In this thesis, $x_S(t)$ models the switch positions between 0 (inverter off – all AC load can be supplied by the diesel generator, but not through the inverter) and 1 (inverter on – All AC load can be supplied through the inverter, but not through the diesel generator).

If a parallel inverter is used, then $x_s \in [0,1]$ and both the diesel and the inverter can supply the AC load at the same time.

4.2.8 Loads

Most common loads are 12V, 24V, 36V, 48V DC appliances or 220V AC appliances. The estimated power consumption should be given in intervals of hours or minutes, for the length of a week, month or year.

If both a DC and AC system bus exist, some of the DC bus energy can be routed through the inverter to the AC loads. The loads can possess different priorities in terms of when they need to be met by the electricity supplied. There are optional loads ($I_{load,OPT}$), which can either be supplied at the specified time instant but do not have to. They are suitable as dump loads. Then there are deferrable loads ($I_{load,DEF}$), which do not have to be supplied at the specified time instant, but need to be covered within a certain time interval. Other high priority loads ($I_{load,HP}$) need to be run at the given time instant.

$$\begin{aligned} I_{Load}(t) &= I_{Load,HP}(t) + x_{Load,OPT}(t) \cdot I_{Load,OPT}(t) + x_{Load,DEF}(t) \cdot I_{Load,DEF}(t) + \\ &+ \sum_{\tau} [x_{Load,DEF2}(t,\tau) \cdot I_{Load,DEF}(\tau) \cdot (1 - x_{Load,DEF}(\tau)) \cdot \sum_{\zeta} (1 - x_{Load,DEF2}(\zeta,\tau))] \end{aligned}$$

Equation 86: Load constituents: high priority, optional, deferrable

where
$\tau = 0 \ldots t-1$
$\zeta = \tau+1 \ldots \min[t-1, T_{stop}(\tau)-\tau]$
$T_{stop}(\tau)$ = amount of time load from time τ can be deferred.
$x_{Load,OPT} = 1$ or 0, $x_{Load,DEF} = 1$ or 0, $x_{Load,DEF2} = 1$ or 0

The $x_{load,opt}$, $x_{load,def}$, $x_{load,def2}$ can be considered for optimisation.

Instead of dividing the load group at each time instant into high priority, deferrable and optional, this can also be done for individual appliances. However, this is computationally intensive in terms of optimising the different load priorities.

4.3 Power flow

4.3.1 Overview

The system model is based on a description of current flows through the system including efficiency losses. The described power flow can be traced in Figure 43.

The aim of the power flow description is to trace the power arriving at the DC and AC loads. The energy flow is followed from its start at the generating power sources, considering losses and the influence of the operating decisions along the way up to the loads.

It can then be assessed whether the currents being supplied to the AC and DC loads are matching the load requirements. If not, a difference results between electricity supplied and demanded. This difference is positive, if there is an oversupply of electricity; it will be negative if there is an under-supply of electricity. This difference between demand and supply, in form of an under-supply or over-supply of electricity, will then be attributed a penalty or cost/benefit description in the overall system cost function. The overall cost function, or so-called objective function, serves as a figure of merit to assess the quality of a certain system sizing and operation control design.

4.3.2 Constraints on operation

The design objective is to provide energy for the lowest possible costs. Without the additional specification that the demand has to be covered with a predefined reliability, the designed system may not possess any system components at all resulting in zero costs. No energy, however, would be generated or supplied. Through the constraint *'satisfy the demand allowing for certain tasks to be postponed or cancelled when necessary but observing the servicing of high priority tasks'* the model is forced to minimise system energy prices, and is also compelled to meet the demand needs with a sufficient amount of electricity. The electricity produced from PV, wind, diesel and other generator sources and discharged from the battery must add up to cover the demand requirements as economically and efficiently as possible, taking a long-term perspective. The operational constraints can therefore be formulated as saying that the current supply arriving at the AC and DC loads needs to equal the required AC and DC demand levels.

$$I_{DCSupply} \overset{!}{\equiv} I_{DCLoad}$$

Equation 87: DC current supply equals demand DC current

$$I_{ACSupply} \overset{!}{\equiv} I_{ACLoad}$$

Equation 88: AC current supply equals demanded AC current

The following sections derive the current description for the AC and DC supply currents arriving at the AC and DC loads respectively.

4.3.3 AC load supply

At the AC load, the arriving current flow can come from two sources: from the DC bus via the inverter or from the AC bus supplied by the AC electricity generators. The aim of the design is to match the demanded load and the supplied electricity as best as possible (Equation 88). This can be described as follows:

$$I_{ACSupply} = I_{Inv-o/p} + I_{ACBus,o/p}$$

Equation 89: AC current demand covered through the inverter and by the diesel

The amount of AC load that is supplied from the DC bus through the inverter is described by $I_{ACload} \cdot x_s$ (Equation 90, Figure 47). If the inverter has bi-directional operation characteristics, the value of x_s will range between 0 and 1. In case the installed inverter is not bi-directional, the value of x_s will be either 1 or 0. A value of 1 for x_s indicates that all AC load needs are required to be covered by the inverter transformed DC bus output. A value of 0 for x_s indicates that all AC load needs are required to be covered by the AC sources only.

$$I_{Inv-o/p} \overset{!}{\equiv} I_{ACLoad} \cdot x_S$$

Equation 90: Amount of demand to be supplied by the inverter

The amount of AC load that is supplied from the AC bus is described by $I_{ACload} \cdot (1-x_s)$:

$$I_{ACBus,o/p} \overset{!}{\equiv} I_{ACLoad} \cdot (1 - x_S)$$

Equation 91: Amount of demand to be supplied by the AC bus

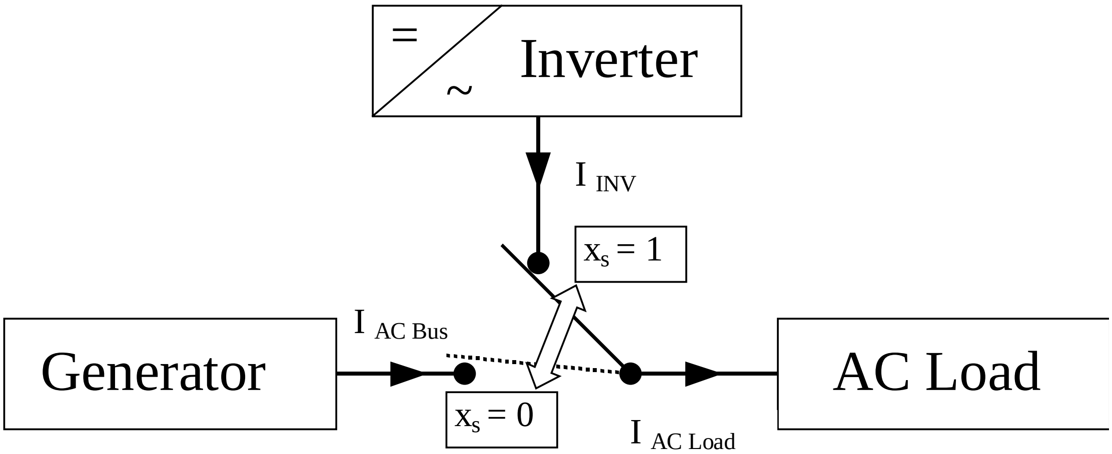


Figure 47: AC load supply

The AC load is supplied with electricity from the AC and DC bus and both contributions are supposed to cover the AC load requirements:

$$I_{ACSupply} = I_{Inv-o/p} + I_{ACBus,o/p} \overset{!}{\equiv} I_{ACLoad} \cdot x_S + I_{ACLoad} \cdot (1 - x_S) = I_{ACLoad}$$

Equation 92: AC load, $x_s \cdot 100\%$ supplied by the inverter, $(1- x_s) \cdot 100\%$ supplied from the AC bus

The AC supply coming from the DC bus through the inverter is composed of as follows:

$$I_{Inv-o/p} = I_{Inv-i/p} \cdot eff_{Inv} \cdot \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}} \overset{!}{\equiv} I_{ACLoad} \cdot x_S$$

Equation 93: Inverter output equated to x_s 100% of AC demand

The AC bus current, from which the AC load is partly or fully supplied, is produced by different AC generating sources such as AC diesel generators, AC renewable energy generators and other AC generators:

$$I_{ACBus} = I_{RE-AC} + I_{Diesel-AC} + I_{o/pOther-AC}$$

Equation 94: Definition of AC bus current

A share of the AC bus current can be routed to the battery charger, and the complementing share can be routed to the AC load. Therefore the decision variable x_{RD} is introduced which reflects the percentage of the AC bus current which goes to the battery charger. (1-x_{RD}) is routed directly to the AC load. The decision variable x_{RD} influences the operation strategy to be adopted for the hybrid system operation. It will be optimised implicitly through optimising the system control settings and thereby defining an optimum system operation strategy.

The part of the AC load that is supplied by the AC bus contribution is then obtained as follows:

$$\begin{aligned} I_{ACBus-o/p} &= (1 - x_{RD}) \cdot I_{ACBus} \\ &= (1 - x_{RD}) \cdot (I_{RE-AC} + I_{Diesel-AC} + I_{o/pOther-AC}) \overset{!}{\equiv} I_{ACLoad} \cdot (1 - x_S) \end{aligned}$$

Equation 95: Direct AC supply equated to (1-x_s) 100% of AC demand

Therefore by combining Equation 93 and Equation 95, the current supplied to the AC load is obtained:

$$I_{ACSupply} = I_{Inv-i/p} \cdot eff_{Inv} \cdot \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}} + (1 - x_{RD}) \cdot (I_{RE-AC} + I_{Diesel-AC} + I_{o/pOther-AC}) \overset{!}{\equiv} I_{ACLoad}$$

Equation 96: AC current supplied to AC load

4.3.4 DC load supply

The arriving current description at the DC load is composed of renewable DC current, battery current, diesel DC current, DC currents from other sources and AC currents routed from the AC bus through the battery charger. It is the task of the optimisation algorithm to match the DC supply current as best as possible to the DC load requirements (Equation 87).

Several DC sources (DC renewable energy sources, DC diesel generators and other possible DC sources) and the DC output of the battery charger generate the DC bus currents (Figure 48).

$$I_{DCBus} = I_{BC-o/p} + I_{DCSources} - I_{Bat}$$

Equation 97: Definition of DC bus current

The battery charger output and the DC source current can be described as

$$I_{BC-o/p} = x_{RD} \cdot (I_{Diesel-AC} + I_{RE-AC} + I_{OtherSources-AC}) \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}}$$

$$I_{DCSources} = I_{RE-DC} + I_{Diesel-DC} + I_{OtherSources-DC}$$

Equation 98: Battery charger output current and definition of DC sources current

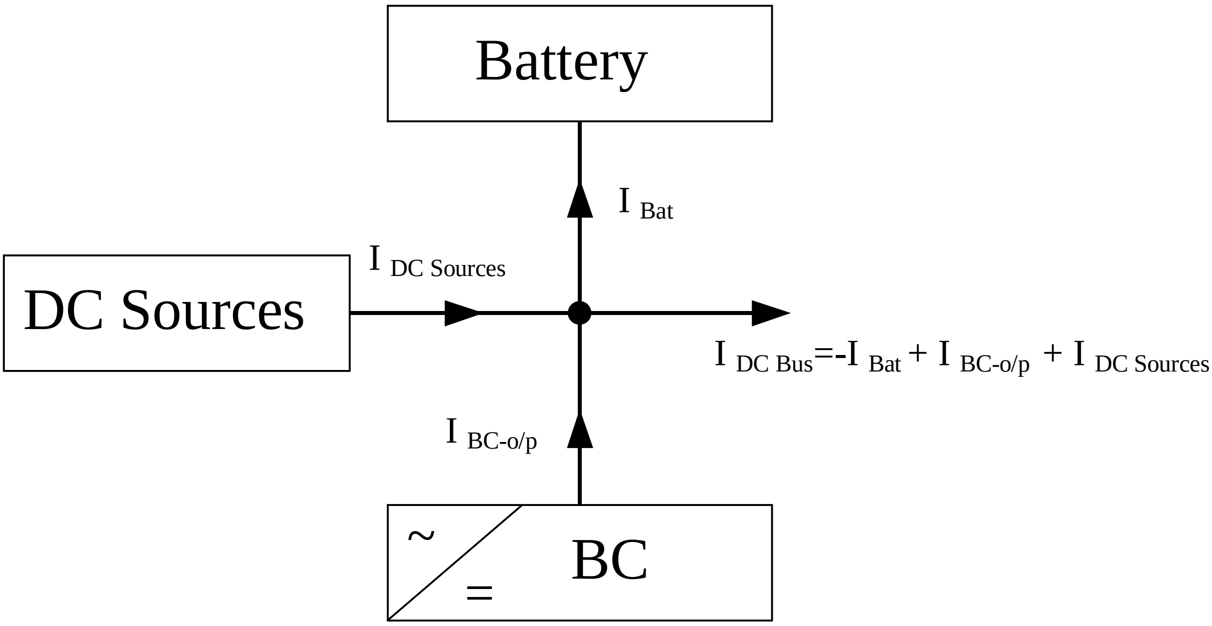


Figure 48: DC bus currents

The DC bus supplies DC current to the DC loads on the bus and to the inverter. The design algorithm needs to ensure that this supply meets the requirements of the loads, that is that it supplies the DC loads sufficiently (with $I_{DCSupply}$) and contributes to the AC loads through the inverter suitably (with $I_{Inv\text{-}i/p}$).

$$I_{DCBus} = I_{DCSupply} + I_{Inv-i/p}$$

Equation 99: DC bus current is split into DC supply current and inverter input current

A share of the DC bus current can be routed to the inverter, and the complementing share can be routed to the DC load. Therefore the decision variable x_R is introduced which reflects the percentage of the DC bus current which goes to the DC load. $(1\text{-}x_R)$ is routed directly to the inverter. The decision variable x_R influences the operation strategy to be adopted for the hybrid system operation. It will be optimised implicitly through optimising the systems control setting and thereby defining an optimum system operation strategy.

The DC load placed on the DC bus obtains the share x_R of the DC bus currents (Figure 49).

$$I_{DCSupply} = x_R \cdot I_{DCBus}$$
$$I_{Inv-i/p} = (1 - x_R) \cdot I_{DCBus}$$
$$x_R \in [0,1]$$

Equation 100: Amount of DC bus current going to the inverter and to the supply of the DC load

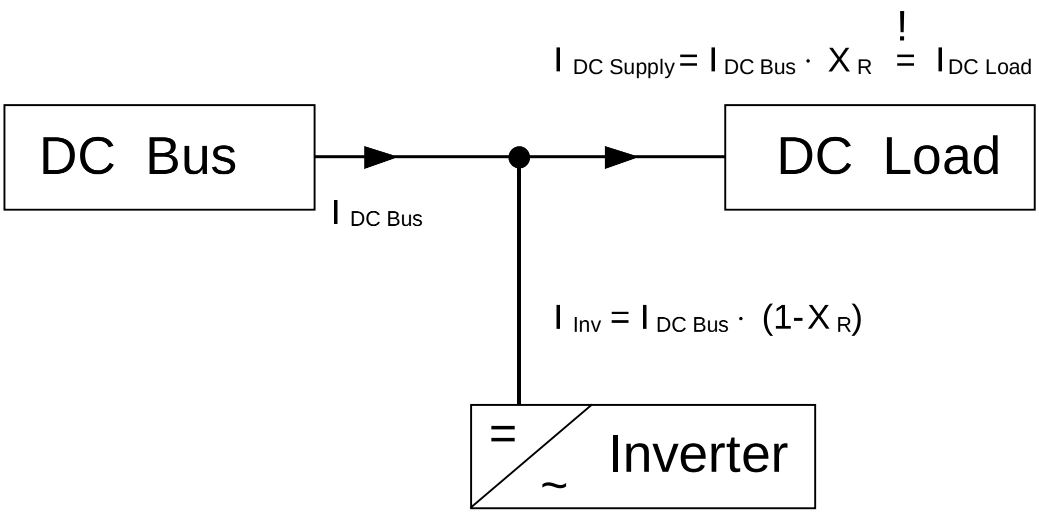


Figure 49: DC bus current routing

The task of the design algorithm is to achieve equal DC demand and DC supply currents.

$$I_{DCSupply} = x_R \cdot [x_{RD} \cdot (I_{ACBus}) \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} + I_{DCSources} - I_{Bat}] \overset{!}{\equiv} I_{DCLoad}$$

Equation 101: DC current supplied to DC load

As a reminder, all these currents depend on the component sizes and the control operational settings.

The design task also includes finding the right amount of DC bus current to go through the inverter to the AC load in order to optimise the overall load supply. The DC bus current going through the inverter is $I_{Inv-i/p}$:

$$I_{Inv-i/p} = (1 - x_R) \cdot [x_{RD} \cdot (I_{ACBus}) \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} + I_{DCSources} - I_{Bat}]$$
$$\overset{!}{\equiv} I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}$$

Equation 102: DC current input to inverter

It is of advantage to reduce the number of design variables that have to be optimised. Therefore x_R is going to be substituted as the amount of AC load that is desired to be supplied through the inverter.

With Equation 101 and Equation 102 we obtain

$$x_R \overset{!}{\equiv} - I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}} \cdot \frac{1}{I_{DCBus}} + 1$$

Equation 103: Determining x_R, the decision on routing percentages between inverter and DC load

Therefore $I_{DCSupply}$ and $I_{Inv-i/p}$ are becoming

$$
\begin{aligned}
& I_{DCSupply} = \\
& = I_{DCBus} - I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}} \\
& = [\, x_{RD} \cdot (\, I_{ACBus}\,) \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} + I_{DCSources} - I_{Bat}\,] - I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}} \overset{!}{\equiv} I_{DCLoad}
\end{aligned}
$$

Equation 104: DC supply relation to AC load and DC bus current

$$
I_{Inv-i/p} \overset{!}{\equiv} I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}
$$

Equation 105: Inverter input and AC load relation

4.3.5 Load balance equations

The load balance equations is the difference between the demand supplied and the demand required for both the DC and AC loads. The aim of the design algorithm is to set this load balance to zero or to a user-defined allowed percentage of unmet or oversupplied load, while minimising system costs.

If the load balance equation is not zero it means that either the demand is oversupplied or undersupplied. In this case of undersupply or oversupply a penalty or cost/benefit description of the excess supply or undersupply is added to the system objective function description which directs design optimisation process.

Therefore the arriving load currents at the DC load should equal the DC demand requirements. If not there is an imbalance which is weighted with a cost/benefit description or penalty description.

$$
I_{DCLoad} - I_{DCSupply} \equiv 0
$$

Equation 106: Definition DC bus balance equation

$$
Imbalance_{DC} = I_{DCLoad} - I_{DCSupply} \neq 0
$$

Equation 107: Definition DC over (<0) or under supply (>0)

$$
\left.
\begin{aligned}
& I_{DCLoad} - \{[x_{RD} \cdot I_{ACBus} \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} + \\
& \quad + I_{DCSources} - I_{Bat}] - I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}\}
\end{aligned}
\right\}
=
\left\{
\begin{array}{l}
< 0 \; Excess \\
0 \;\; Balance \\
> 0 \; Unmet
\end{array}
\right\}
$$

Equation 108: DC Imbalance equation

$$x_S = \frac{I_{DCBus} - I_{DCLoad}}{I_{ACLoad} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}}$$

$$\Leftrightarrow x_S = \frac{1}{I_{ACLoad} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}} \cdot \left(\left[[x_{RD} \cdot I_{ACBus} \cdot eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} + I_{DCSources} - I_{Bat}] \right] - I_{DCLoad} \right)$$

Equation 109: Determining x_S, the decision on output share between inverter and AC bus

The arriving current flow description at the AC load is the amount of inverter output current and diesel current on the AC bus routed to the AC load (Equation 89) and should equal the amount of AC load demanded (Equation 88):

$$I_{ACLoad} - I_{ACSupply} \equiv 0$$

Equation 110: Definition AC bus balance equation

$$Imbalane_{AC} = I_{ACLoad} - I_{ACSupply} \neq 0$$

Equation 111: Definition AC over (<0) or under supply (>0)

$$\left. \begin{aligned} & I_{ACLoad} - \{(1 - x_{RD}) \cdot I_{ACBus} + \\ & + [I_{DCSources} - I_{Bat} - I_{DCLoad} + eff_{BC} \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot x_{RD} \cdot I_{ACBus}] \cdot eff_{Inv} \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}} \} \end{aligned} \right\} = \left\{ \begin{matrix} < 0 \; Excess \\ 0 \; Balance \\ > 0 \; Unmet \end{matrix} \right\}$$

Equation 112: AC Imbalance equation

$$x_{RD} = \frac{(I_{ACBus} - I_{ACLoad}) + (I_{DCSources} - I_{Bat} - I_{DCLoad}) \cdot eff_{Inv} \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}}}{I_{ACBus} \cdot (1 - eff_{BC} \cdot eff_{Inv})}$$

Equation 113: Determining of x_{RD}, the routing decision for the diesel generator output

Then it follows that

$$x_S = \frac{(I_{DCSources} - I_{Bat} - I_{DCLoad}) \cdot \frac{1}{1 - eff_{Inv} \cdot eff_{BC}} + (I_{ACBus} - I_{ACLoad}) \cdot \frac{eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}}}{1 - eff_{BC} \cdot eff_{Inv}}}{I_{ACLoad} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot \frac{1}{eff_{Inv}}}$$

Equation 114: x_S in terms of DC and AC load, and DC and AC resources

Plugging in x_{RD} and x_S into the equations for $I_{ACSupply}$ and $I_{DCSupply}$ yields I_{ACLoad} and I_{DCLoad} respectively. However, x_{RD} and x_S can only take on certain values between 0 and 1 therefore it can happen that for values of x_{RD} and x_S outside this range the DC and AC loads are not covered exactly, but an imbalance occurs through oversupply or undersupply of electricity.

In order to determine the overall unmet or dumped load in a system, it is useful to be able to express the overall current imbalance and overall required load current in either AC or DC.

The AC and DC imbalance equations can be converted into each other by

$$Imbalance_{DC} = Imbalance_{AC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom} \cdot eff_{Inv}}$$

Equation 115: DC/AC external conversion

The overall load in AC and DC can be expressed as:

$$Load_{AC} = I_{ACLoad} + I_{DCLoad} \cdot eff_{Inv} \cdot \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}} = Load_{DC} \cdot eff_{Inv} \cdot \frac{U_{DCBus,Nom}}{U_{ACBus,Nom}}$$

Equation 116: Overall load placed on the system expressed in DC and AC current

4.3.6 Operation strategy formulation

4.3.6.1 From operation decisions at each time instant to control strategies

In the previous sections the flow of currents in the hybrid system has been described and modelled. The current flow depends on the size and number of devices as well as the operation decisions at each time instant. The operation decisions identified were routing and switching decisions as well as battery and diesel output current decisions. As shown in the previous sections, the routing and switching decisions could be derived from solving the DC and AC balance equations at different nodes in the hybrid system network.

Therefore, the remaining operation decisions at each time instant concern the battery and diesel output current levels. The operation decisions can be optimised for every time step. However, this demands much computing time as optimising the output current levels at each time instant requires a large number of decision variables to be optimised if the simulations is carried out over a large number of time intervals. In addition, adjusting the battery and diesel current output levels at each time instant in a field-operated hybrid system in a remote area is difficult as it would require reliable weather and demand estimates to be available to the system control. The system control would have to be very sophisticated and well tested. The system operation would be vulnerable to any malfunctioning or failures of the control electronics or to the reliability of the data estimates upon which the control strategy was based.

Therefore the development of optimised system control strategies, rather than optimised operating decisions at each time instant, has been undertaken. A control strategy consists of certain predetermined control settings that are set when installing the system. Such settings concern the timing of when to switch on the diesel or not, based on certain values representing the system state, such as the battery state of charge and demand placed on the system. The general time-independent controller settings are modelled and optimised in the developed design algorithm instead of optimising every decision variable at each time instant.

In order to develop operation strategies, the battery and diesel output levels need to be linked to adjustable control settings for a field-operated hybrid system. The battery and diesel output levels are contained in the diesel and battery current equations (Equation 117, Equation 120) derived from the DC and AC balance equations.

$$I_{Bat} = ((1-x_{RD}) \cdot I_{ACBus} - (1-x_S) \cdot I_{ACLoad}) \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom} \cdot eff_{Inv}} +$$
$$+ I_{DCSources} - I_{DCLoad} + eff_{BC} \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom}} \cdot I_{ACBus} \cdot x_{RD}$$

$$I_{ACBus} = I_{Diesel-AC} + I_{RE-AC} + I_{OtherSources-AC}$$
$$I_{DCSources} = I_{RE-DC} + I_{Diesel-DC} + I_{OtherSources-DC}$$

Equation 117: Battery current I_{bat} based on DC balance equation

The battery can accept as charge at time t:

$$I_{Bat,ch}(t) = Max[\ 0, Min\ [(\frac{SOC_{max} - SOC(t)}{\Delta t}), I_{Bat\,max\,Ch}, I_{BatsysCh}\ ]],$$

Equation 118: Battery charging current

where $I_{batmaxch}$ is the maximum allowed charging current. $I_{batsysch}$ is the charge the system wants to supply to the battery

The battery can discharge at time t:

$$- I_{Bat,Dh}(t) = Max[\ 0, Min\ [(\frac{SOC(t) - SOC_{Min}}{\Delta t}), I_{Bat\,max\,Dh}, -I_{BatsysDh}\ ]],$$

Equation 119: Battery discharging current

where $I_{batmaxdisch}$ is the maximum allowed discharging current

$I_{batsysdisch}$ is the discharge the system needs from the battery.

$$I_{Diesel-AC} = (I_{DCLoad} + I_{ACLoad} \cdot x_S \cdot \frac{U_{ACBus,Nom}}{U_{DCBus,Nom} \cdot eff_{Inv}} + I_{Bat} - I_{DCSources}) \cdot \frac{U_{DCBus,Nom}}{U_{ACBus,Nom} \cdot eff_{BC}} +$$
$$+ I_{ACLoad} \cdot (1-x_S) - I_{RE-AC} - I_{OthSources-AC}$$

Equation 120: Diesel current based on AC balance equation

All these variables are time-dependent.

Both the diesel output current and battery current equations can be converted into each other. Once either the battery or diesel current output level is determined, the other one follows automatically.

4.3.6.1.1 Prefer AC diesel generator bank

If the AC diesel current output is determined first, then it is realistic to assume that the AC diesel array output level should be as high as possible in order to obtain a high capacity loading level and a high output/cost ratio. Therefore the AC diesel generator bank will cover as much as possible of the AC load share not covered by any AC renewable energy sources, the maximum possible battery charge acceptance, and maybe any remaining uncovered DC demand.

AC demand not coverable by AC diesel bank

If the diesel generator cannot fully supply the AC demand that was not covered by any available AC renewable energy sources, then the AC demand could be additionally covered by the inverter output (bi-directional inverter) or covered by the inverter output instead of the AC bus output (normal inverter).

For the latter case, the decision whether to direct the AC diesel output to the AC load, or to the DC bus and use the inverter output to cover the AC demand, depends on which option yields the lowest unmet AC demand.

Determining DC output levels

After having determined the AC diesel generator output level through this process, the DC battery output level and DC diesel generator output levels can be derived for the case that further DC currents on the DC bus are needed. Here again a decision might have to be made whether the DC diesel output is determined before the battery output level.

Prefer DC diesel array

If the DC diesel generator output is determined first, then again the highest possible loading factor for the DC diesel is desired, and the battery covers any additional DC current requirements.

Prefer battery bank

In case the battery output level is determined first before the DC generator output level for covering any additional energy requirements which the AC diesel generator was not able to cover, the battery discharges as much as possible to meet the required DC current levels. If the battery cannot supply the required DC currents, the DC diesel generator is used instead and its output is determined, again to yield highest possible load levels and any remaining DC current requirements are tried to be covered by the battery bank.

4.3.6.1.2 Prefer battery bank

In case the battery output level is determined before the AC diesel generator output level, then if the battery bank can cover the AC and DC loads together with renewable and other energy sources, the battery is discharged with the appropriate level.

In case the battery plus renewable energy sources cannot achieve demand coverage, the ‘prefer AC diesel array’ option is executed.

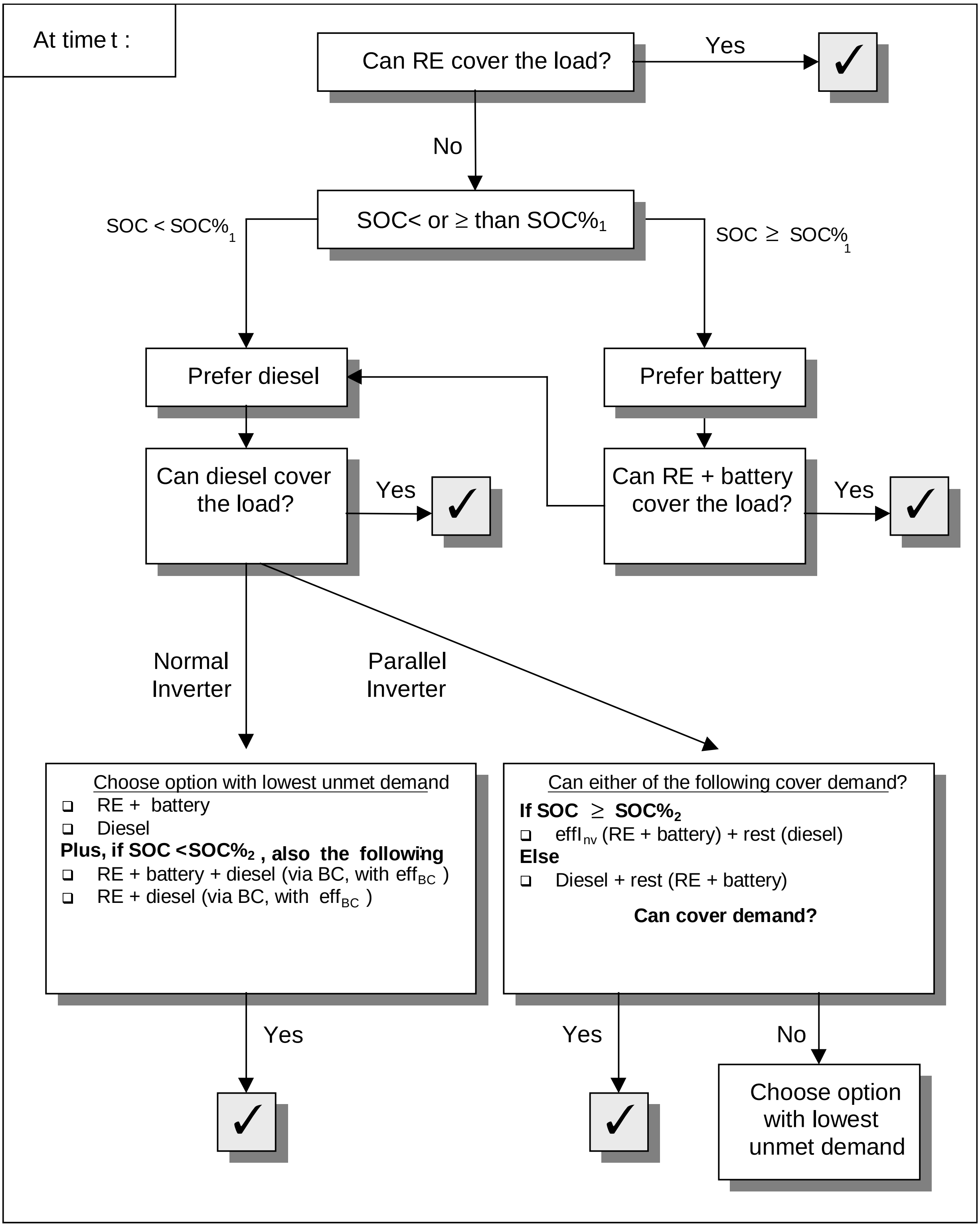


Figure 50: Overview over the decision strategy for system operation

4.3.6.2 Control settings linked to system state

The previous sections developed the operation decision equations from the DC and AC bus balance equations and identified the decision-making for the operation decisions at each time instant assuming certain 'preference' settings. The decision-making is demonstrated in Figure 50 showing the different possible operation decisions at a time instant depending on the 'preference' settings.

As can be seen the decision-making depends on the amount of demand that could not be covered by renewable energy sources, and the ‘preference’ setting regarding component usage.

That means the only actual ‘outside’ or controller decision-making occurs when determining which components to prefer namely the battery bank, AC diesel generator or DC diesel generator, to satisfy the AC and DC load requirements.

If several battery banks and several diesel generators exist, the decision making indicates in which order to prefer the different diesel generators and battery banks in the system to cover the AC and DC loads. This decision depends on the efficiency with which the different diesel generators and batteries can cover the loads. Therefore in a case where several diesel generators are available to cover the load, then the generator or the combination of generators is chosen which have together the closest nominal power rating to the desired load level.

If additional other DC or AC energy sources are available, the decision making needs to be extended to include those as well in the preference settings.

In order to optimise the component preference settings, they have to be linked to system state indicators. The main system state indicators are the state of charge of a battery bank, the diesel capacitor factors, the achieved system reliability and the diesel runtimes.

The preference settings are encoded when installing the system controller. During system operation, the system is operated according to the answers ‘yes’ or ‘no’ to the preference questions, i.e. whether the values of the battery state of charges and the diesel capacity factors are in the range as predefined in the controller settings. Also included can be the number of times the batteries have reached full state of charge or have been in the minimum state of charge, as well as the number of diesel runtime hours.

The boundaries of these decision ranges can then be optimised by the algorithm which is a big advantage over optimising each operation decision at each time instant because the boundaries are valid for the whole simulation interval and do not change at every time instant.

To illustrate the following example is given:

Table 4: Example on component preference decision making

4.3.6.3 Prefer diesel generator to battery	***4.3.6.4 Prefer battery to diesel generator***
IF SOC of battery is between s_{A1}% and s_{A2}%.	IF SOC of battery is between s_{B1}% and s_{B2}%.
AND	AND
IF capacity factor of diesel generator is between c_{A1}% and c_{A2}%.	IF capacity factor of diesel generator is between c_{B1}% and c_{B2}%.

The ranges c_{Ai} and c_{Bi}, as well as s_{Ai} and s_{Bi} are optimised. The more components used, the more control setting decision ranges need to be optimised.

The output of minimising the objective function is the desired decision variables for operation control settings and sizing. They give a system design which, when operated according to the operational control settings, will yield satisfactory electricity supply at lowest life cycle costs.

4.3.6.5 Formulation of system performance indicators

An indication of the overall system performance of the designs is given in terms of the ratios between supplied and generated energy, and the average ratios for battery cycling and diesel loading.

$$Index_{Performance} = \frac{SuppliedEnergy}{GeneratedEnergy} = \frac{P_{DCSupply} + P_{ACSupply}}{P_{DCSources\backslash Bat} + P_{ACSources}}$$

Equation 121: Overall system efficiency as performance index

$$Ratio_{BatteryCycling} = \frac{\sum_{t=1}^{T} SOC(t)}{SOC_{Max} \cdot T}$$

Equation 122: Average battery cycling ratio during a time interval

$$Ratio_{DieselLoading} = \frac{\sum_{t=1}^{T} Power_{Diesel}(t)}{Power_{Diesel,Max} \cdot T}$$

Equation 123: Average diesel generator capacity loading during a time interval

These ratios are useful when comparing different designs for the same or similar application.

4.4 Summary

The developed hybrid system performance model has been presented in this chapter. Thereby the component models, the power flow between energy sources and demand and the modelling of the operation strategy was presented.

The sizing variables, i.e. sizes of component types and their number to be installed, which are desired to be optimised were collected in a vector x_{size}. The operation decision variables to be optimised represent routing and operation decisions that are based on the power flow modelled for the hybrid system in this chapter. The hybrid system model needs to be optimised with respect to the decision variables x_{Size} and $x_{OpStrat}$ such that a minimum of the life cycle costs is achieved. Table 5 gives an overview over the main decision variables used in the optimisation.

As it is computationally intensive to optimise each individual decision variable for the operation decisions at each time instant, an alternative was to formulate, within the model and based on the operation decisions, possible operating strategies that can be implemented in the field with available controllers. The optimisation then does not have to find the optimal value for each $x_i(t)$, but will find the optimal values for the time-independent controller settings, which requires less computation.

The identified decision-making for the operation decisions at each time instant depends on the amount of demand that could not be covered by renewable energy sources, and the ‘preference’ settings regarding which components to prefer to satisfy the AC and DC load requirements. The decision which component to prefer is made between the battery bank, AC diesel generator or DC diesel generator.

The component preference settings are linked to system state indicators such as the state of charge of a battery bank, the diesel capacitor factors, the achieved system reliability and the diesel runtimes.

During system operation, the system can be operated according to whether the values of the battery state of charges and the diesel capacity factors are in the range as predefined in the controller settings. Because only the time-independent boundaries of these decision ranges need to be optimised by the developed algorithm this is a big advantage over optimising each operation decision at each time instant.

With Chapter 3 and 4 the modelling of the hybrid system has been presented and Chapter 5 will describe how based on the modelling the optimisation algorithm is implemented.

Table 5: Overview over the decision variables in the hybrid system performance model

Modelling steps	Decision variables x
Sizing	$x_{Size} = [\, x_{PV,parallel}, x_{WT,parallel}, x_{sizeD}, x_{bat,parallel}, x_{sizeBat}, inverter_{type}, batch\arg er_{type}, x_{sizeOtherSources}\,]$ Equation 124: Sizing optimisation variables
Operation decisions	$x_{OpDec}(t) = [x_{bat}, x_{diesel}, x_S, x_R, x_{RD}, x_{RInv}, x_{RBC}, x_{load}](t)$ Equation 125: Operation decisions to be optimised at time t
Operation strategy	$x_{OpStrat} = [\, x_{SOC\%1}, x_{SOC\%2}, x_{UnmetLoad}\,]$ Equation 126: Time independent operation strategy
Constraints	$I_{DCSupply}(t, x_{Size}, x_{OpStrat}) \overset{!}{\equiv} I_{DCLoad}(t), \quad I_{ACSupply}(t, x_{Size}, x_{OpStrat}) \overset{!}{\equiv} I_{ACLoad}(t)$ Equation 127: Constraints on operation
Objective Function	$LCC = CaptialCosts(x_{Size}, x_{OpStrat}) + Discounted\ OperationCosts(x_{Size}, x_{OpStrat})$ Equation 128: Life cycle costs as dependent on sizing and operation strategy

Chapter 5

Simulation

5.1 Introduction

The development of the model that forms the basis of the simulation algorithm to optimise hybrid system design was explained in the previous chapters. The model and an optimisation algorithm, that uses genetic algorithms to optimise the model parameters, were implemented with the computer language MATLAB©. The simulation runs with MATLAB© are useful to verify the developed optimisation model through evaluating the validity of the simulation outcomes and the match between the simulation outcomes and real system operation and sizing in the field. The simulation is performed to present the algorithm as a new and improved tool to use in optimising hybrid system design.

MATLAB© is a user-friendly computing language that is not using computer hardware resources in an optimal way. In addition to the MATLAB© implementation, the algorithm has been implemented as part of a project for the Department of Minerals and Energy of South Africa, entitled: 'Hybrid system design as applied to Reconstruction and Development Programmes (RDP) projects in rural areas'. Thereby the algorithm is being implemented in C++ with a very sophisticated, user-friendly interface. The simulation runs in this thesis are based on the MATLAB implementation, as it allows for more flexibility for research purposes and because the C++ version was not finished at the time of writing. The C++ version of the algorithm is described in [Kuik et al-97].

The following sections will go through the structure of the developed algorithm, describe the simulated case studies, compare the simulation performance with other optimisation methods and with data of real implementations. A summary will be given at the end of the chapter.

5.2 Structure of the Implemented Computer Algorithm

In general, an optimisation algorithm is changing decision variables of a model in such a way as to minimise (or maximise) the model's performance indicator (Figure 51). The change in the values of the identified variables is achieved by applying specifically defined optimisation procedures to every iteration of the algorithm, until a desired level of convergence is achieved. In case of the hybrid system design optimisation, the hybrid system model and the corresponding variables to be optimised have been produced in Chapter 4. The input parameters are weather and demand data, as well as data on component characteristics and costs. For the optimisation, genetic algorithms have been chosen - as was explained in Chapter 1 - in order to be able to model the hybrid system with a high degree of accuracy. The more accurate the underlying model of an optimisation is, the more exact the simulation results become. Genetic algorithms have the advantage that they do not require partial system gradient calculations. Often these gradients do not exist or their calculation can become too cumbersome and lengthy to be implemented effectively in a computer optimisation algorithm. For this reason many optimisation models, for which classic optimisation methods are used, tend to be highly simplified, thereby impacting on the quality of the produced results.

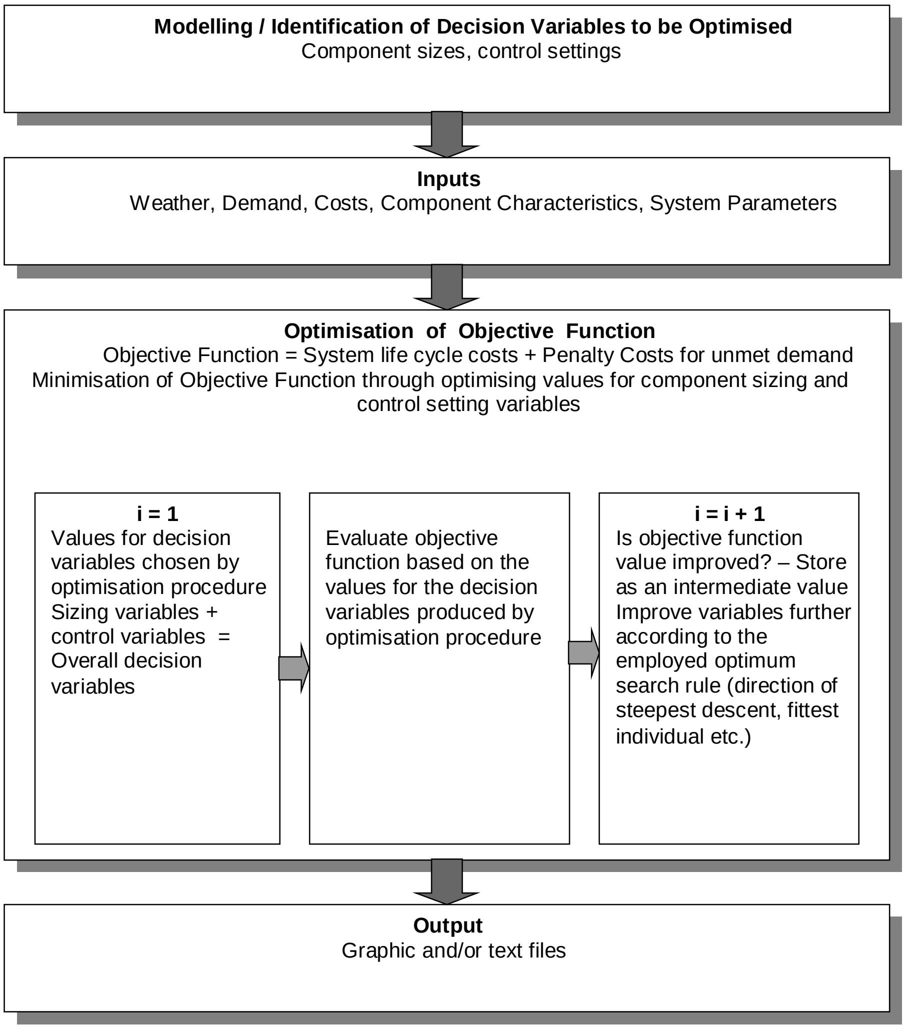


Figure 51: General structure of an optimisation algorithm

5.2.1 Algorithm Goals

The developed optimisation algorithm for hybrid system design has two general goals: choosing the sizes of hybrid system components and the operation control of a hybrid system in such a way that the system net present value costs will be minimised while yielding reliable system performance. The latter is defined in terms of satisfying both demand requirements and operating system components economically in terms of replacement and maintenance needs.

The aim in implementing the algorithm was to accommodate realistic component sizes available on the market, together with their individual operating and costing characteristics, to determine a recommendable hybrid system design. Another feature implemented was to produce an output data file that contains the system operation, the sizing and the net present value costing in a meaningful format, which can also be exported to a spreadsheet program for more detailed examination. The algorithm implementation has shown that the developed hybrid system design model and the applied optimisation algorithm using genetic algorithms is a new and innovative tool for optimising hybrid system design.

5.2.2 Simulation approach

The developed optimisation process utilises genetic algorithms to change the variables of the hybrid system model, in terms of sizing and operation, in such a way as to minimise the life cycle costs or net present value costs of the hybrid system design while meeting demand requirements.

Minimising net present value costs and minimising unsatisfied demand are achieved not only by selecting an appropriate system configuration, i.e. a set of values for the sizing variables, but also by optimising system controller settings, i.e. the values for the operation decision variables, as part of a system operation strategy. The sizing and operation variables taken together constitute the decision variables of the hybrid system model that are optimised by the genetic optimisation algorithm. The optimised controller settings enable suitable operation decisions on-line, taking account of the operational requirements of system components and the demand to be serviced. The operating strategy adopted in handling the hybrid system combined with the sizing choice affects system costing, system performance and degradation and ageing of components.

The goals of sizing a system to minimise costs and operating a system to yield best possible system performance are interlinked and influence each other (Figure 52). This is due to the fact that the sizing of components is related to the operation strategy adopted for a system. On the other hand, the type of operation strategy that can be implemented also depends on component sizes.

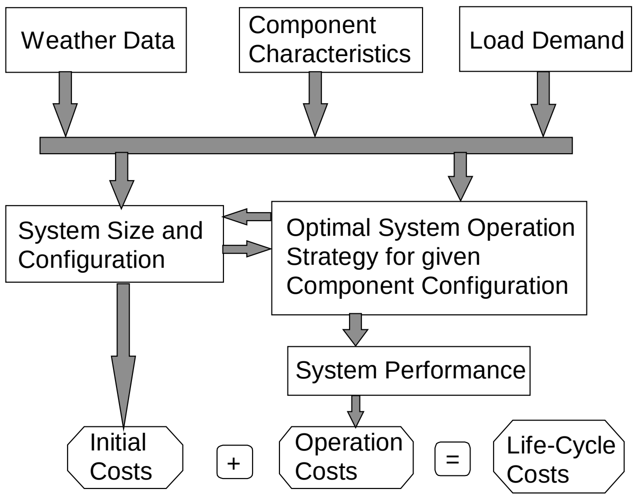


Figure 52: Interdependence between system sizing and operation

This interdependence between sizing and operation control has been taken account of in the developed algorithm. The genetic algorithm finds a set of values for the decision variables of the hybrid system model. With these values the sizing of the hybrid system is calculated in the so-called main algorithm. Each sizing configuration in the main algorithm communicates with a so-called sub-algorithm, which implements the design of the system operation using the values for the operating decision variables from the genetic algorithms.

It is important that the chosen operating actions are beneficial to the system in its long-term performance and long-term cost efficiency. A very good short-term operating decision might not be optimal in a long-term perspective of achieving low costs and satisfying system performance.

Thus, the operation performance for a hybrid system configuration needs to be simulated and evaluated over a period of time, not only at one time instant. However, if component output levels at each time instant were taken as decision variables to be optimised then the amount of optimisation variables would be very large if every possible operation decision (diesel currents, battery currents, switch positions, routing percentages) at each time instant were to be evaluated. The advantage of using controller settings as operation decision variables instead is that the amount of decision variables and computation is greatly reduced (see also the corresponding discussion in Chapter 4). In addition, the solution can be more readily implemented in real life applications through adjusting controller settings correspondingly.

Different operation strategies can be envisaged. Some use the renewable energy sources plus the energy stored in the battery to cover demand, and switch on the diesel only as a back-up. Alternatively, the diesel can be employed to cover the bulk of the demand and other energy sources are used as an additional source for small load levels. In some operating strategies, the diesel, once it is switched on, is required to run for some time period. Or the diesel is only run if it has a capacity load above a certain amount. Other strategies switch on the diesel when the battery is discharged to a certain level, or only use renewable energy sources to charge the battery once it has reached a certain level of charge. Many different strategies have been researched, e.g. in [Barley *et al*-95].

The control settings in the algorithm that determine the decision or operation strategies, are linked to the amount of battery state of charge and the amount of demand not met with the renewable energy sources alone. The control settings decide whether to prefer the battery or the diesel to cover DC or AC loads.

Figure 53 gives an overview of the implemented algorithm. The following sections explain the hybrid system sizing and choice of its operational settings, as implemented in the algorithm, in more detail.

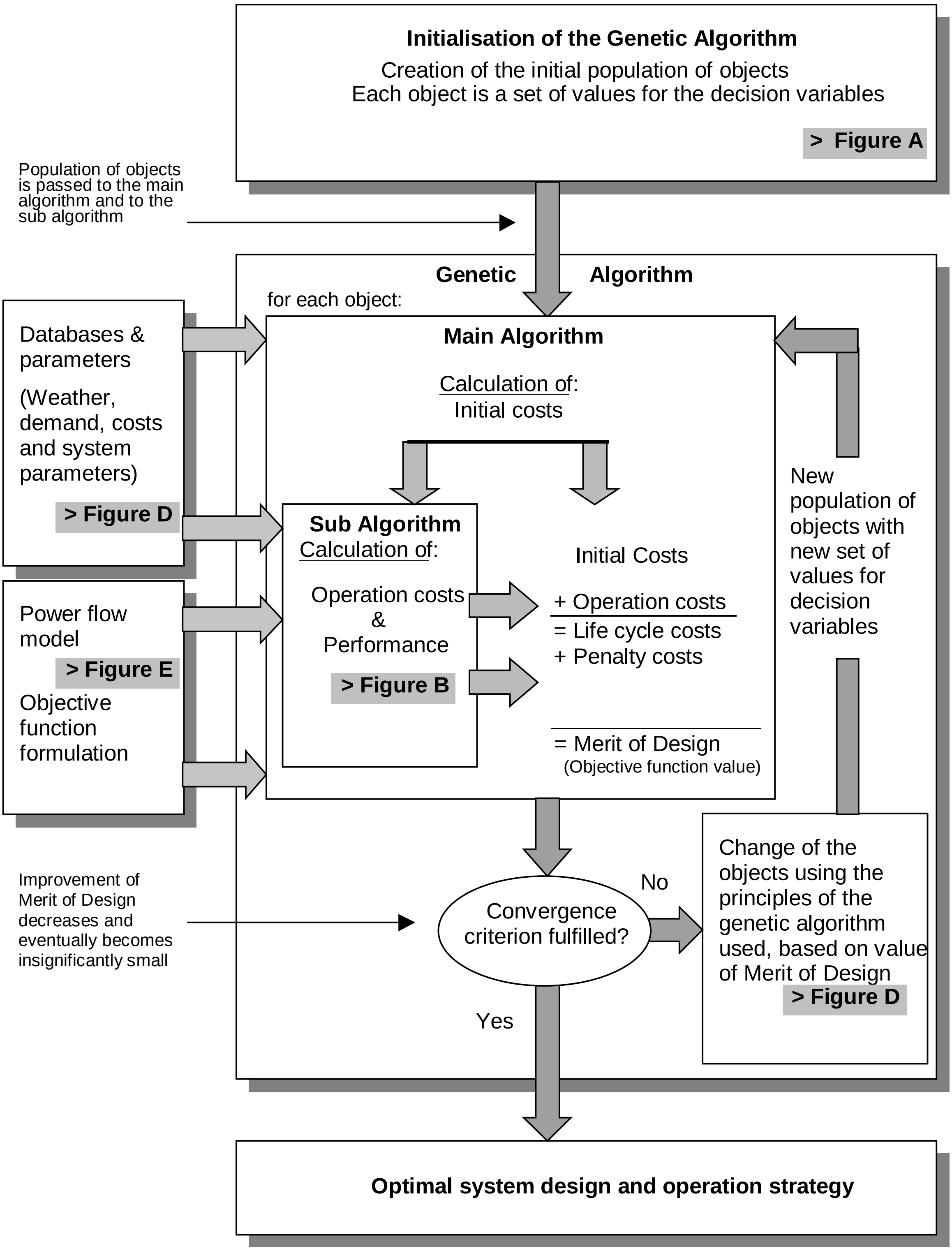


Figure 53: Overview over developed algorithm (for Figures A,B,C,D,E see Figure 55, Figure 54, Figure 56, Figure 57, Figure 43 plus Figure 50 respectively)

5.2.2.1 Sizing

The main algorithm produces the configuration and mix of system components for the initial system installation. The decision variables are the size of the capacities of components such as diesel generator, PV array, wind turbine, battery and others; the numbers of each component type, and relevant installation parameters.

Its goal is to find a suitable system set-up for the given demand, weather data and available components while minimising costs and maximising performance.

The system component mix is initially chosen randomly within certain reasonable limits. The main algorithm passes the currently computed system configuration, in form of capacities, numbers and initial costs of components on to the system performance simulation in the sub-algorithm. There the values of the system control settings are evaluated and the resulting operating costs and operational performance for the given component mix are investigated. For this purpose the individual component characteristics and costs are downloaded from the database. The operational performance and costs are then passed back to the main algorithm.

5.2.2.2 Control settings

The sub-algorithm evaluates the long-term system operation and resource allocation of the available capacities to meet the electricity demand, while calculating fuel and other operating costs for a given system configuration.

The information available to the sub-algorithm consists of the system configuration and its initial costs, as passed on by the main algorithm, the local weather data or the renewable energy outputs, and the demand. Operation costs for maintenance, overhaul, replacement, refuelling, and administration, together with characteristic component operation data are downloaded from the component information as entered by the user of the algorithm. The power flow of the system is then calculated as described in Chapter 4, using the values for the operation decision variables as generated by the genetic algorithm. The decision variables are equivalent to controller settings that enable certain operations as a function of battery state of charge and demand level. During on-line operation these controller settings yield suitable battery and diesel operation for good reliable long-term system performance at low costs.

Based on the control setting values, supplied and varied by the genetic algorithm, the sub-algorithm assesses the merit of the operation strategy over the project life by calculating running and life cycle costs, and performance efficiency. During the simulation a tally is kept of the amount of use of each component, e.g., the number of running hours. The corresponding costs and discount factors are then compiled, enabling the discounting of the non-regular operation costs. The life cycle costing part of the algorithm extrapolates system performance and operation cost data over the project life time and discounts future maintenance, overhaul and replacement activities.[3] Finally, all the discounted cashflows are summed to obtain the life cycle costs. In many cases these are also called net present value costs.

The sub-algorithm passes the life cycle costing and system performance of the operation strategies to the main algorithm (see Figure 54).

[3] The net present value costs are the sum of initial costs and discounted operation costs. The initial capital costs occur at the beginning of the project time frame without discounting. Costs that occur at regular time intervals such as monthly administration costs are accumulated for a year and are then discounted over the project life. Costs that depend on usage require information from the system performance, and can be estimated or more accurately simulated [Marrison,Seeling-Hochmuth-97].

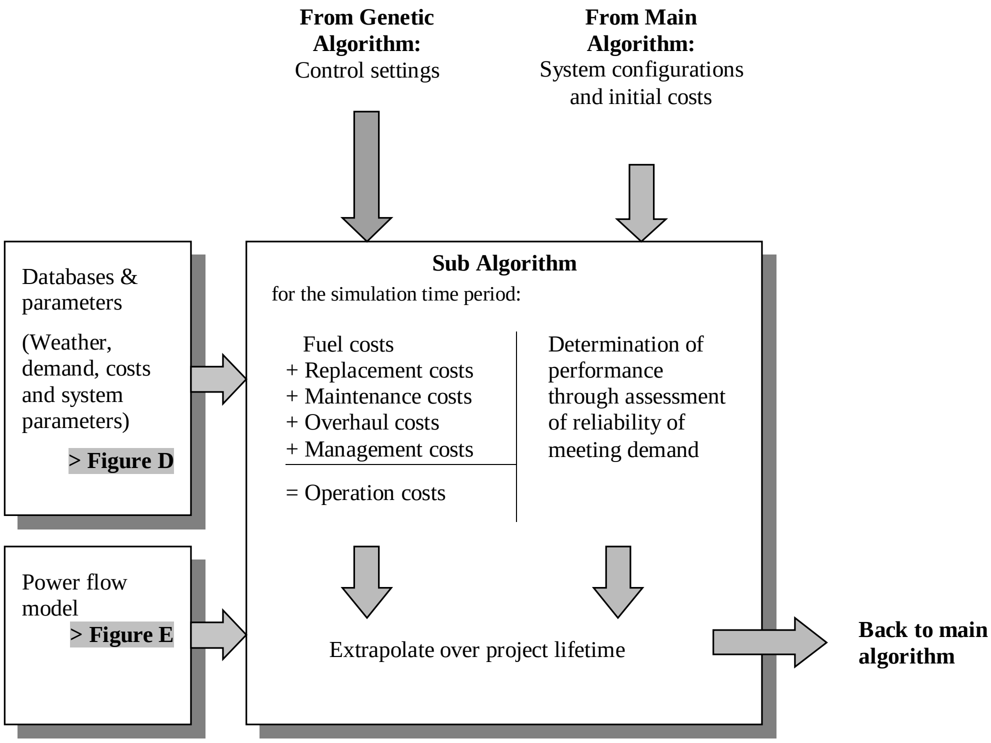


Figure 54: Set-up of the sub-algorithm (for Figure D and E see Figure 43 plus Figure 50, and Figure 57 respectively)

5.2.2.3 Optimisation of the objective function

The main algorithm determines the quality, or merit, of each system sizing and operating strategy through calculating the value of the corresponding objective system function; which is a combination of life cycle costs, and benefit or penalty costs for unmet demand (see Chapter 3). As a reminder, the life cycle costs and benefit or penalty costs are calculated using the values of the decision variables generated by the genetic algorithms.

The genetic algorithm continues to vary the component sizes and types, and the control settings until the achieved improvements become insignificantly small and the algorithm is terminated.

The genetic optimisation strategy for the hybrid system design problem works as follows: the different decision variables for the component sizes and the operation actions are collected in one vector, as indicated by the box in Figure 55.

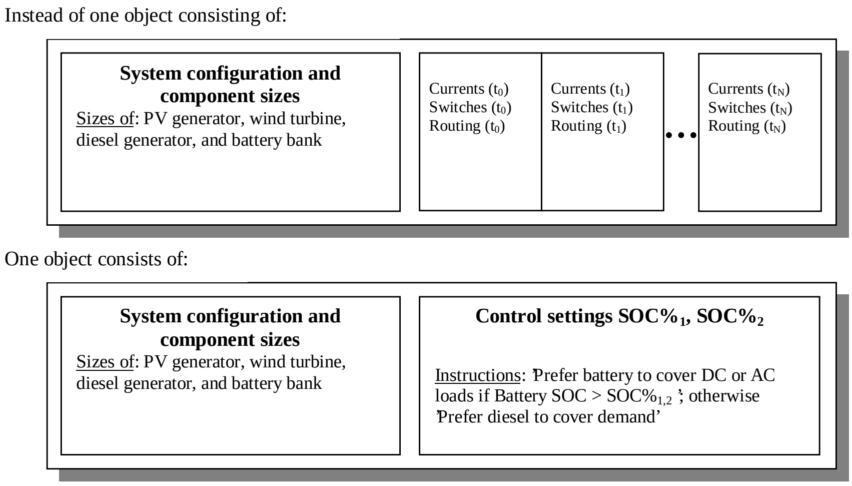


Figure 55: Object structure for the optimisation

Each different combination of these parameters can constitute a possible object. The numbers of variables of one object are the number of variables for the component sizes, and the number of operation setting variables. The aim is to find the best possible combination of component sizes in conjunction with recommendable operating actions to meet a given demand profile while minimising the given cost function subject to component sizes and their operating characteristics available on the market.

The number of objects in one population, i.e. in one iteration, is initialised by the genetic optimisation strategy according to the size of the problem. In addition, to speed up the search process for optimum combinations, the computations can be carried out with several populations, also called 'sub-populations', at the same time instead of using only one population. The number of sub-populations is also determined by the genetic optimisation method but can be changed by the user. The maximum number of iterations or object generations can be limited as well.

The algorithm is given the time interval over which to perform the optimisation as well as the weather data, demand data and renewable energy output over that time period. The nominal operating voltages and constraints on the sizes of renewable and non-renewable energy sources as well as battery capacity are also stated.

Each population consists of a certain number of objects. The variables of all these generated objects of one generation, i.e iteration, are collected in a matrix. On this matrix the genetic optimisation operations are performed through the processes of

- selection (selecting the best objects and a few other objects randomly for creating new objects),
- recombination (mixing values between 2 selected objects),
- mutation (changing values in one object) and
- reinsertion (reinserting the newly formed objects into the 'old' population to form the 'new population'),

(see Chapter 1) in order to produce new objects and to improve the quality of the objects (Figure 56).

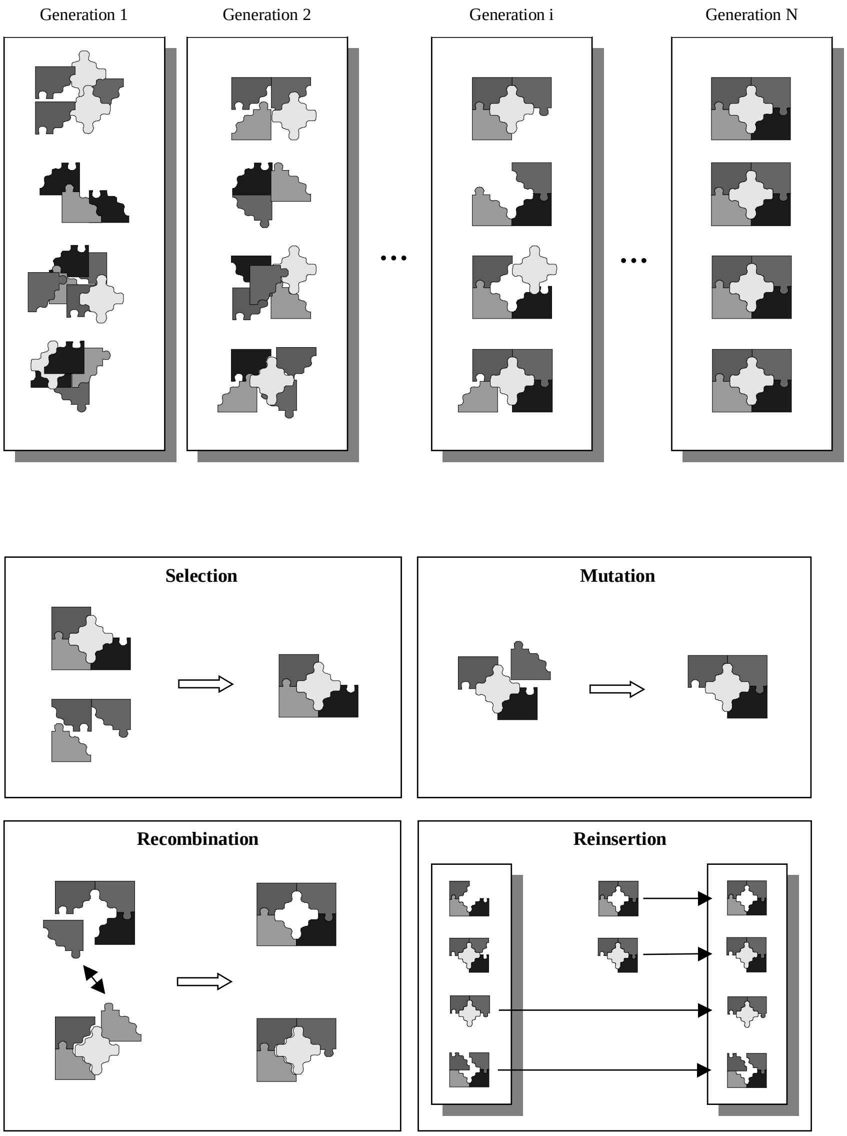


Figure 56: Genetic optimisation procedure

At the end of the genetic optimisation, the best objects (which should all be more or less the same by now) are chosen and recommended to the system designer. In addition, the time series' of the technical performance of the systems are displayed, and the financial cost flows are shown for the best systems.

5.2.3 Input data

The design process requires initial information (Figure 57) in order to determine an appropriate hybrid system that will match local conditions and needs. The information used to initialise the algorithm describes characteristic data for the region and location where the implementation of a hybrid system is considered. The data required from the users are specifics about their electricity demand requirements, weather conditions, and descriptions of available components, including operation characteristics and costs. Other site characteristics are local costs for maintenance and operation, economic factors, and costs of transport etc. Demand can vary between working days and weekend or holidays. In addition, seasonal variations can exist. Demand can also change over time. If possible, this should be considered in designing and planning a system. Management of demand is also an important consideration in constructing a demand profile as it can reduce the system costs substantially if demand is adapted to available energy.

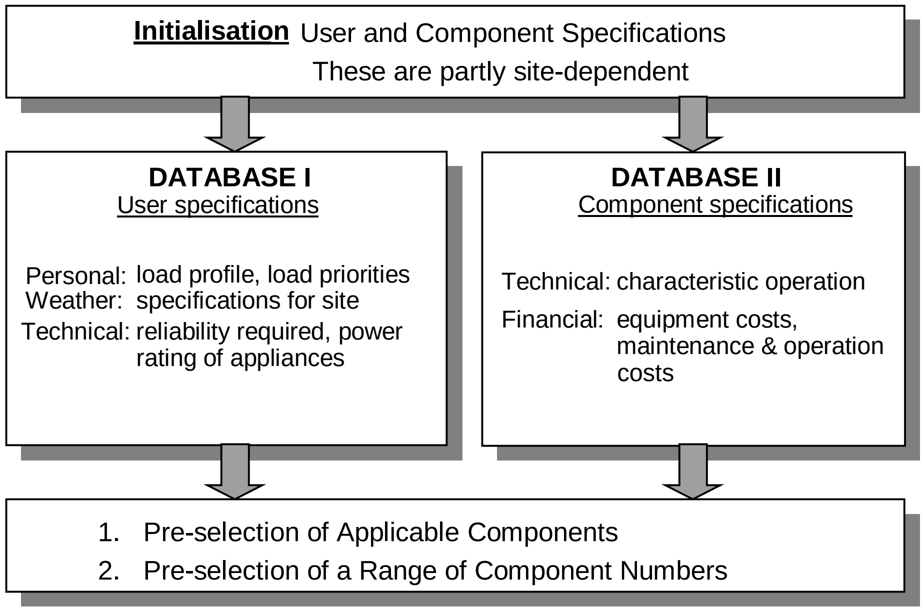


Figure 57: Data initialisation for algorithm

5.2.3.1 Weather information

The wind speeds, irradiation and temperatures for every time step of the simulation are needed in order to calculate the energy output of the wind turbines and photovoltaic panels. This data can be imported from a file in a suitable ASCII text format.

5.2.3.2 Demand information

The AC and DC demand requirements need to be entered for every time step. The software user can allow and specify a certain percentage of loads that may be unmet or dumped. The nominal operating voltage of each of the AC and DC busses must also be specified.

5.2.3.3 Component characteristics information

A component database is provided with typical makes of components that are commercially available. The software user can add new components to the database. The input parameters for the different components are as follows:

Diesel Generator

Operating voltage, Nominal power output, Lifetime (in hours), Component costs, Installation costs, Balance of system costs, Maintenance costs, Overhaul costs, Fuel price, Tank costs, Table indicating fuel consumption versus capacity factor, Maintenance intervals, Overhaul intervals.

Battery

Nominal operating voltage, Nominal capacity, Maximum state of charge as percentage of nominal capacity, Minimum state of charge as percentage of nominal capacity, Initial state of charge at start of project, Lifetime vs. DoD, Component costs, Installation costs, Balance of system costs, Maintenance costs, Maximum allowed (dis)charging currents, Table indicating efficiency versus state of charge for the particular type of battery or Wood factors

Wind turbine

Nominal operating voltage, Installation height, Nominal output power, Lifetime, Component costs, Installation costs, Balance of system costs, Maintenance costs, Overhaul costs, Table indicating output power versus wind speed

PV panels

Nominal operating voltage, Nominal output power, Lifetime, Component costs, Installation costs, Balance of system costs, Maintenance costs, Table indicating output current versus irradiation

Inverter or Battery charger

AC and DC nominal operating voltages, Nominal output power, Parallel capabilities, Component costs, Installation costs, Balance of system costs, Maintenance costs, Table indicating efficiency versus output power.

Economic input data

Discount factor, Time horizon, Project Lifetime

Simulation data

Duration of simulation, Time step in simulation, general genetic algorithm options

Based on this data a preselection of system components (e.g. only use 12V components) is carried out, and the possible size of each component is limited to the maximum size required in a single-source/single-component system.

5.2.4 Output

The sizing and operation control algorithm yields the least cost solutions for the given design problem. The solution consists of a set of component sizes and types taken from the components in the database, and numbers of each component, together with recommendations for the control settings of the system operation.

The control settings consist of a set of parameters, SOC_{SET} and Unmet_Load, that describe the operation strategy. The diesel will be switched on or stay on when the battery SOC falls below SOC_{SET} and the unmet load is above Unmet_Load.

In addition to these design recommendations, the time series of all system parameters (currents, power output, efficiencies, fuel consumption, costs etc) can be viewed.

A sensitivity analysis can be carried out for the recommended design to assess the impact of changes in input parameters such as demand, availability of renewable energies, estimated component lifetimes, fuel prices and O&M costs.

5.2.5 Description of the simulated example systems

The algorithm is applied to two case studies to demonstrate its usefulness and potential to improve present hybrid system design approaches. The two case studies describe typical rural farming applications (see [Williams-94], [Auerbach,Gandar-94]) in different areas of South Africa, namely Upington and Mabibi (see Figure 58). The area around Upington in the Northern Cape Province was chosen, because the solar irradiation there is highest due to Upington being near the Kalahari desert region, and because there are already quite a number of established farms using PV/diesel hybrid systems. Mabibi was chosen because there has been a development project with a PV/Wind hybrid system [Diab et al-92] and some monitoring data is available from this system. In addition, Mabibi is situated in a coastal area with good wind resources. The weather profiles of the regions are shown in the appendix A.

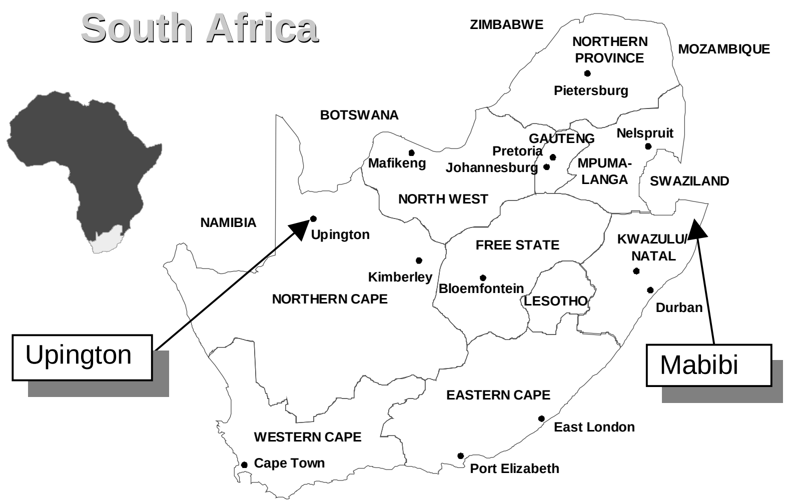
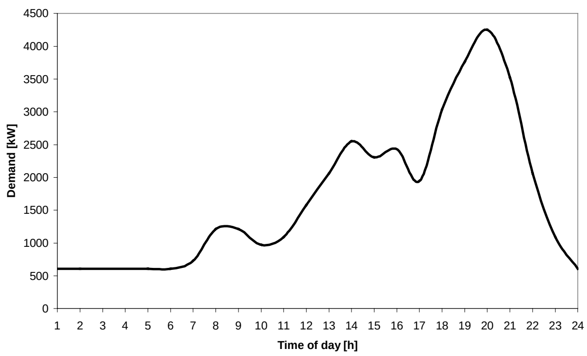


Figure 58: Location of Upington and Mabibi

The three different demand and load profile scenarios chosen are described in Table 6 and displayed in Figure 59 and Figure 60.

Table 6: Demand profile description

Demand profile	Description
D1	Domestic farm energy use (evening peak), regular profile
D2	Low industrialised farm energy use (high energy use during the day time), irregular profile
D3	Low industrialised farm energy use (high energy use during the day time), regular profile



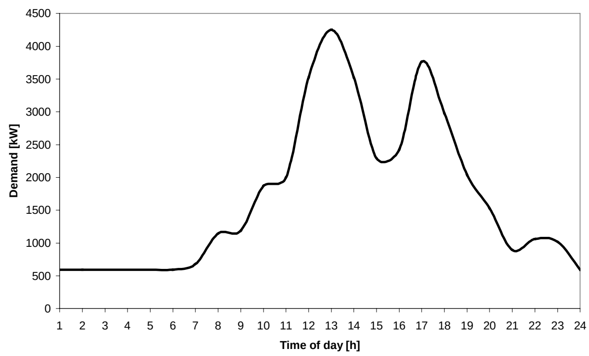


Figure 59: Regular demand profiles D1 (left) and D3 (right) with an evening peak and day-time peak respectively, average 40kWh/day

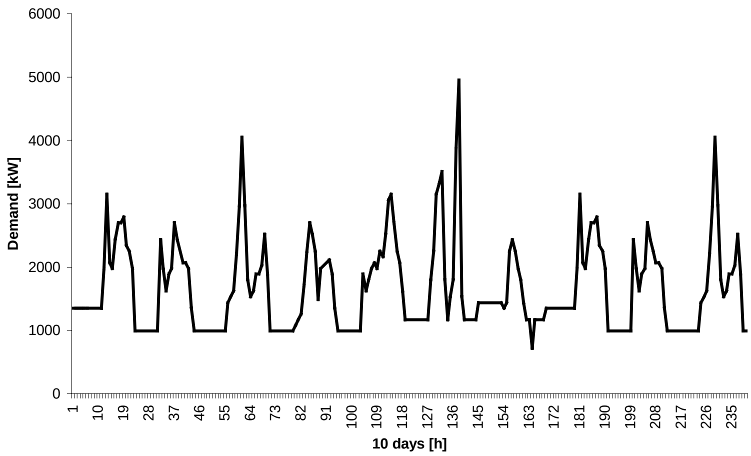


Figure 60: First 10 days of the irregular demand profile D2 with day-time peaks, average 40kWh/day

For all three demand profiles an average electricity consumption of 40 kWh/day is assumed. The load profiles differ, however, with regard to the timing of peaks and the regularity or irregularity of the profile patterns. All applications have base loads and make use of refrigerators, freezers, TV, radios, tools, lights and other smaller appliances. Profile D2 is based on measurements in [Rehm-97] taken at a farm near Upington. The owners of the farm use energy-efficient equipment and are very energy-conscious in using their system. The energy consumption pattern for the farm on which demand profile D2 is based is highly irregular, with different patterns nearly every day and distinct variations between weekdays and weekend days. The obtained measurements were scaled up to yield 40kWh/day. D3 is the averaged profile to D2, however, it is regular with the same pattern each day, also at 40kWh/day. Demand pattern D1 has a regular profile with a day-time peak. In addition, different levels in energy demand are simulated as part of the sensitivity analysis.

The compilation of the input data used in the simulations is shown in Table 7.

Table 7: Component and system parameters (References: [Helios-96], [Hochmuth-96], [RAPS manual-92], [Morris-94], [Davis,Horvei-95], [Schuhmacher-93],)

PV
Panel op. voltage 12 V | lifetime 20 years Panel sizes 18 25 30 40 50 55 70 75 W_p with 6.3 5.9 5.9 5.2 5.2 5.2 4.45 4.45 ECU_{1996}/W_p Maintenance cost: 4.64 ECU_{1996}/month, plus 0.001% of capital costs/year
Wind
Lifetime 20 years Capital cost: 2.78 ECU_{1996}/Watt | overhaul cost 10% of capital cost Maintenance cost: 1.85 ECU_{1996}/month, plus 0.001% of capital costs/year
Diesel
Lifetime 30.000hours Capital cost: 1.1 ECU_{1996}/W: 500W-9.5kW , 0.74 ECU_{1996}/W: 10-19.5kW 0.56 ECU_{1996}/W: 20-50kW , <0.19 ECU_{1996}/W : >50kW Overhaul 15.000 hours | overhaul cost: 20% capital cost Maintenance cost: 0.73 ECU_{1996}/h run-time plus 0.001% of capital costs/year Fuel cost: 0.56 ECU_{1996}/litre | Storage tank capacity : 100 l
Battery
Battery voltage 2V | Average Ah available during battery life: 1100 * nominal capacity Capital cost: 0.46 ECU_{1996}/Ah@2V, maintenance cost: 9.27 ECU_{1996}/month Initial battery state of charge level: 100% Minimum/maximum state of charge setting: 50% and 100% Max. battery current: 20% of nominal capacity Self-discharge rate: 0.166% in 100 days
System
System bus-voltages: DC=48V, AC=220V System installation cost: 10% of capital costs BoS costs: 35% of overall capital costs, building costs: 2% of overall capital costs
Economics
Project life: 20 years | Discount rate: 8%

5.3 Results

5.3.1 Overview of the simulation set-up

The simulations for each demand profile were run for different iteration lengths to determine when convergence takes place. After 150 iterations the simulation results had already converged for a number of iterations. In addition, the results did not change when the simulation was rerun.

Due to the implementation of the program in MATLAB, the simulations were relatively slow. Simulations were therefore only run for individual months. While simulating over several different months individually, a typical design month was determined and all further design runs and sensitivities were carried out for this particular month. It needs to be noted, therefore that the designs are produced for the design month for a region and a demand profile, but could maybe be adjusted in some cases to take advantage of the fact that the system might be able to operate with less energy resources in other months.

The designs for Upington and Mabibi were carried out for each of the three demand profiles D1-D3. In addition, for each design the different cases of using either a normal inverter or a parallel inverter were investigated (see Table 8). The results are summarised (see Table 10) and are discussed and displayed in more detail in terms of costing and operational settings and efficiencies of the best systems in appendices B and C for all design cases.

Table 8: Overview over design cases (each cell presents one design case)

REGION	Upington			Mabibi		
DEMAND PROFILE	D1	D2	D3	D1	D2	D3
Normal inverter						
Parallel inverter						

Each simulation yields, together with a recommendation for the optimum system configuration and their cost and system performance, the energy outputs of each component and the energy supplied to the load in hourly time steps. To ease the viewing of this data, the time series were averaged over one day and are displayed for the Upington design cases and for the Mabibi design cases. For each case of Table 8 one diagram shows the levels of demand and component energy outputs and inputs, whereas the battery state of charge level and the energy cycled through it are displayed in a separate figure. The averaged time series' obtained for each design can be found in appendix D.

In addition, a detailed sensitivity analysis was carried out for demand profile D1 in Upington and Mabibi, using a normal. The parameters of the sensitivity analysis are highlighted in Table 9. The results of the sensitivity analysis can be found in appendix E.

Table 9: Overview for the sensitivity analysis

Upington, Demand profile D1, Normal inverter	
Capital costs of PV panels	Discount rate
Capital costs of wind turbines	Project life
Capital costs of diesel generators	Fuel price
Capital costs of batteries	System reliability
O&M costs of renewable energy sources	Bus voltage
O&M costs of diesel generator	Size of daily energy demanded
Total lifetime of diesel generator	Number of energy sources
Total lifetime of battery	
Mabibi, Demand profile D1, Normal inverter	
Number of energy sources	

Furthermore the simulation results are compared with other design approaches, including the rule of thumb method, the Ah method, spreadsheet methods, other software and actual installations.

5.3.2 Design simulations

5.3.2.1 Convergence

During each iteration of the genetic algorithm, data regarding costing and performance of the system with the lowest objective function value is recorded. As an example, Figure 61 - Figure 63 show how life cycle costs per kWh, initial costs and fuel costs per kWh develop for each demand profile during the algorithm's iterations. It can be seen how the costs change over time. It is for example interesting that the lowest life cycle costs per kWh are achieved for demand profiles D1 and D3, which both are regular profiles. The irregular profile D2, which is also a more realistic profile, has the highest life cycle costs per kWh. Both the daytime profiles, D2 and D3, incur the highest fuel costs per kWh at the end of the iterations. However, the initial costs for demand profile D3, the regular profile, are much lower than for demand profile D2, the irregular profile. The impact of the irregular profile, which shows higher differences between peak demands and lowest demand levels than the regular profile D3, results in larger system sizing, and therefore higher costs than for the regular profile D3. The following sections will look at the results in more detail.

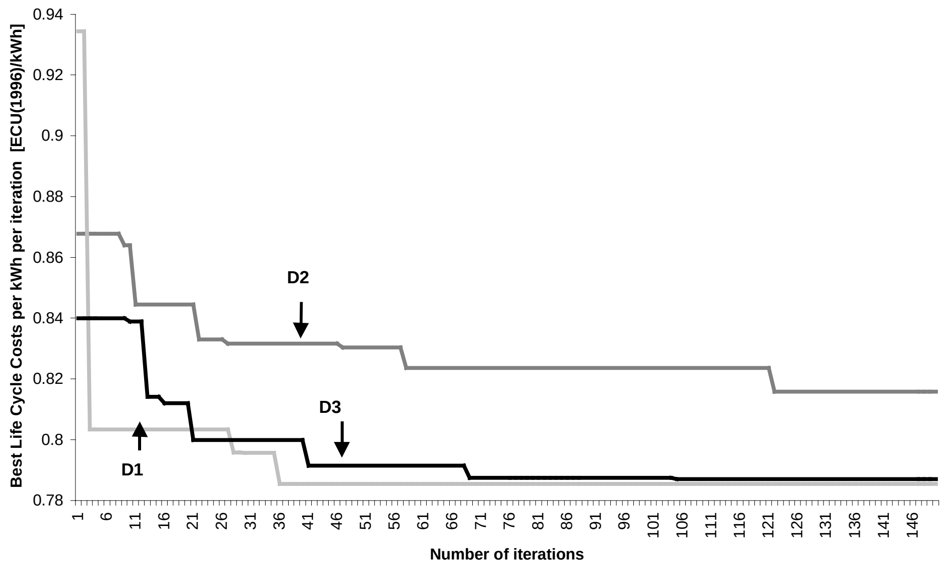


Figure 61: Convergence of life cycle costs per kWh, for best objective value system at each iteration, for the demand profiles D1-D3, Upington, normal inverter

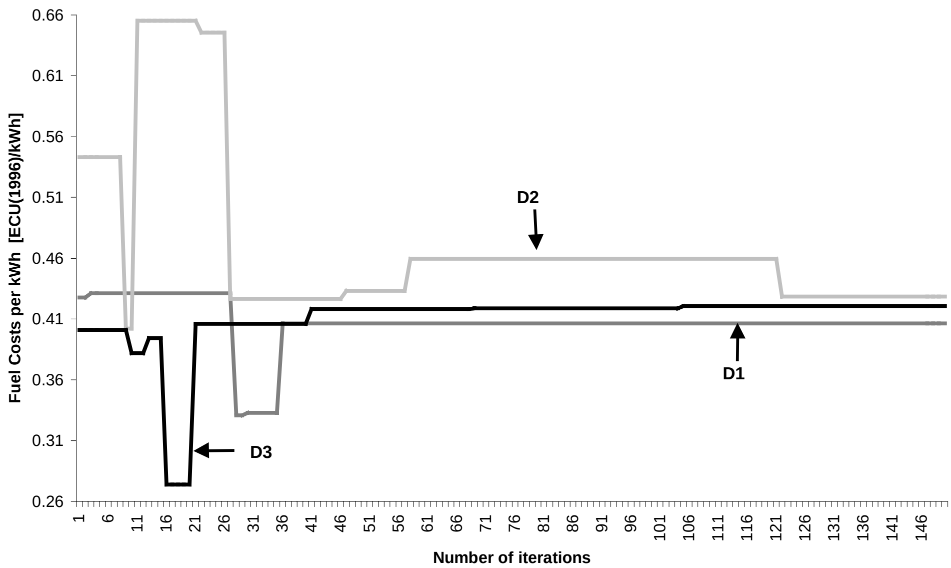


Figure 62: Convergence of fuel life cycle costs per kWh, for best objective value system at each iteration, for the demand profiles D1-D3, Upington, normal inverter

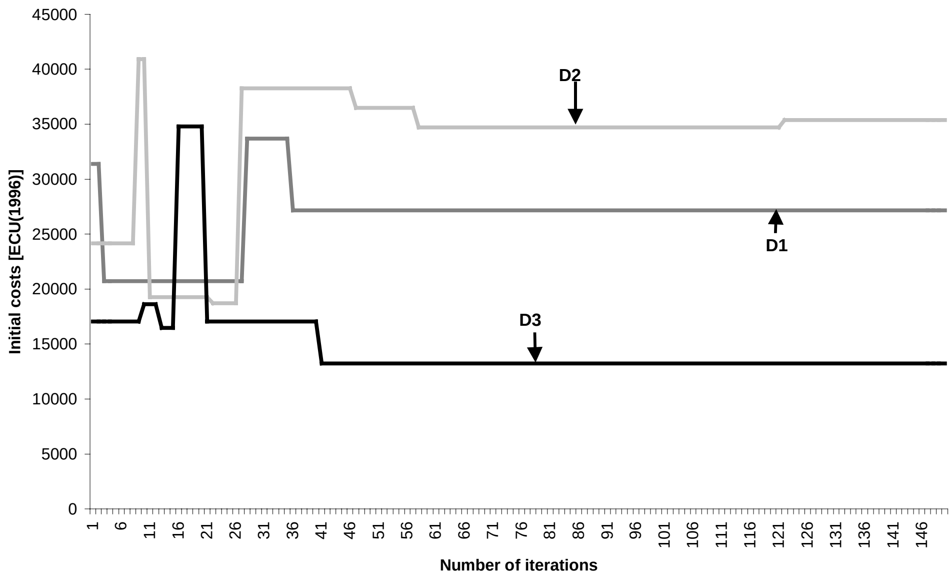


Figure 63: Convergence of initial costs, for best objective value system at each iteration, for the demand profiles D1-D3, Upington, normal inverter

Similar graphs can be displayed for the other runs of Table 8. The following sections concentrate on the analysis of the best system design at the end of the simulations, when the designs have converged to an optimal system recommendation. The objective function value of the converged system designs is equivalent to the value of the life cycle costs per kWh, as the converged designs meet demand reliably and therefore the added penalty costs become zero.

5.3.2.2 Summary Upington design

The following findings could be identified for the Upington design case scenarios. As expected, PV is a more cost-efficient renewable energy source than wind for the Upington site. The use of wind turbines is not encouraged and sizes assume very low values in all six scenarios.

If the demand pattern in the simulated scenarios is highly irregular, then the corresponding system costs rocket up as compared to a regular demand pattern with the same average kWh/day. This can be due to required redundancy sizing, and low load factors incurring higher fuel and diesel operation costs per kWh than for regular demand patterns. In addition, extensive use in the simulated scenarios (higher than for the regular profiles) is made of renewable energy sources to reduce diesel generator costs in the face of highly peaky supply requirements. It could be due to this reason that the losses in the simulated scenarios with irregular demand patterns are highest and consist mainly of inverter losses.

Regarding the scenarios with regular daytime demand patterns, surprisingly the diesel generator is running during the day, mostly at full capacity, and the contribution of the diesel generator to the total energy production is very high. In addition, very little use is made of PV. This can be due to the fact that the renewable energy sources become more cost-effective in a region of demand that is below the peak demand of the simulated case scenarios, which is around 5kW. It is proposed that future work investigate these relations in more depth with the developed tool, also with a focus on the impact of control settings. Losses are lowest for the simulated regular demand patterns and mainly consist of storage losses. Interestingly, and contrary to perception, the daytime peak demand profiles require more expensive systems than the evening demand peak profile. Again, it can be assumed that this can be due to the specific demand levels for which a specific energy source can be more cost-effective. It seems that the PV sources are more cost-effective in the simulated daytime peak scenarios for the lower demand levels during the evening (adding storage losses) than for the high demand peaks during the day.

In this context, the design for the evening peak demand pattern resulting from the simulations utilises a fair amount of PV and incurs lowest cost per kWh. As it was mentioned above, this can be due to the PV sources supplying the lower daytime demand cost-effectively, while the diesel generator supplies the evening demand more efficiently than daytime renewable energy cycled through batteries. In addition, the diesel generator also charges the batteries in the evening. Losses are smallest in the designed system for the evening peak pattern, and consist mainly of battery charging losses. The simulation results for the Upington case scenarios also showed that battery costs per kWh for the evening peak pattern are higher in the normal inverter configuration, possibly indicating the advantage in adding renewable energies directly on to the AC bus through a parallel inverter.

In addition, the parallel inverter configurations in the simulations obtained lower life cycle costs per kWh than the normal inverter configurations. There are a few indications why the parallel configuration can become cheaper than the normal configuration: the diesel generator is sized smaller than the peak demand and fuel costs per kWh are lower. The PV array size is selected larger for the daytime peak pattern design than in the normal inverter configuration. Related to that, the diesel generator is sized smaller and battery sizes can be reduced for the daytime peak patterns in the parallel inverter configuration. In addition, the overall system efficiency for the parallel inverter configurations is somewhat higher (and losses lower), maybe due to more efficient use of the AC and DC bus energies as they can be combined instead of used alternatively. The battery's average state of charge is also slightly higher than for the normal inverter configurations in the simulated case scenarios. On the other hand, the diesel operation costs per kWh are higher than in the normal inverter configuration, and diesel capacity factors can be significantly lower. That can be related to the control strategy proposed by the algorithm that if both the diesel generator and the inverter output can cover the load, then in the parallel configuration the inverter output is used more often to cover the load than in the normal inverter configuration.

With a parallel inverter configuration and for both regular patterns in the Upington case scenarios, however, the diesel generator is nearly always preferred to cover the load, when neither inverter output nor diesel generator can cover the load alone, whereby additional energy is taken from the inverter output. For the irregular pattern for Upington and a parallel inverter, if neither the diesel generator nor the inverter output can cover the load, then in most cases the diesel generator also supplies the load first and any additional energy is taken from the inverter output.

In the normal inverter configurations for the Upington case scenarios, the diesel generators are generally sized to meet peak demands alone. In addition, for the regular demand patterns in the normal inverter configurations, if neither the diesel generator nor the inverter output can cover the load, the designed operating strategy quite often allows the diesel generator to supply the load through the DC bus, thereby incurring battery charger and inverter conversion losses. Even though this kind of routing of diesel generator energy through the battery charger and then inverter is very inefficient it seems to help a normal inverter configuration to meet demand nearly as well as a parallel inverter system at comparable costs. In contrast, if neither the inverter nor the diesel generator can cover the load of the irregular demand pattern for Upington, then the diesel generator is not operated by the controller settings to supplement the DC energy sources, possibly due to sufficient renewable energy sources being available.

As can be seen, further investigations of similar case studies are expected to lead to further insight and advanced findings regarding innovative and cost-effective system sizing and operation.

5.3.2.3 Summary Mabibi design

The simulation results of the six scenarios for Mabibi indicated that the wind turbine component is much larger compared with the Upington designs. This is due to Mabibi being a windy coastal location, and Upington being located in a very solar irradiation intensive region with little wind. As expected, the PV array is a very small component of any hybrid system designed for Mabibi, reflecting the lower radiation as compared to the Upington site.

The irregular daytime peak demand pattern D2 requires, as in Upington, the highest life cycle cost per kWh design for both inverter configurations. For the evening peak demand pattern D1, the design has the largest wind turbine capacity, whereas the battery size is smallest, which can be a result of the fact that most of the wind energy is used directly. Extensive use is made, by the controller settings in the simulations, of the inverter output for load coverage; if the battery discharge and the renewable energy sources can cover the demand, they are almost always allowed to do so instead of the diesel generator. The overall losses are lowest, but the inverter losses for the simulated scenarios are highest for this particular demand pattern. The diesel capacity factor is lower than for the simulated daytime peak patterns and the fuel costs per kWh are lowest.

For the simulated regular daytime peak pattern D3 the designed system requires lowest life cycle costs per kWh. This can be due to the good wind resources during midday and the afternoon in Mabibi (in

Upington, with good PV resources, the design for the evening peak pattern D1 is lowest in costs). The difference in life cycle costs per kWh between the normal and parallel inverter configuration for the regular daytime peak pattern can be neglected. This can result from the fact that the diesel generator seems to cover the majority of load and at high capacity factors, whereas the wind turbine size is very small. In this regard the control settings allow the diesel generator to cover the load if the battery's state of charge is below around 80%, even if the battery and renewable energy sources would be sufficient to supply the load. It seems that the wind resources at Mabibi work better for a demand level and pattern similar to the evening peak profile D1. The wind resources are quite good during the afternoon and can perhaps cover certain levels of demand similar to profile D1 cost-effectively. Further investigations with the developed tool should be able to analyse the different effects of demand levels and patterns, renewable energy resources, and operation strategy on costs in more depth.

For the simulated normal configuration, the diesel generator size is chosen to meet peak demand, and therefore is largest for the irregular daytime peak pattern D2 for which the fuel costs per kWh are also highest. The diesel generator can cover the load for the daytime peak profiles D2 and D3 if the battery's state of charge is below around 80%, even if the battery and renewable energy sources would be sufficient to cover the load. In contrast, the inverter output covers the load instead of the diesel generator for the evening demand profile D1, which has a higher renewable energy component, if both busses are able to cover the load. In case neither the inverter output nor the diesel generator can cover the load alone, the diesel generator can nearly never cover the load through the inverter due to the controller settings, except for the regular daytime peak profile D3 where this is possible around 33% of time.

In the simulated parallel inverter configurations for Mabibi, the diesel generators are sized smaller than would be required to cover peak loads. This is also the case for the simulated scenarios for Upington. The fuel costs per kWh are highest for the system designed for the daytime peak demand profile D3 where the inverter output supplies the load on average 29% of time, and any energy needed additionally is taken from the diesel generator. If neither the inverter output nor the diesel generator can fully cover the load, for the profiles D1 and D2 the diesel generator output is nearly always taken first to satisfy the load and the inverter outputs tops up the rest of any additionally needed energy to cover the load.

Table 10 summarises the obtained design results for all three demand profiles for the Upington and Mabibi site.

Table 10: Summary of design results for the Upington and Mabibi sites

DESIGN		Design algorithm					
Demand profile		D1 evening peak, regular		D2, daytime peak, irregular		D3, daytime peak, regular	
Inverter type		NI	PI	NI	PI	NI	PI
Sizing	Upington						
	PV size [kW_p]	3.6	3.6	5.2	5.6	0.4	1.2
	Wind turbine size [kW_p]	1	1	1	1	1	1
	Diesel generator size [kW]	4.5	4	5	3.5	4.5	3
	Battery size [Ah]	300	200	300	200	300	200
	Mabibi						
	PV size [kW_p]	0.4	0.4	0.4	0.4	0.4	0.4
	Wind turbine size [kW_p]	4	4	3	1	1	1
	Diesel generator size [kW]	4.5	4	5	3.5	4.5	4
	Battery size [Ah]	200	200	300	300	300	300
	Both sites						
	Inverter size [kW]	4.5	4.5	5	5	4.5	4.5
	Battery charger size [kW]	4.5	4.5	5	5	4.5	4.5
	DC Bus voltage	48V					
Operation	If both diesel generator and inverter output can cover load	Use inverter output if SOC >					
	Upington [Control setting 1]	82%	84%	83%	87%	81%	85%
	Mabibi [Control setting 1]	54%	53%	84%	84%	79%	79%
	In case the load cannot be fully covered neither by the AC bus nor by the inverter output :						
	Normal Inverter: Allow [not allow] the AC bus output through the battery charger to cover the load through the inverter if SOC < [≥]						
	Upington [Control setting 2]	82%		53%		96%	
	Mabibi [Control setting 2]	59%		60%		81%	
	Parallel Inverter: Cover the load with the AC bus [inverter] output and draw additionally required energy from the inverter [AC bus] output if the SOC < [≥]						
	Upington [Control setting 2]		100%		96%		99%
	Mabibi [Control setting 2]		100%		93%		79%
	System efficiency (see Equation 121)						
	Upington [%]	60%	61%	59%	63%	56%	57%
	Mabibi [%]	64%	63%	56%	57%	56%	56%
	Average diesel generator capacity factor						
	Upington [%]	100%	88%	97%	89%	100%	100%
	Mabibi [%]	76%	86%	96%	100%	100%	100%
	Average battery state of charge						
	Upington [%]	89%	90%	87%	91%	83%	84%
	Mabibi [%]	79%	78%	87%	82%	82%	82%
Costing	LCC/kWh						
	Upington [ECU_{1996}/kWh]	0.785	0.76	0.82	0.80	0.79	0.78
	Mabibi [ECU_{1996}/kWh]	0.795	0.785	0.825	0.80	0.78	0.78
	Fuel costs/kWh (based on diesel kWh produced)						
	Upington [ECU_{1996}/kWh]	0.41	0.38	0.43	0.40	0.42	0.38
	Mabibi [ECU_{1996}/kWh]	0.38	0.38	0.44	0.41	0.42	0.42
	PV cost/kWh						

	Upington [ECU_{1996}/kWh]	0.47	0.45	0.50	0.46	0.69	0.47
	Mabibi [ECU_{1996}/kWh]	1.81	1.81	2.07	1.93	1.99	1.99
	Wind electricity cost/kWh						
	Upington [ECU_{1996}/kWh]	2.11	2.01	2.23	2.09	2.18	1.98
	Mabibi [ECU_{1996}/kWh]	0.54	0.54	0.63	0.61	0.63	0.63
	Diesel generator cost/kWh						
	Upington [ECU_{1996}/kWh]	0.27	0.32	0.28	0.36	0.26	0.33
	Mabibi [ECU_{1996}/kWh]	0.32	0.32	0.27	0.3	0.26	0.26
	Battery cost/kWh						
	Upington [ECU_{1996}/kWh]	0.16	0.11	0.10	0.11	0.10	0.10
	Mabibi [ECU_{1996}/kWh]	0.12	0.11	0.08	0.10	0.10	0.10
Load Profile	Farming load	40 kWh/day					

As can be seen, the results obtained for the six case scenarios in Upington and Mabibi verify some of the expected outcomes and also indicate trends that future work can analyse in more depth with the developed tool. However, it could be demonstrated that the developed tool is an innovative methodology that can be applied to hybrid system design.

5.3.3 Sensitivity Analysis

The design process of an off-grid system needs to be followed by another important step, the sensitivity analysis. As was described earlier, the results of the design process are only as good as the quality of the data that can be fed into the model. Some of the assumed input parameters might be different once a system is installed and used. Costs of components or labour might change, the level of demand can be higher or lower than expected. In order to decide for what ranges and type of changes the designs remain good choices it needs to be analysed how "sensitive" the recommended designs are to such changes. The base case chosen is a required demand as given by profile D1 (see Table 6,Figure 59) for the Upington site. The costs and system parameters for this base case are as presented in Table 7. The variations in input parameters were carried out according to the listing given in Table 9 and a summary of the results of the sensitivity analysis is presented in Appendix E. It was found that the parameters whose changes can impact most on the life cycle costs are diesel generator O&M costs, discount rate, length of project life, fuel prices, reliability requirements, DC bus voltages and demand level and weather resources.

5.4 Comparison with other design approaches

5.4.1 Rule-of-thumb method

As described for the rule-of-thumb method in Chapter 1, first the daily demand of 40kWh/day is adjusted in the method to account for 20% losses, thereby requiring a daily energy production of 50kWh/day or more. If the renewable energy sources are supposed to cover 40%-50%-60% of the Wh load demand, then they need to cover 20kWh/day (7305kWh/year) - 25kWh/day (9131 kWh/year) - 30kWh/day (10958 kW/year). In case that PV and wind energy sources share the energy production equally, then both PV and wind generators have to cover each 3653kWh/year - 4565 kWh/year – 5479 kWh/year. This leads to Table 11, assuming that in Upington, the average peak sunshine hours are 6 hours and in Mabibi 4.7 hours. In addition, the average wind speed in Upington is 3.9m/s, whereas in Mabibi it is 5.5m/s-6m/s. Based on the average wind speeds, the diameter of an appropriate wind turbine rotor is selected, based on which the kW rating of the turbine can be estimated. However, it needs to be kept in mind that the kW rating of the wind turbine can only be an estimate, as the ratio of rotor diameter length to turbine kW rating depends on the type and make of each turbine.

Table 11: Rule-of-thumb sizing

DESIGN		Rule of Thumb		
		D1	D2	D3
SIZING	Renewable energy sizing [40%-60% of Wh load]	Upington: PV-Diesel: $3kW_p$ – $5kW_p$ PV Wind-Diesel: $10kW_p$-$30kW_p$ Wind turbine PV-Wind-Diesel: $2kW_p$ PV, $3kW_p$ WT Mabibi: PV-Diesel: $4.3kW_p$-$6.4kW_p$ PV Wind-Diesel: $3kW_p$ Wind turbine PV-Wind-Diesel: $2.7kW_p$ PV, $1kW_p$ WT		
	Diesel generator size	4.5kW	5kW[4]	4.5kW
	Battery size	1000 Ah @ 48V, 80% inverter efficiency		
	Inverter size	4.5kW	5kW	4.5kW
	Battery charger size	4.5kW	5kW	4.5kW
	DC Bus voltage	48V		
OPERATION	Diesel generator operation	Load factor ≥ 50%		
	Battery operation	40% maximum DoD, regular equalisation, topping up with water		
LOAD PROFILE	Farming load	40 kWh/day		

The sizing results derived from the simulation of the 40kWh/day demand profiles for Upington and Mabibi in the previous sections fall in the same range as derived by the rough sizing method, except for the battery which is sized much smaller with the design algorithm. The advantage of the simulated design is the accurate division of energy production between the different energy sources. The operation criteria of running the diesel generator above 50% capacity factor is met by the simulated designs and even exceeded through the determined control settings. The average battery state of charge obtained through the design algorithm stays between 80% and 90%, but could go down to 50% during operation.

The rule of thumb method is a useful guideline in determining rough sizing ranges, however, it can neither accurately determine the component sizes and the system configuration nor their operation. Therefore the developed design approach presents an improvement over the rule of thumb method.

5.4.2 ‘Ah method’

The Ah method in Table 12, which is followed according to the SANDIA guidelines, is basically a more detailed rule-of-thumb method, yielding the number of components needed in parallel and in series and the size of the diesel generator. Again, the battery size is chosen according to numbers of days of storage desired. The diesel generator size is quite large as it is required to cover peak demands and battery charging requirements simultaneously. This seems overly strict and cost intensive. Nonetheless, some users prefer an oversized diesel generator to possess enough redundancy for emergencies or increased demand requirements.

The battery strings in parallel obtained by the Ah method is quite high, as the battery is supposed to be able to cover the full load requirements for a day even in a hybridised system set-up. The sizing of the share of the PV energy production for the overall energy production is chosen quite small in the Ah method, however this can be adjusted easily to accommodate user preferences. In this way wind energy contributions could be included through determining certain percentages of energy contributions from the different energy sources.

[4] Average peak demand is 3kW, but the highest actual peak demand is 5kW.

However, it can be seen that the amount of energy produced from each energy sources is left to chance and not related to the site conditions, demand profile characteristics or system operation. Improvements are possible using the results from a simulation tool such as the developed prototype.

Table 12: Design with the 'Ah method'

DESIGN	Ah METHOD
LOAD PROFILE ESTIMATE [Wh/day] and [Ah/day]	Compiled load is 40 kWh/day
	Multiply by loss factors (power conversion, battery cycling, wire inefficiency): 62.5kWh/day
	Divide by system voltage yielding load in Ah/day: 1.3 kAh/day
BATTERY number of batteries/cells in series and in parallel	Select battery type and number of days of storage: 2V, 1000Ah cells, 1 day of storage
	Number of batteries/cells in series obtained through dividing system voltage with battery/cell voltage: 24 cells in series
	Number of parallel battery strings obtained through matching Ah load current with the maximum discharge rate: 7 strings
PV number of PV panels in series and in parallel	Divide the load in Ah/day by peak sun hours per day, yielding so-called 'DC bus current' in A: 217A (6 hours of sunshine, Upington), 277A (4.7 hours sunshine, Mabibi)
	Number of panels in series obtained through dividing system voltage with panel voltage: 4 in series
	Number of panels in parallel obtained through dividing DC bus current with panel output current: 38 (10.6kW$_p$ - 6 hours of sunshine, Upington), 48 (13.5kW$_p$ - 4.7 hours of sunshine, Mabibi)
HYBRIDISE? Yes or No	Follow decision guide: Yes, determine PV Array to Load Ratio to be around 12.5%
BATTERY redefine storage size?	In case smaller battery storage is desired in the hybrid system configuration, redo the calculation on number of batteries required with new number of days of storage
DIESEL Choose kW size	Choose diesel generator size to cover peak demand plus maximum charging rate simultaneously 17kW
PV redefine number of PV panels in series and in parallel	Redo PV calculation taking account of battery and diesel generator sizing and the percentage of load to be covered by PV (12.5%)
Round off BoS and costing	Choose inverter size, wiring sizes and determine life cycle costs (LCC)

5.4.3 Spreadsheet methods

Similarly to the Ah method whose design results were discussed in the previous section, sizing can be carried out using spreadsheet calculations. The Ah method, for example, can also be implemented in a spreadsheet. However, the design can be done in even more detail making use of advanced spreadsheet features. A rather complex spreadsheet design had been presented in chapter 3 in order to give visual examples of some of the complexities encountered in the sizing and design process. In chapter 3 the shortcomings of such spreadsheet designs, even though helpful and providing good support if no software tools are available, were described. They include limitations due to having to specify the number of diesel runtime hours each day (5 and 2 hours in Chapter 3), and not taking account of storage or conversion losses. For the spreadsheet calculations a parallel inverter was always implicitly assumed thereby using energy resources to their full extent when they are available. Looking back at the results presented in chapter 3, and when adjusting the obtained sizing and life cycle costing to account for the conversion and storage losses, the designs obtained from the spreadsheets in Chapter 3 and from the developed algorithm become comparable. For example, the design load of 40kWh/day needs to be increased to around 60kWh/day-70kWh/day to account for the described losses. This brings the life cycle costs in the range of the life cycle costs computed by the developed design algorithm. Another encountered drawback is that in the spreadsheet calculations in Chapter 3, only 3 to 4 different sizes for PV, wind and diesel generator components were used, therefore giving only a vague indication of the recommendable component sizes.

In addition, it needs to be noted that the spreadsheet method cannot give guidelines on operation strategy selection and cannot give insights into the effects of demand profile characteristics. The spreadsheet calculations are useful in verifying results of a simulation package and to carry out some quick sizing steps. However, they will not provide the full amount of information as a software design tool can.

5.4.4 Other software

As described in the introduction, a few software packages exist to assist hybrid system designers. The package chosen for verification in this thesis was Hybrid 2, as it is a very well tested and evaluated performance simulation package for hybrid systems, that has also been verified with measured data from operating hybrid systems. SOMES is also a well proven package, but the SOMES developers have been feeding into the development of HYBRID2 and the latter seems to integrate most hybrid system performance analysis needs. HYBRID2 is also user-friendlier and allows for different levels and layers of input. The software package INSEL is also a reliable and sophisticated software tool, however it would require to first build up a hybrid system configuration and program the features of certain hybrid system components into it. That was seen as rather time consuming and did not seem to offer a benefit over the HYBRID2 simulations.

At the time of writing the optimisation package HOMER was still under redevelopment and the package RAPSIM still under beta testing, as was the package SOLSIM.

In HYBRID2, the design results for demand profile D1 (evening peak) for Upington in switched and parallel system configuration were entered and simulated.

The results of the HYBRID2 run confirmed that the systems recommended by the developed algorithm prototype are well designed. The load is met in the switched system, i.e. the configuration with a normal inverter, with 99.8% reliability, where simultaneously 0.2% of the demand are unmet and simultaneously 0.2% of generated energy are dumped over one year. The costs of the switched system have been calculated as 0.73 ECU_{1996} in HYBRID2, similar to the costs calculated with the prototype in the range of 0.785 ECU_{1996}. The reason for the slight difference in the costing are different ways of entering the costing information (e.g. in HYBRID2 often in cost/kWh instead of cost/h, or yearly percentages instead of monthly amounts etc.), and processing the information (e.g. the diesel replacements are not calculated in HYBRID2 therefore incurred replacement costs must be included in the maintenance costs).

For the parallel system configuration, again the system's design parameters were entered as obtained by the prototype design algorithm and run in HYBRID2. The results showed a very well designed system, covering 99.9% of the demand, leaving 0.1% unmet while at the same time 0.2% were dumped as excess energy over one year. The life cycle costs of the parallel system were computed to be 0.6 ECU_{1996}, showing the trend that the parallel system is cheaper than the switched system due to smaller component sizes. Again, the difference in life cycle costs as compared to the prototype output is due to the different handling and processing of the cost data.

The printouts of the HYBRID2 runs can be viewed in appendix F.

5.4.5 Installed systems

5.4.5.1 PV/Wind school system at Mabibi

The existing system at Mabibi (Figure 64) is a 36V DC bus system, with all appliances being AC. A 2.5kW LMW wind turbine is installed and a PV generator of 450W_p. There is a battery bank of 650 Ah @ 36V(23.4kWh). The initially estimated load was 4.2kWh/day (1534 kWh/y) [Diab-92]. Rule of thumb sizing carried out for this demand level and the site parameters actually yields a 2.5kW_p – 3kW_p wind turbine.

Figure 64: The Mabibi school/clinic facilities

The averaged system operation for logged data from the 1st of June 1995 to the 9th of August 1995 [Diab,Sokolic-97] can be seen in Figure 65. The battery is charged during daytime and is discharged substantially during the evening. Looking at the measured data it can be seen that the renewable energy current often has to be dumped to a large extent during the daytime because the battery is sometimes full already during the midday hours. Around every 10 days there is a high daytime discharge and the following day is mainly used for recharging the battery. The demand pattern of the Mabibi system is an evening peak pattern with a slight irregular characteristic.

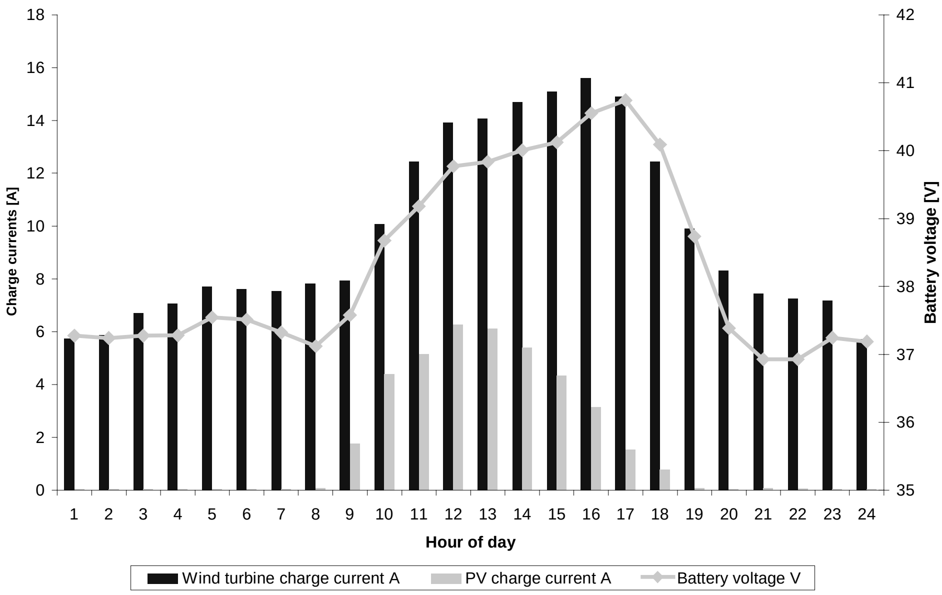


Figure 65: Averaged system operation of the Mabibi PV/wind/battery system

The simulation run to find a wind/PV/battery design for the Mabibi site with an energy requirement of around 4-5kWh/day resulted in a 0.4kW$_p$ PV, 2kW$_p$ wind turbine and 200Ah (9.6kWh) battery system as the lowest life cycle cost solution for a wind/PV/battery system (Figure 66). It needs to be noted however, that the prototype simulation algorithm couldn't use less than 400Wp of PV. In addition, the simulation runs also yielded the recommendation, that a wind/battery system (2kW$_p$ wind turbine and a 9.6kWh battery) was even lower in cost and is the overall lowest cost system configuration, followed by the PV/wind/battery system. The simulation runs show that the existing Mabibi system is well designed with a large battery storage capacity. The additional PV array seems not to be necessary, which is confirmed by the logged data that shows that most of the PV current gets dumped. The large battery storage, which is 2.5 times as big as the size recommended by the simulation, increases the system costs but also gives a back-up in times of increased demand or component failures. This is important, as Mabibi is very remote and not easily accessible.

It needs to be noted that the costs of components and operation for the Mabibi plant could not be established, however, that the costs used in the simulation (Table 7) are realistic and sufficient to give a reasonable indication of a recommendable system design.

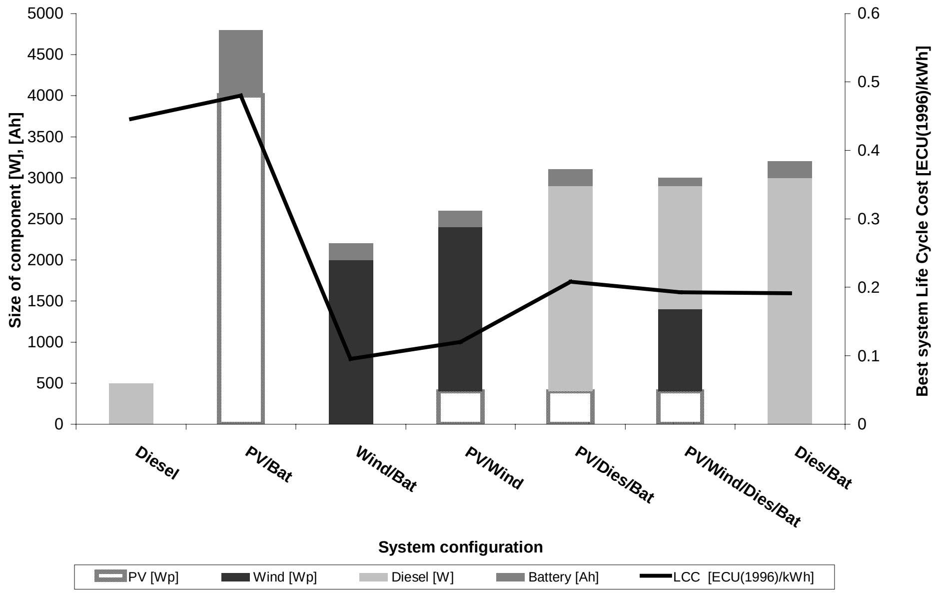


Figure 66: Different system configurations for the 4.5 kWh/day school load in Mabibi

As can be seen in Figure 67 and Figure 68 the averaged system operation obtained from the simulated designs is quite similar to the averaged system operation based on the logged system data. The battery gets charged in the early morning hours, slightly discharged during the late morning hours, gets charged during midday and on average deep discharged during the late afternoon / evening hours. It can be seen that the wind turbine currents charging the battery in the actual Mabibi system are less than the amount of wind turbine currents produced. This can be caused by the renewable energy currents also supplying the load directly which is not reflected in the measured currents. In addition, the actual load demand may be smaller than the initially estimated 4.2kWh/day for which the system was designed.

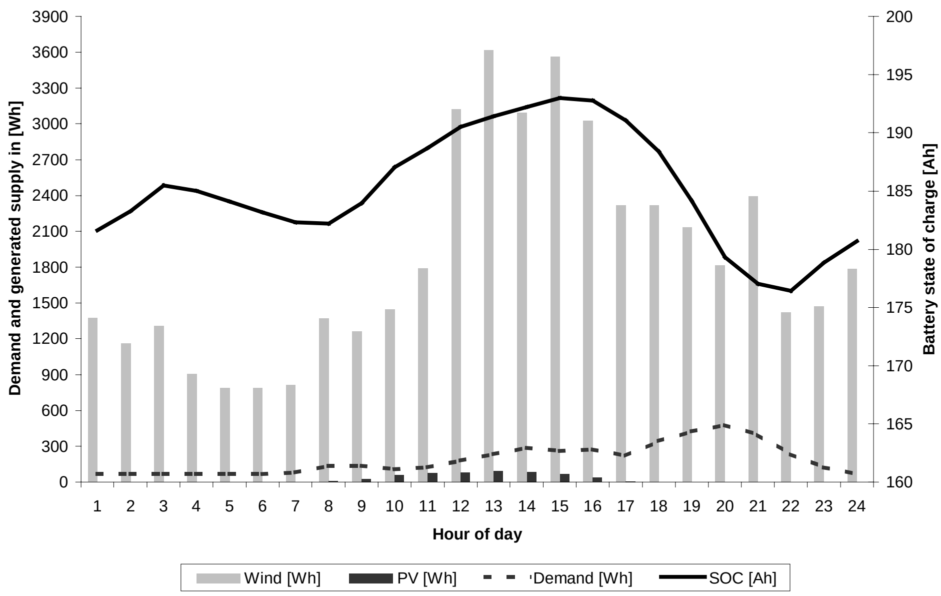


Figure 67: Averaged system operation of the simulated Mabibi PV/wind/battery system

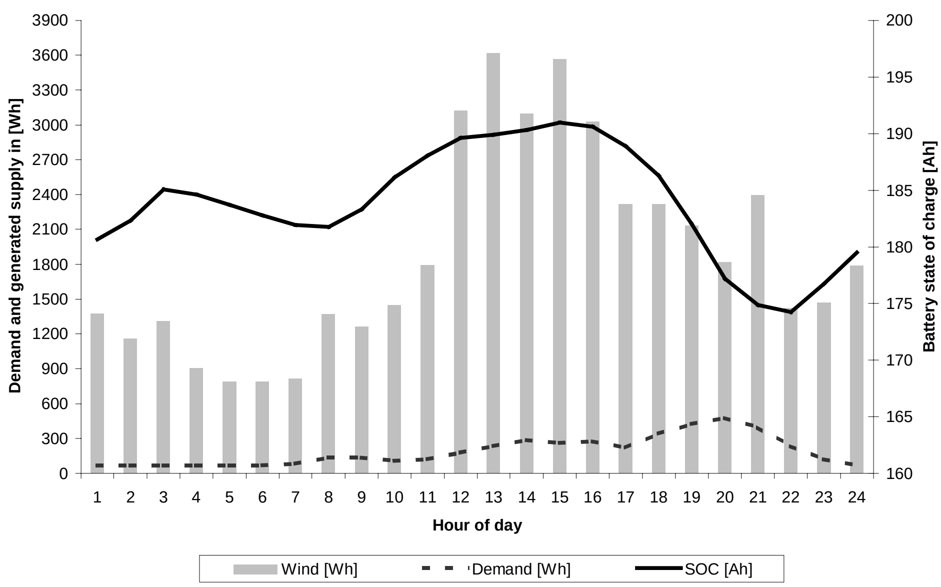


Figure 68: Averaged system operation of the simulated Mabibi wind/battery system

A general recommendation based on the simulation results is to try a smaller battery size in the Mabibi system. However, this would reduce back-up energy, which might be important for Mabibi's remote location. The simulations confirm that the chosen wind/battery system with additional PV back up is the right system combination, and the sizing of the wind turbine was confirmed. It can also be suggested that one could try to run the Mabibi system without the PV array.

5.4.5.2 PV/diesel farm systems at Upington

A number of PV/diesel/battery systems are in installed around Upington in South Africa. Some of these systems are retrofits of existing diesel generators. A typical system consists of a 36V DC bus with 1.8kW$_p$ PV, 1000 Ah (36kWh) battery. A switched inverter of 2.5kW - 3.5kW is operated besides a 3kW - 5kW diesel generator. The switching is done manually. The diesel generator is often only run for around 2 hours/day for a few days during the week thereby making sure that the batteries get fully charged. Wind generators are rarely used, and if they are used, then they are only a few hundred Watts in size. The average farming load is around 4kWh/day – 5kWh/day. The daily load will be higher if farming is carried out that is intensive in using electrical equipment such as in a dairy. The PV constitutes a large share of the energy production, the battery is sized for quite a few days of storage and only little use is made of the diesel generator.

Figure 69: Farm near Upington with a PV/diesel hybrid system

The simulated system designs confirmed that a PV/diesel/battery system is indeed the lowest life cycle cost system choice for the region. The system size recommended by the algorithm (Figure 70) was a 1.2kW$_p$ PV array, a 1kW diesel generator and a 100Ah (4.8kWh) battery. The PV array size is smaller (0.6kW$_p$) than in the actual farm systems and so are the diesel generator and the battery size. The battery is chosen considerably smaller, the installed battery sizes are 7.5 times larger than recommended in the simulation. This is due to the fact that the actual farm batteries are designed for 3-5 days of storage. It could be tried to run the Upington farm systems with smaller storage capacity, however, the large storage might be required to have a secure emergency back-up. In addition, the diesel generator is only run half as often in the Upington systems as opposed to the algorithm output where the diesel generator runs on average each day for 2.2 hours with full capacity. The farmers might resent the idea to run their diesels every day instead of every second or third day, therefore the larger battery storage seems to be warranted. The diesel generator size on the Upington farms being larger than recommended by the simulation indicates that the diesel generators might at some point have been supplying the farm as a single source system before they were retrofitted with PV. It is also possible that some applications are run solely with the diesel generator such as a washing machine requiring a diesel generator larger in size than 1kW. In addition, a diesel generator is usually not available in sizes as small as 1kW.

The suggested operation strategy is to use the inverter output instead of the diesel generator whenever the inverter output can cover the load, and only run the diesel generator through the inverter if the battery SOC is below 64%, i.e. very seldom. This confirms the actual practice with farm systems near Upington, where most of the time the inverter output is used to supply the loads.

The averaged operation strategy recommended by the simulation as shown in Figure 71 suggests that diesel generator runs mostly during the evening and sometimes during the early morning hours. That applies for an assumed demand profile with an evening peak, where most of the energy consumption occurs towards the late afternoon / evening.

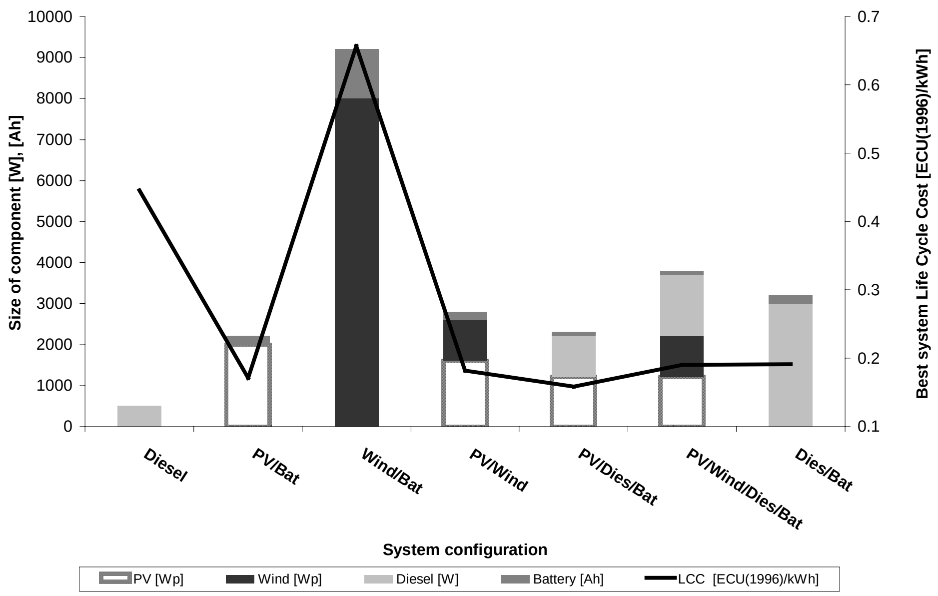


Figure 70: Different system configurations for the 4.5kWh/day Farmload in Upington

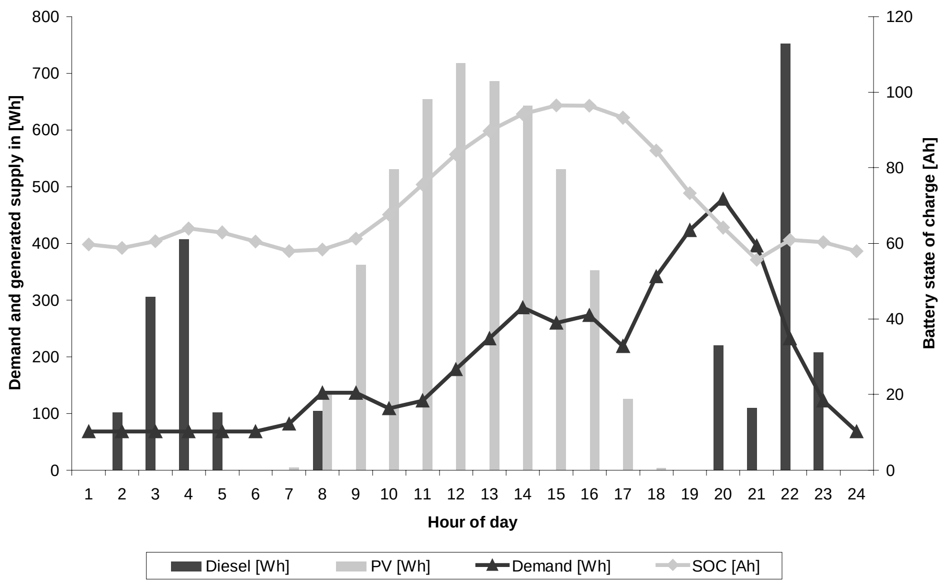


Figure 71: Averaged system operation of the simulated Upington PV/wind/battery system

In summary, the simulation results suggest that the Upington system configuration of a PV/diesel/battery system is the recommendable set-up. A smaller battery size could be tried, however this might result in increased diesel generator runtimes which might not be suitable for the users. It needs to be mentioned that the installations near Upington have been designed over years on a trial and error basis with care and experience.

5.5 Summary

The chapter on simulation introduced the structure of the developed and implemented algorithm with the goal to optimise hybrid system design with regard to system sizing and operation control. The algorithm was applied to two case scenarios for typical South African demand profiles and sites. The system and component parameters used were presented and the simulation results evaluated.

It was found that the shape of the profile and the regularity of the profile pattern impact to a large extent on the design of a system and its operation. This emphasises the need for demand management to use resources efficiently and cost-effectively. In the simulated case scenarios the designs for the irregular demand patterns made more use of a highly hybridised design with a larger renewable energy share than the design for regular demand patterns.

As could be expected, the type of renewable energy sources used most in a hybrid system depends on the weather resources of the region. For the solar intensive region, the design for the evening peak was lower in costs than for the daytime peak. For the wind intensive site, the design for the regular daytime peak profile was lowest in cost. The design for the evening peak generally utilised more renewable energy sources than the designs for the daytime peak. It is expected that this is due to the fact that the renewable energy sources become more cost-effective in a region of demand that is below the peak demand of the simulated case scenarios. It is proposed that future work investigate these relations in more depth with the developed tool, also with a focus on the impact of control settings.

In the simulated scenarios, the use of a parallel inverter instead of a normal inverter lowers costs, due to smaller component sizes required. For example, in the parallel inverter configuration the diesel generator does not have to be sized to meet peak demands anymore as is the case in the normal inverter configuration.

Even though routing diesel generator energy through the battery charger and then back through inverter is very inefficient it helps a normal inverter configuration in the simulated scenarios to meet demand nearly as well as a parallel inverter system at comparable costs.

In addition, a sensitivity analysis was carried out and found that parameters whose changes can impact most on the life cycle costs are diesel generator O&M costs, discount rate, length of project life, fuel prices, reliability requirements, DC bus voltages, and demand level and weather resources.

The simulation results were also compared with other design approaches, namely rule-of-thumb methods, Ah methods, spreadsheet methods, performance simulation with HYBRID2, and with data from installed systems.

It was found that the developed algorithm indeed presents a new and useful tool in optimising hybrid system design. The results for the case studies obtained from the simulations were sensible and were verified by comparisons with the other approaches and actually installed systems. In addition, the results show that the tool can offer new insights how system parameters and operation strategies impact on sizing and costing. It is hoped that through analysing more case studies with the tool, new operation strategies and sizing approaches will be developed.

Chapter 6

Conclusions

In this thesis, the existence of a niche was confirmed for an optimisation tool that recommends hybrid system designs with lowest life cycle costs while meeting required demand through simultaneously optimising the system sizing and control.

It was further shown that in the presence of highly complex and non-linear system and component characteristics, the use of genetic algorithms for the optimisation process constitutes an advantage over common optimisation alternatives. Genetic algorithms do not require gradient calculations; therefore the hybrid system could be modelled with a high degree of accuracy considering the highly complex workings of actual systems while still keeping computation time at reasonable levels.

Optimisation algorithms change the values of so-called decision variables of an underlying model in such a way as to optimise the resulting value of the model's objective function. The objective function value is equivalent with the merit of a particular design. When using genetic algorithms, the values of decision variable are changed based on the best solutions of an iteration, thereby utilising some elements of probabilistic variation to help the solution out of local minima. The algorithm converges when the values of the decision variables, the model's performance and its merit of design do not change significantly anymore.

In this thesis the objective function was developed whose value for a specific hybrid system design serves as a classification of merit for the design. The objective function is a combination of life cycle costs per kWh and penalty costs per kWh for unmet demand. In addition, the hybrid system model was developed through a precise power flow description of the energy transmission in a hybrid system.

The power flow can only be calculated if the values for its variables are determined. These decision variables consist of component sizing variables and control setting variables. Where possible the number of variables was reduced through substitution with characteristic system and component operation equations.

The remaining operating decisions encountered in the power flow are battery and diesel generator outputs. Once battery or diesel generator output is chosen, the other output level and therefore the power flow is determined automatically. However, independent of which output value is determined first, this needs to be performed for every single time instant during system operation and the number of decision variables to be optimised would then become very high. For this reason, control settings were introduced to indicate at what level of battery state of charge and unmet demand either the value for the battery output or the diesel generator output is determined first. Thereafter, the computation of the other output value and the complete power flow can follow automatically. An advantage of optimising the control settings instead of component outputs at each time instant is that the values for the control settings can be more readily implemented in actual systems through correspondingly adjusting the system controller settings. The value of a control setting is determined in the genetic algorithm, together with the values of the sizing variables, and then remains constant during the simulation of the model until it is changed in the next iteration of the genetic algorithm.

The developed algorithm was used for the simulation of two case scenarios for typical farming demand profiles and for typical remote sites in South Africa for which the use of hybrid systems can be considered. The results were meaningful and gave insight into the relation between system operation and sizing and costs. A sensitivity analysis was carried out for the results and found that parameters whose changes can impact most on the life cycle costs in the simulated scenarios are diesel generator O&M costs, discount rate, length of project life, fuel prices, reliability requirements, DC bus voltages, and demand level and weather resources.

It was further found that the shape of the profile and the regularity of the profile pattern impact to a large extent on the design of a system and how it is operated. This emphasises the need for demand management to use resources efficiently and cost-effectively. In the simulated case scenarios the designs for the irregular demand patterns made more use of a highly hybridised design with a larger renewable energy share than the design for regular patterns.

As could be expected, the type of renewable energy sources used most in a hybrid system depends on the weather resources of the region. The use of a parallel inverter instead of a normal inverter in the simulated scenarios lowers costs, due to smaller component sizes required. For example, in the parallel inverter configuration the diesel generator does not have to be sized to meet peak demands anymore as is the case in the normal inverter configuration.

The algorithm results were also compared with other approaches, namely the rule-of-thumb method, the Ah method, spreadsheet methods, the performance simulation tool HYBRID2, and with the sizing and operation data from actually installed systems. It was found that the recommended designs and the calculated costs by the algorithm were realistic.

The advantages of the algorithm over other methods are that

- an optimised design recommendation is given (as opposed to simulation only)
- the demand requirements and local weather can be simulated for a period of time
- components operate at various capacity levels to meet the demand
- the different component efficiencies encountered in inverter losses, battery charging losses, fuel efficiency, renewable energy production are taken into account during the simulation
- component maintenance, overhaul and replacement needs can be determined more accurately based on actual operation
- the impact of different control strategies can be evaluated
- the overall life cycle costing is more accurate
- large numbers of combinations of component sizes and operation settings can be evaluated and results presented in a user-friendly format
- a detailed insight can be gained how the sizing, costs and operation relate under different input parameters

It is recommended that further work be focused on the professional implementation of the algorithm including the further programming of helpful or advanced features, an on-going in-depth evaluation and sustainable maintenance of the program. In addition, further work should concentrate on evaluating many more case scenarios with the goal of gaining a general understanding how operating decisions, sizing choices and costs are correlated for different demand profiles, weather conditions and other relevant input parameters as described in the sensitivity analysis. This should enable the preparation of advanced sizing and operation guidelines for hybrid systems.

References

[A]

[Auerbach,Gandar-94] Auerbach R., Gandar M. (1994), Energy and Small-Scale Agriculture, published by the EDRC, University of Cape Town, South Africa

[B]

[Barley et al-95] Barley C.D., Winn C.B., Flowers L., Green H.J. (1995), Optimal Control of Remote Hybrid Power Systems, Part I: Simplified Model, In Proceedings of Windpower '95, Washington, DC

[Beyer,Langer-95] Beyer H.G., Langer C. (1995), A Method for the Identification of Configurations of PV/Wind/Hybrid Systems for the Reliable Supply of Small Loads, Proceedings of the 13th EU PV Solar Energy Conference, Nice, France

[Bezerra et al–91] Bezerra P., Hille G., Siegler M., Schott T. (1991), Hybrid Systems for Decentral Electricity Generation: Lessons from a Brazilian-German Co-operation, In Proceedings of the World Renewable Energy Conference, Reading

[Bodgan,Ziyad-94] Bodgan S. B., Ziyad M. S. (1994), Optimum Photovoltaic Array Size for a Hybrid Wind/PV System, IEEE Transactions on Energy Conversion, Vol. 9, No.3

[Borchers-93] Borchers M.L. (1993), RAPS computer tools: Phase II, EDRC, University of Cape Town, Final Project Report for the Department of Mineral and Energy Affairs

[Braun-93] Braun H. (1993), Unit Commitment and Thermal Optimization - Problem Statement, Optimization in Planning and Operation of Electric Power Systems, pp143, Physica-Verlag, Heidelberg.

[C]

[Cawood-97] Cawood W. (1997), Rural Homes Solar Electrification Programme, Proceedings of 3rd STRC/OAU Inter-African Symposium on renewable and solar energies, Pretoria

[Chichocki,Unbehauen-93] Chichocki A, Unbehauen R. (1993), Neural Networks for Optimisation and Signal Processing, Wiley, Chicester

[CSS-95] [CSS] Central Statistics Services (1995), October Household Survey, South Africa

[D]

[Dantzig,Infanger-93] Dantzig G., Infanger G. (1993), Approaches to Stochastic Programming with Application to Electric Power Systems, Optimization in Planning and Operation of Electric Power Systems, Physica-Verlag, Heidelberg.

[Davis,Horvei-95] Davis M., Horvei T. (1995), Handbook for the Economic Analysis of Energy Projects, Development Bank of Southern Africa, PO Box 1234, Halfway House 1685

[Degner et al-94] Degner T., Gabler H., Stoecklein A. (1994), A Model for the Ageing of Lead/Acid Batteries in PV Systems, Proceedings of the 12th EU PV Conference, Amsterdam, Holland

[Diab et al-92] Diab R.D., Ligoff D, Viljoen R.P., Kidgell H. U., (1992), The Mabibi Wind Energy Project: Part I and II, Journal of Energy R&D in Southern Africa, Vol. 3, No 2, pp.13-17 and No 3., pp. 9-12

[Diab,Sokolic-97] Diab R., Sokolic F.(1997), Report on Wind and Wind Turbine Monitoring at Mabibi, Period: September 1994 to February 1995, submitted to the Department of Minerals and Energy, Pretoria, South Africa

[Diab-95] Diab R. (1995), Wind Atlas of South Africa, Prepared for DME, Pretoria

[Dijk et al-91a] Dijk V. A. P. van, Alsema E.A., Albers R.A.W., Degner T., Gabler H., Wiemken E. (1991), Autonomous Photovoltaic System with Auxiliary Source for Battery Charging, Proceedings of the 11th EU PV Conference, Lisbon, Portugal

[Dijk et al-91b] Dijk V. A. P. van, Alsema E.A., Blok K., Turkenberg W.C. (1991), A Simulation and Optimisation Model for Autonomous Energy Systems, In Proceedings of the World Renewable Energy Conference, Reading

[Dijk-94] Dijk V. van, Alsema E., Horst M. van der, Jager R.E.A., Grip B.V., Groningen (1994), SOMES 3.1, User Manual

[Dijk-96] Dijk V. A. P. van (1996), Hybrid Photovoltaic Solar Energy Systems, Design, Operation, Modelling, and Optimization of the Utrecht PBB System, PhD Dissertation, Utrecht University, Faculteit Scheikunde, Holland

[Duffie,Beckman-91] Duffie, J. A., Beckman, W. A. (1991), Solar Engineering of Thermal Processes 2nd ed., John Wiley & Sons, Inc. New York

[E]

[Eberhard-90] Eberhard A. A. (1990), A solar radiation data handbook for Southern Africa, Cape Town: Elan Press

[Engler et al-97] Engler A., Haas O., Raptis F., Sachau J., Zacharias P. (1997), Standard Interface for PV and Hybrid Systems, Proceedings of the 14th EU PV Solar Energy Conference, Barcelona, Spain

[F]

[FSEC-87] FSEC Energy Short Course (1987), Photovoltaic System Design – Course Manual, Florida Solar Energy Centre, Cape Canaveral, Florida

[G]

[Gipe-93] Gipe P. (1993), Wind Power for Home & Business, Renewable Energy for the 1990s and Beyond, A Real Goods Independent Living Book, Chelsea Green Publishing Company, Post Mills, Vermont

[Glavitsch-93] Glavitsch H (1993), Use of linear and quadratic programming techniques in exploiting the nonlinear features of the optimal power flow, published in Optimisation in Planning and Operation of Electric Power Systems, Physica Verlag, Heidelberg

[Goldberg-89] Goldberg D.E. (1989), Genetic Algorithms in Search, Optimization, and Machine Learning, Addison Wesley, New York

[Gonzalez,Mayer-91] Gonzalez A., Mayer D. (1991), Design of a Hybrid PV/Diesel System from the Analysis of the present PV System Performance in a Dairy Farm in Pozoblanco, Spain, Proceedings of the 11th EU PV Conference, Lisbon, Portugal

[Gowan-85] Gowan M. M. (1985), Renewable Energy Assessments, East-West Center

[Green,Manwell-95] Green, H. J., Manwell J.F. (1995), HYBRID2 - A versatile model of the performance of hybrid power systems, In Proceedings of Windpower '95, AWEA conference, Washington DC.

[H]

[Haas et al-97] Haas G., Kleinkauf W., Raptis F., Zacharias P. (1997), Power System Technology Based on PV Foundation Stones, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Hancock et al-95] Hancock M., Outhred H.R., Kaye R. J. (1995), A New Method for Optimising the Operation of Stand-Alone PV Hybrid Power Systems, Proceedings of the 12th EU PV Solar Energy Conference, Nice, France

[Helios-96] Helios Solar Co. 1996 Price list, now AfricaSolar, prices converted from 1996 South African Rand to 1996 ECU

[Hochmuth,Morris-98] Hochmuth F., Morris, G.J. (1998), Evaluation of a PV solar home electrification project in the Free State Province, Proceedings of the Domestic Use of Electrical Energy Conference, Cape Town

[Hochmuth-96] Hochmuth F. (1996), Evaluation of the SHS demand survey in Maphephete, DECON & EDRC, Scheme for large-scale implementation of solar home systems in South Africa Final Report, European Commission, DG XII, RENA-CT94-0048, Brussels, 1996

[Holland-73] Holland J.H. (1973), Genetic Algorithms and the optimal allocations of trials. SIAM Journal of Computing 2(2), 88-105

[Hollenstein,Glavitsch-90] Hollenstein W. , Glavitsch H. (1990), Linear Programming as a Tool for Treating Constraints in a Newton OPF, Proceedings of the 10th Power Systems Computation Conference PSCC, Graz, Austria

[I]

[IDT-97] [IDT] (1997), Source Independent Development Trust, Cape Town, South Africa

[Infield et al-83] Ingfield D.G., Slack G.W., Lipman N. H., Musgrove P.J. (1983), Review of Wind/Diesel Strategies, IEE Proceedings, Vol. 130, Pt. A, No. 9, pp. 613-619

[J]

[James-95] James B. (1995) The impacts of rural electrification: Exploring the silences. Unpublished discussion document, Energy and Development Research Centre, University of Cape Town

[Jansen et al-93] Jansen B., Roos C., Terlaky T. (1993), Interior Point Methodology for linear programming: duality, sensitivity analysis and computational aspects, Optimisation in Planning and Operation of Electric Power Systems, pp111, Physica-Verlag, Heidelberg.

[Jennings et al-95] Jennings S. U., Pryor T.L., Remmer D.P. (1995), Combining Simulation Techniques and Design Expertise in a Renewable Energy System Design Package, RESSAD, Proceedings of the ISES conference, Harare, Zimbabwe

[Jennings-94] Jennings S. U. (1994), Use of Computer Simulation in the RAPS Field, In Proceedings of Solar ‘94 Conference, Sydney

[Jennings-96] Jennings S. (1996), Development and Application of a Computerised Design Tool for Remote Area Power Supply Systems, PhD Thesis at Murdoch University, Dept. of Electrical Engineering

[Jimenez-98] Jimenez T. (1998), Hybrid Design Handbook, NREL/EDRC production, Chapter 6 components, Draft copy

[Joule II-93] Joule II Proposal (1993), Development fo an innovative autonomous 2kW Hybrid PV/Wind Power Supply Pilot System for Rural Electrification, University of Karlsruhe

[K]

[Kaiser et al-97] Kaiser R., Sauer D. U., Armbruster A., Bopp G., Puls H.-G. (1997), New Concepts for System Design and Operation Control of Photovoltaic Systems, Proceedings of the 14th EU PV Conference, Barcelona, Spain

[Kaye-91] Kaye R. J. (1991), Optimising the Value of Photovoltaic Energy in Electricity Supply Systems with Storage, Proceedings of the 11th EU PV conference, Lisbon, Portugal

[Kaye-94] Kaye R. J. (1994), A New Approach to Optimal Sizing of Components in Stand-Alone Photovoltaic Power Systems, Proceedings of the 1st World Conference on Photovoltaic Energy Conversion, Hawaii

[Keiderling-90] Keiderling S. (1990), Simulation und Optimierung von kombinierten Wind- und Solaranlagen zur Stromversorgung, Berlin, VDI Verlag

[Kuik et al–97] Kuik E. van, Seeling-Hochmuth G., Weber P. (1997), Off-Grid Hybrid Design Tool Using Genetic Algorithms, Proceedings of the 14th EU PV Solar Conference, Barcelona

[L]

[Lilienthal et al-95] Lilienthal P., Flowers L., Rossmann C. (1995), HOMER: The Hybrid Optimization Model for Electric Renewables, In Proceedings of Windpower '95, Washington DC, March 1995

[Llobet et al-94] Llobet E., Miro M., Prats J., Arnal I., Sibuet C. (1994), Results obtained from PV Rural Electrification Projects Applied to the Design of Control and Power Conditioning Units for Stand-Alone PV and Hybrid Systems in the Range between 5 and 20kW, Proceedings of the 12th EU PV conference, Amsterdam, Holland

[Loois et al-93] Loois G., Weiden T.C.J. van der, Hoekstra K.J. (1993), Technical set-up and use of PV diesel systems for houseboats and barges, Technical Digest Intn'l PVSEC-7, Nagoya, Japan, pp. 163-164

[Lorenz-88] Lorenz U. (1988), Elektrizitaetsversorgungsplanung für laendliche Gebiete in Entwicklungslaendern - Ein Optimierungsmodell, Springer Verlag, Berlin

[M]

[MacGill,Kaye-97] MacGill I.F., Kaye R. J. (1997), Denctralised coordination of power system operation using dual evolutionary programming, Submitted to IEEE Transmission Power Systems

[Manninen,Lund-91] Manninen L.M., Lund P.D. (1991), Design Tool PHOTO for Sizing of Hybrid Power Systems: Program Verification, Proceedings of the 10th EU PV conference, Lisbon, Portugal

[Manwell et al-96] Manwell, J.F., Rogers, A., Hayman, G., Avelar, C.T., McGowan, J.G., (1996), Draft Theory Manual for Hybrid2: The Hybrid System Simulation Model, NREL/TP-440-21182, Golden, CO

[Manwell,McGowan-93] Manwell J.F., McGowan J. G. (1993), Lead Acid Battery Storage Model for Hybrid Energy Systems, Solar Energy, Vol 50, No 5, pp.399-405

[Markland-89] Markland R. E. (1989), Topics in Management Science, John Wiley, New York, Third Edition

[Marrison,Seeling-Hochmuth-97] Marrison C.I., Seeling-Hochmuth G. C. (1997), A Design Tool using Genetic Algorithms to Size Hybrid Systems for Power Supply at Remote Sites, Part One: Analytic Framework, Proceedings of the CASE conference 1997, New Delhi, India

[Marrison,Stengel-94] Marrison C. I., Stengel. .R.F. (1994), The Use of Random Search and Genetic Algorithms to Optimize Stochastic Robustness Cost Functions, Proceedings of the 1994 American Control Conference, Baltimore, pp. 1484-1489

[Marrison-95] Marrison C.I (1995), The Design of Control Laws for Uncertain Dynamic Systems Using Stochastic Robustness Metrics, PhD thesis, Princeton University, Dept of Mechanical and Aerospace Engineering

[May et al-95]] May J., Carter M., Posel D. (1995), The composition and persistence of poverty in rural South Africa: An entitlements approach. Policy Paper 15. Land and Agriculture Policy Centre, Johannesburg

[Ministry of the Office of the President-95] Ministry of the Office of the President (1995), Rural development strategy of the Government of National Unity.

[Morgan et al-95] Morgan T. R., Marshall R. H., Brinkworth B.J., (1995), SEU-ARES - A Refined Simulation Program for the Sizing and Optimization of Autonomous Hybrid Energy Systems, Proceedings of the Annual Meeting of the International Solar Energy Society, Harare.

[Morris-88] Morris G. J. (1988), Performance evaluation of diesel and photovoltaic electricity generation applications in the Kruger National Park. NEC report, Energy Research Institute, University of Cape Town

[Morris-94] Morris G. J. (1994), Diesel Genset Design Manual, EDRC, University of Cape Town.

[N]

[Nayar et al-93] Nayar C.V., Philips S.J., James W.L., Pryor T.L., Remmer D. (1993), Novel Wind/Diesel/Battery Hybrid Energy System, Solar Energy, Vol. 51, No.1, pp.65-78

[NER-97] NER (National Electricity Regulator) (1997), Lighting Up South Africa 1996, Progress report on electrification, available from the NER South Africa

[O'Riordan et al-94] O'Riordan A., Wrixon G.T., Klein H.P. (1994), Sprayfield 9kW Domestic Hybrid Test System, Proceedings of the 12th EU PV Conference, Amsterdam, Holland

[P]

[Papalexopoulos-93] Papalexopoulos A. (1993), Optimal Power Flow Packages – Requirements and Experiences, Optimization in Planning and Operation of Electric Power Systems, pp309. Physica-Verlag, Heidelberg

[Piller et al-97] Piller S., Hanitsch R, Seeling-Hochmuth G, Stephan R. M. (1997), Estimation Of Battery Ageing In Hybrid Energy Supply Systems - A Fuzzy Approach, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Piller-97] Piller S. (1997), Assessment of Battery Ageing and Diesel Genset Degradation in Hybrid Energy Supply Systems – A Fuzzy Approach, Final Year Thesis, EDRC Cape Town, TU Berlin, Dept of Electrical Engineering

[Pohlheim-95] Pohlheim H. (1995), Ein genetischer Algorithmus mit Mehrfachpopulationen zur Numerischen Optimierung, at-Automatisierungstechnik 3 (1995), Berlin

[Protogeropoulos et al-91] Protogeropoulos C., Marshall R. H., Brinkworth B.J. (1991), SEU/ARES-A Hybrid Solar PV/Wind Simulation Program Description and Dynamic Battery Simulation Results, In Proceedings of the World Renewable Energy Conference, Reading

[Protogeropoulos et al-94] Protogeropoulos C., Marshall R. H., Brinkworth B.J. (1994), Battery State of Voltage Modelling and Algorithm Describing Dynamic Conditions for Long-Term Storage Simulation in a Renewable System

[Purcell-91] Purcell C J de (1991), Battery performance characteristics in stand-alone photovoltaic systems, EDRC publication prepared for the National Energy Council South African, Private Bag x03, Lynnwood Ridge 0040

[R]

[RAPS manual-92] RAPS manual (1992), Remote area power supply design manual, EDRC, University of Cape Town

[Rehm et al-95] Rehm M., Bopp G., Roessler E. (1995), First Implementation of Demand-Side Management by Dynamic Pricig in an Autonomous PV-Wind-Diesel System, Proceedings of the 13th EU PV Solar Energy Conference, Nice, France

[Rehm,Seeling-Hochmuth-97] Rehm M., Seeling-Hochmuth G. (1997), The Influence of Electricity Demand Profiles on the Design of Hybrid Systems - A Case Study for South Africa, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Rehm-97] Rehm M (1997), Demand profiles of hybrid systems, draft chapter, Fraunhofer Institut, Department for systems analysis, Freiburg, Germany

[Remmer,Dymond-91] Remmer D. P., Dymond M. S. (1991), RAPSIM – A Computer Simulation For Remote Area Power Supply Systems, Proceedings of Solar'91 Conference, Australia

[Remmer,Dymond-93] Remmer D. P., Dymond M. S. (1993), Economic Viability of Remote Area Power Supply Systems: Three Case Studies, Proceedings of Solar'93 Conference, Australia

[Riess et al-94] Riess H., Roessler E., Sobirey A., Sprau P. (1994), Performance and Reliability of the Photovoltaic Demonstration Plants in the German Measurement and Documentation (MuD) Programme, Proceedings of the 12th European PV Conference, Amsterdam

[Rural and Remote Area Power Supplies for Australia-93] Rural and Remote Area Power Supplies for Australia (1993), Australian Government Publishing Services, Canberra

[S]

[Sandia-95] Sandia National Laboratories (1995), Stand-Alone Photovoltaic Systems – A Handbook of Recommended Design Practices, SAND87-7023, available from National Technical Information Service, U.S. Dept of Commerce, 5285 Port Royale Road, Springfield, VA 22161, first published 1991

[Schaffrin,Litterst-97] Schaffrin C., Litterst T. (1997), SolSim Ein Simulationsprogram für Solarenergieanlagen, available at Fachhochschule Konstanz, Insitut für angewandte Forschung, 78405 Konstanz

[Schmid-97] Schmid, J. (1997), New Trends in PV-Systems Technology, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Schmidt-95] Schmidt M. (1995), SUNTAINER®- An Economical Hybrid System Option for Rural Power Supply, Proceedings of the ISES conference, Harare, Zimbabwe

[Schuhmacher-93] Schuhmacher J., University of Oldenburg (1993), INSEL - interactive simulation of renewable electrical energy supply systems, reference manual, renewable energy group, Dept. of Physics, PO Box 2503, D-26111 Oldenburg

[Seeling-95] Seeling G. (1995), A Combined Optimisation Concept for the Design and Operation Strategy of Hybrid PV Energy Systems, ISES conference, Harare, September 1995

[Seeling-Hochmuth,Marrison–97] Seeling-Hochmuth G. C., Marrison C. I. (1997), A Design Tool using Genetic Algorithms to Size Hybrid Systems for Power Supply at Remote Sites, Part Two: Implementation, In Proceedings of CASE conference on Village Electrification, New Delhi, India

[Seeling-Hochmuth-95a] Seeling-Hochmuth G. (1995), Optimisation of PV-Hybrid Energy System Design and System Operation Control using Genetic Algorithms, 13th European Photovoltaic Conference in Nice

[Seeling-Hochmuth-95b] Seeling-Hochmuth G. (1995), Report on the solar home systems demand survey carried out in Maphephete, Kwazulu-Natal, South Africa, DECON & EDRC, Scheme for large-scale implementation of solar home systems in South Africa Final Report, European Commission, DG XII, RENA-CT94-0048, Brussels, 1996

[Seeling-Hochmuth-96] Seeling-Hochmuth G. (1996), Small Village Hybrid Systems Performance Workshop – Expert Meeting, NREL, CO, US

[Seeling-Hochmuth-97a] Seeling-Hochmuth G. (1997), A Combined Optimisation Concept for the Design and Operation Strategy of Hybrid PV Energy Systems, Solar Energy Journal

[Seeling-Hochmuth-97b] 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

[Seeling-Hochmuth-97c] Seeling-Hochmuth G. (1997), Electricity Supply of Rural Households and Productive Activities using Hybrid Systems , Proceedings of DUEE (domestic use of electrical energy) conference, Cape Technikon, Cape Town

[Shephard-65] Shephard C. M. (1965), Design of Primary and Secondary Cells II, An Equation Describing Battery Discharge. Journal Electrochemical Society, 1965, 112, 657

[Sibuet et al-95] Sibuet C., Llobet E., Miro M. (1995), The Hybrid Wind-Solar Power Plant of Polanco: Promotion, Design and StartUp, Proceedings of the 13th EU PV Conference, Nice, France

[Slabbert,Seeling-Hochmuth-97] Slabbert C., Seeling-Hochmuth G. (1997), Review of hybrid energy system design and performance, Draft document, EDRC, University of Cape Town

[Smith-95] Smith G. (1995), Rural Electrification in Central America using Renewable Energy Technologies, Alternative Technologies for Rural Electrification Workshop, The South African Institute of Electrical Engineers, June 1995, Johannesburg

[Stoehr et al-97] Stoehr M., Stadler I., Schmid J. (1997), Standardised PV systems for rural areas, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Stoll-92] Stoll M. (1992), Experiences with a Novel Method to Estimate the State of Charge of a Lead-Acid Battery, 11th EU PV Solar Energy Conference, Montreux

[Thom-97] Thom C. (1997), A development framework for rural electrification: Some preliminary findings. Energy and Development Research Centre, University of Cape Town

[V]

[Valente et al-95] Valente L.C.G., Araujo, M.R.P. de, Hill R., Taylor R. W. (1995), PV Power for Villages in the North Region of Brazil, Proceedings of the 13th EU PV Solar Energy Conferene, Nice, France

[Vallve,Serrasolses-95] Vallve X., Serrasolses J. (1995), Design and Operation of a 50kWp PV Rural Electrification Project of Remote Sites in Spain, Proceedings of the 13th EU PV Solar Energy Conference, Nice, France

[W]

[Warner et al-995] Warner C.L., Taylor R.W., Ribeiro C.M., Moszkowicz M., Borba A.J.V. (1995), PV-Hybrid Village Power Systems in Amazonia, Proceedings of the 12th European PV Energy Conference, Amsterdam

[Weiden et al–94] Weiden T.C.J. van der, Bourmans J.H., Hoekstra K.J.(1994), Optimized Design Terrschelling PV/Wind/Diesel/Battery System, Proceedings of the 12th European PV Energy Conference, Amsterdam

[Wichert,Lawrance-97] Wichert B., Lawrence W.B. (1997), Intelligence Control of Modular Hybrid Energy Systems, Proceedings of the 14th EU PV Solar Conference, Barcelona

[Williams-94] Williams A. (1994), Small and Medium-Scale Agricultural Power Requirements and Energy Use, An Analysis of Energy Needs for the Small & Medium Black Farming Sector in South Africa, Published by Data Research Africa and EDRC

APPENDIX A

WEATHER DATA FOR TWO SELECTED REGIONS

1 WIND SPEED 2

1.1 YEARLY DATA 2
1.2 SEASONAL DATA 2
1.3 MONTHLY DATA 3

2 GLOBAL IRRADIATION 4

2.1 YEARLY DATA 4
2.2 SEASONAL DATA 4
2.3 MONTHLY DATA 5

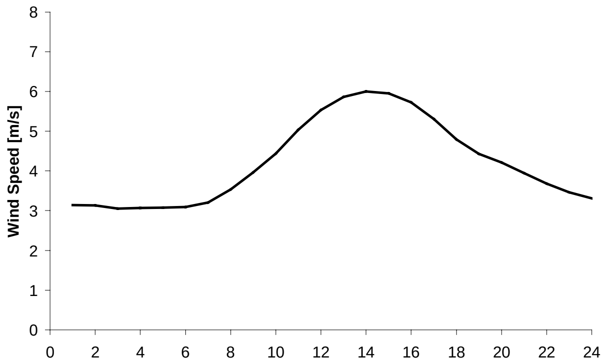
3 AMBIENT TEMPERATURE 6

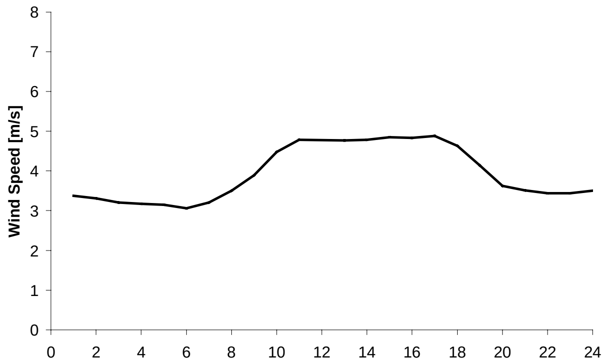
3.1 YEARLY DATA 6
3.2 SEASONAL DATA 6
3.3 MONTHLY DATA 7

1 Wind Speed

1.1 Yearly data

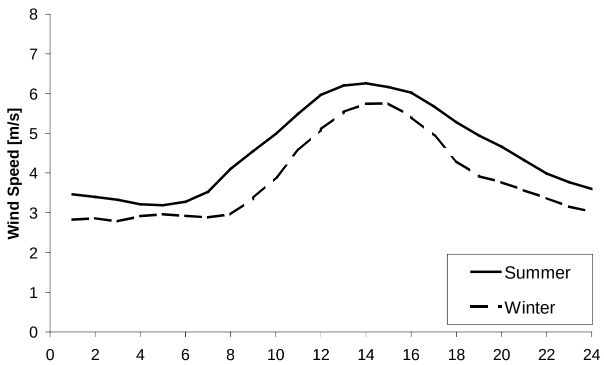
Mabibi Region	**Upington Region**
(Yearly average per hour of the day)	(Yearly average per hour of the day)

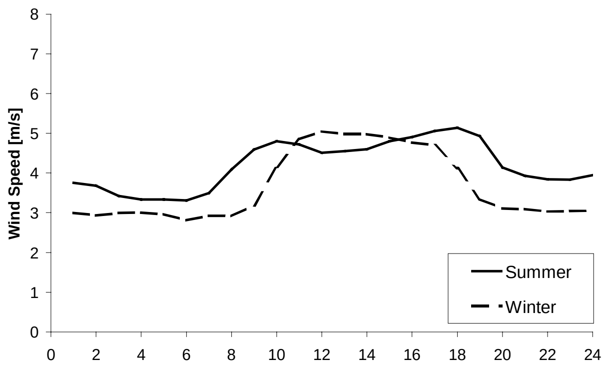




1.2 Seasonal data

Mabibi Region	**Upington Region**
(Summer/Winter average per hour of the day)	(Summer/Winter average per hour of the day)

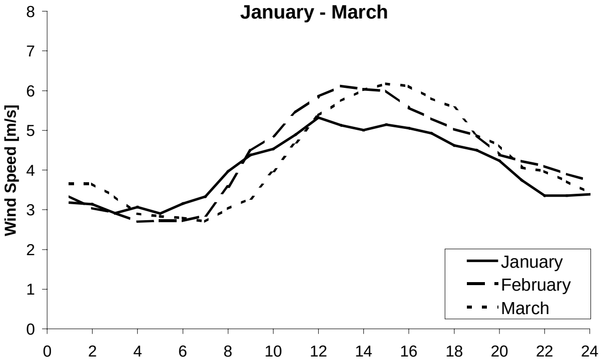


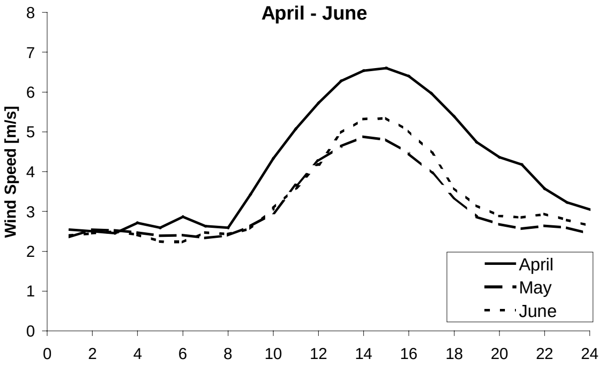


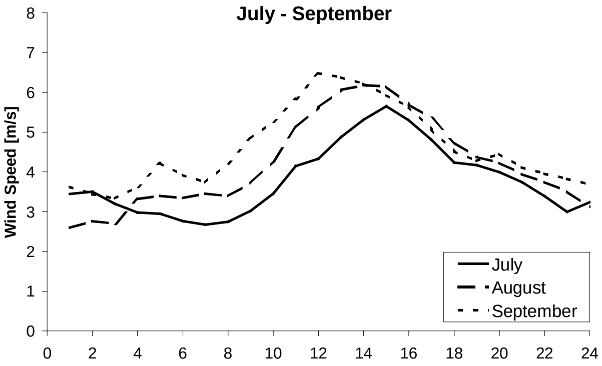
1.3 Monthly data

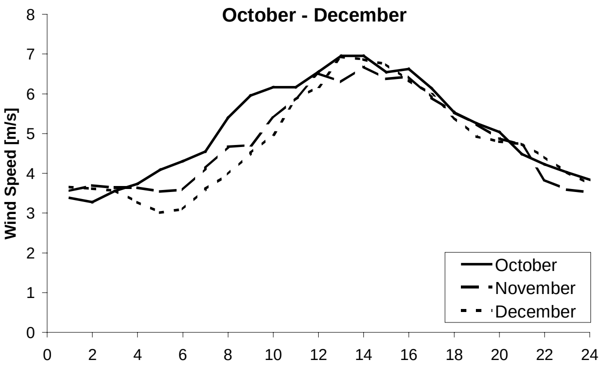
Mabibi Region

(Monthly average per hour of the day)



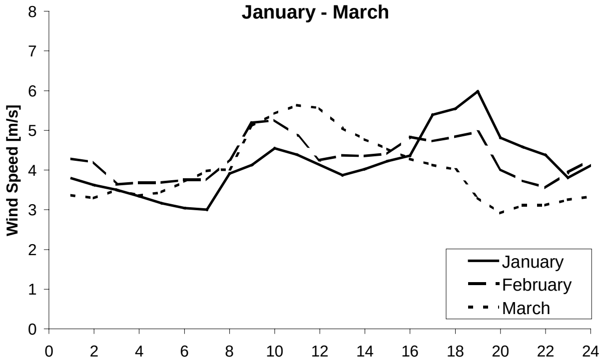


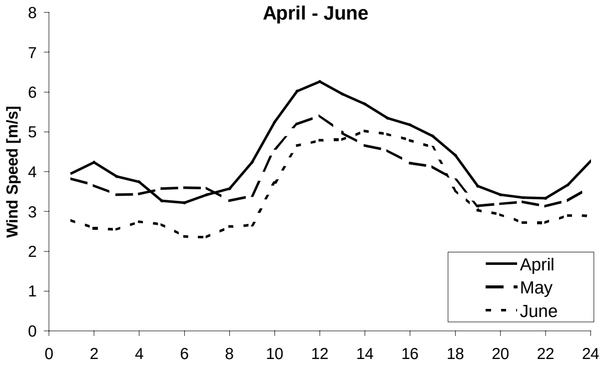


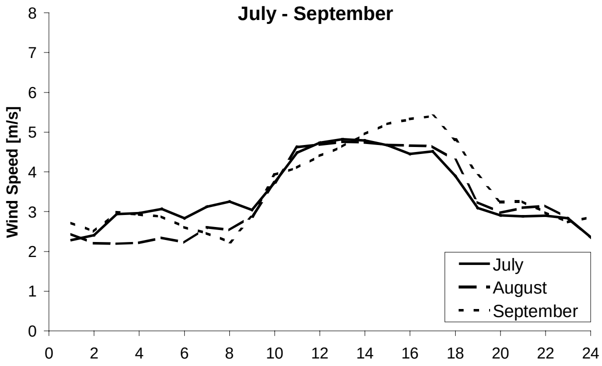


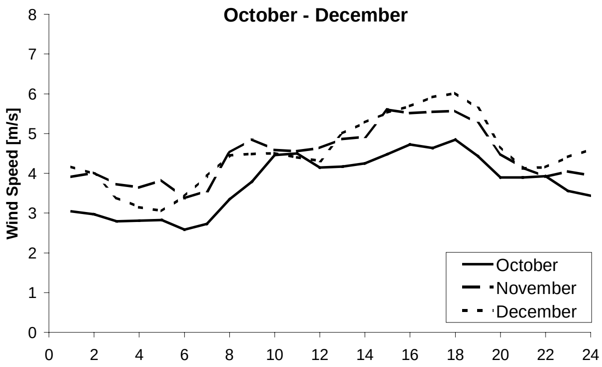
Upington Region

(Monthly average per hour of the day)





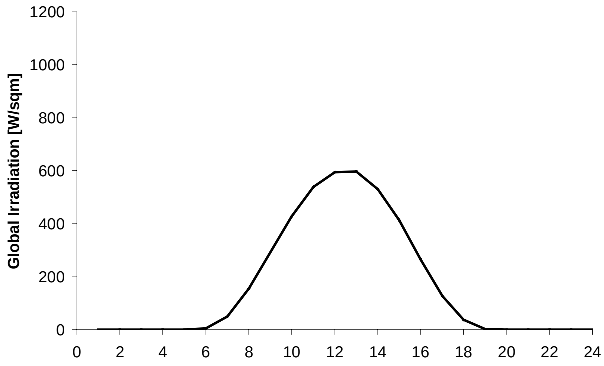


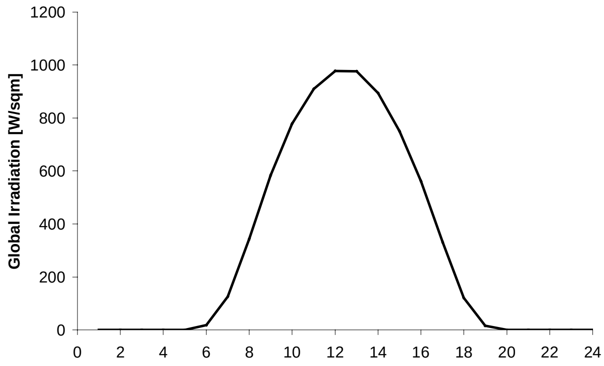


Global Irradiation

1.4 Yearly data

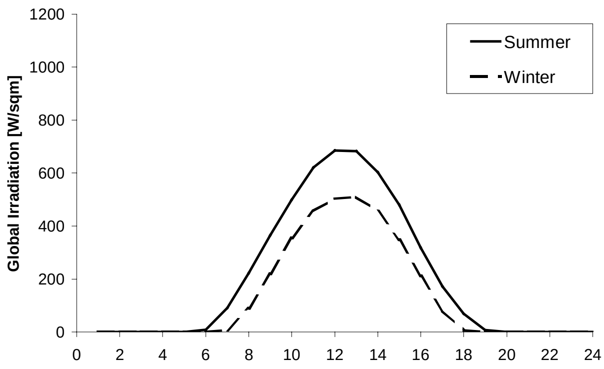
Mabibi Region	Upington Region
(Yearly average per hour of the day)	(Yearly average per hour of the day)

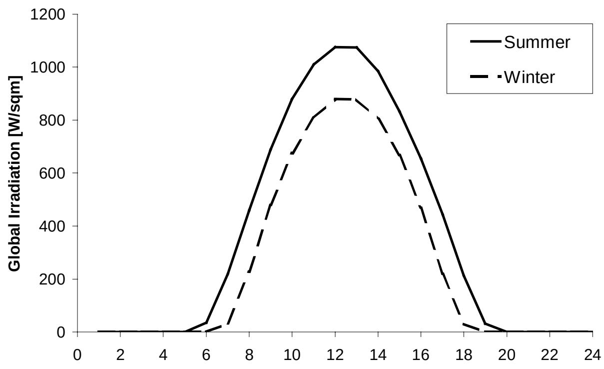




1.5 Seasonal data

Mabibi Region	Upington Region
(Summer/Winter average per hour of the day)	(Summer/Winter average per hour of the day)

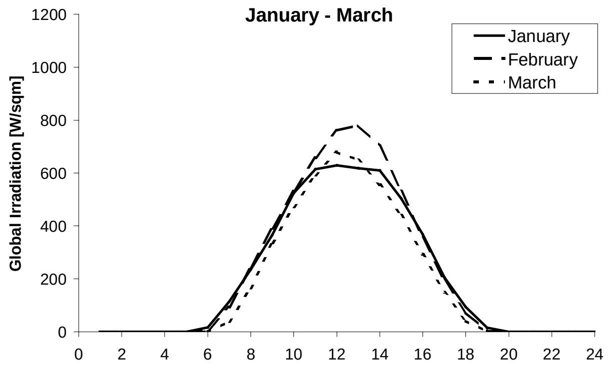


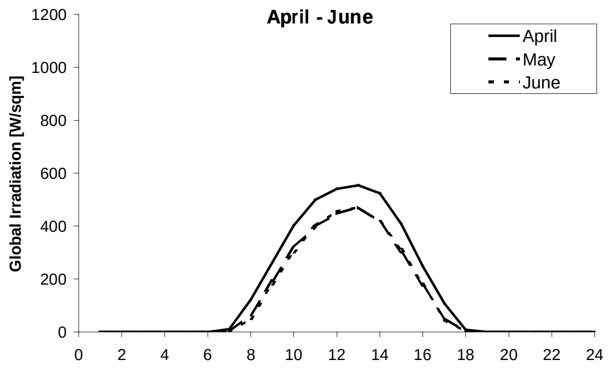


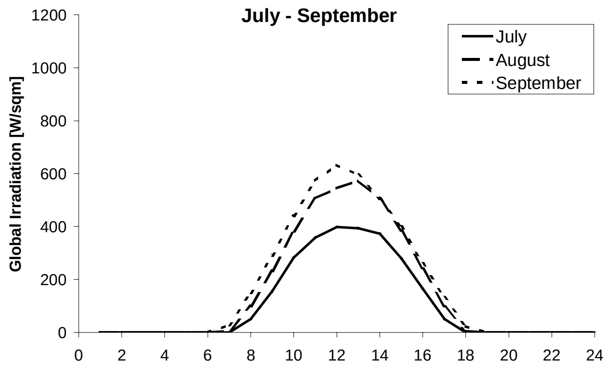
1.6 Monthly data

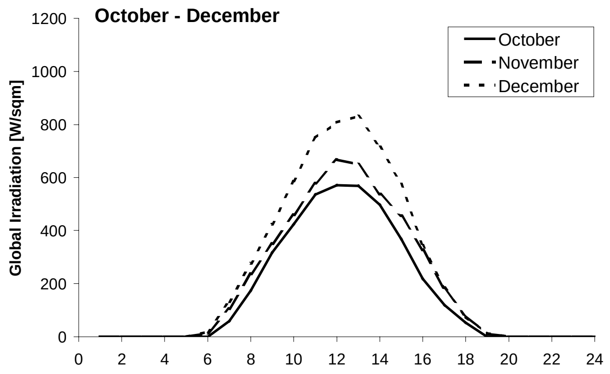
Mabibi Region

(Monthly average per hour of the day)



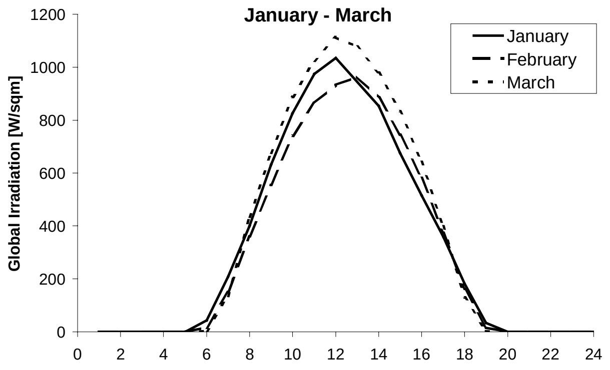


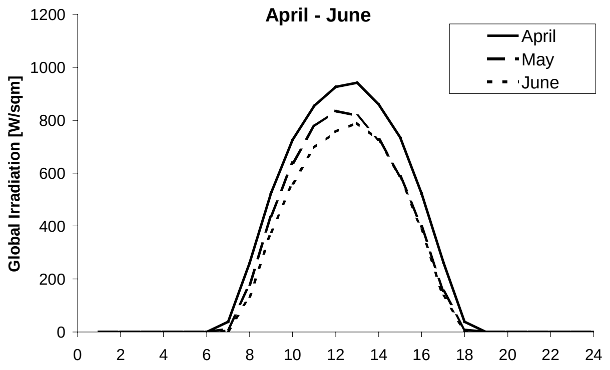


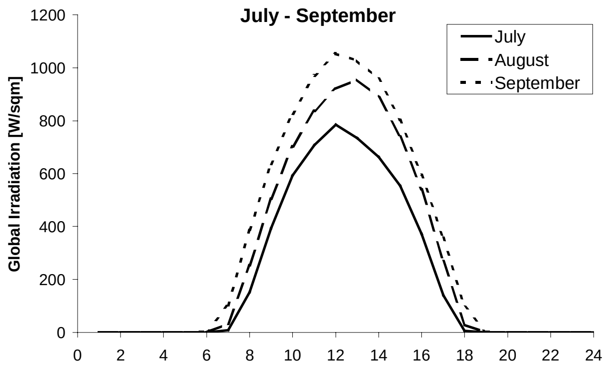


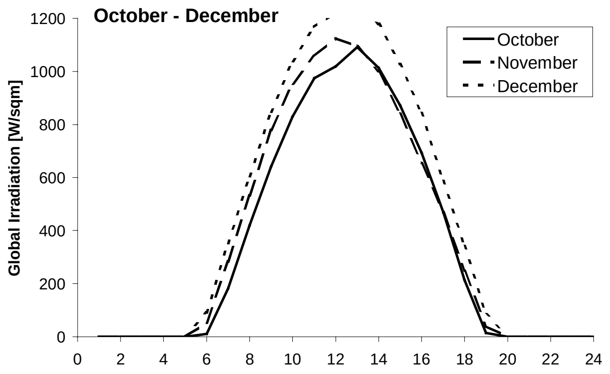
Upington Region

(Monthly average per hour of the day)





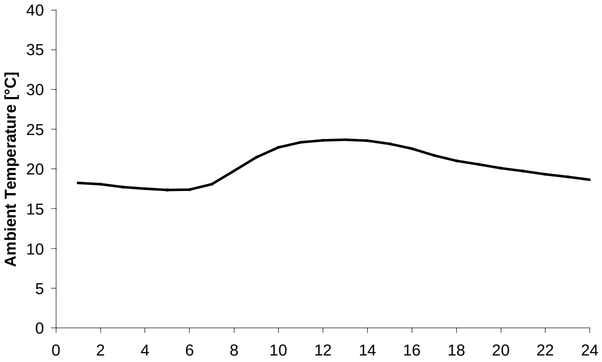


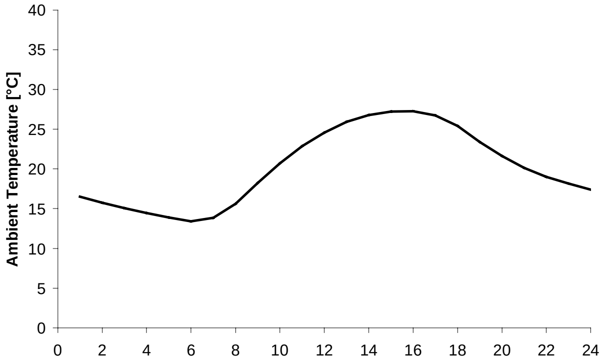


2 Ambient Temperature

2.1 Yearly data

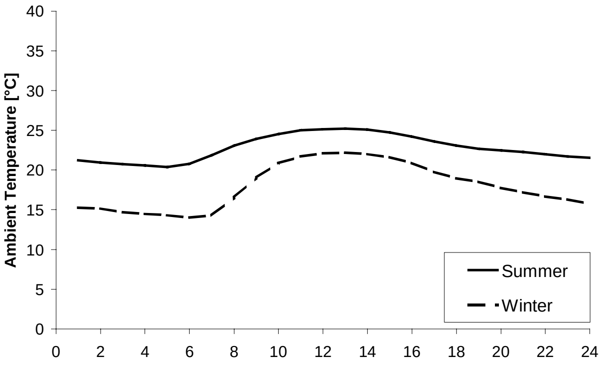
Mabibi Region	Upington Region
(Yearly average per hour of the day)	(Yearly average per hour of the day)

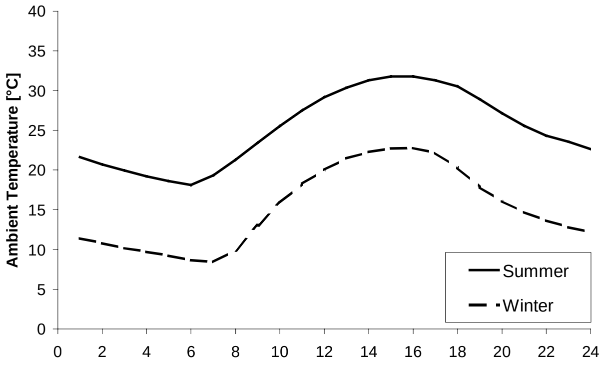




2.2 Seasonal data

Mabibi Region	Upington Region
(Summer/Winter average per hour of the day)	(Summer/Winter average per hour of the day)

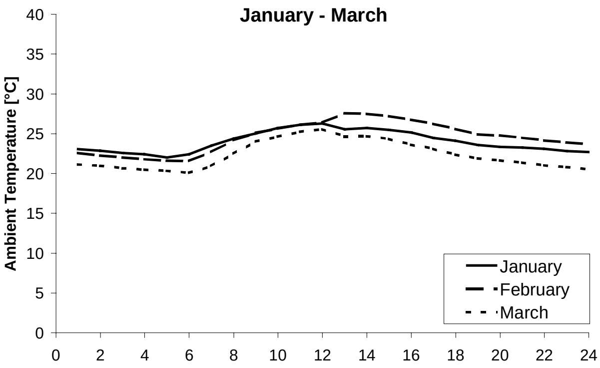


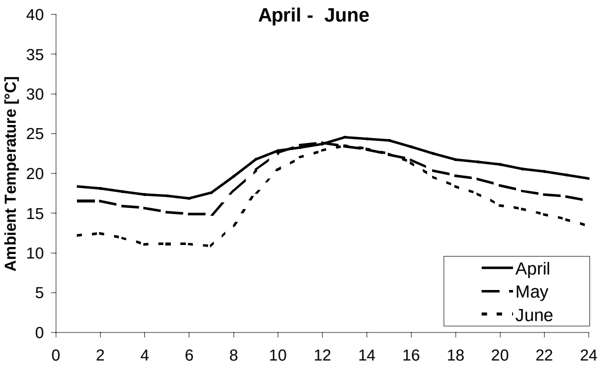


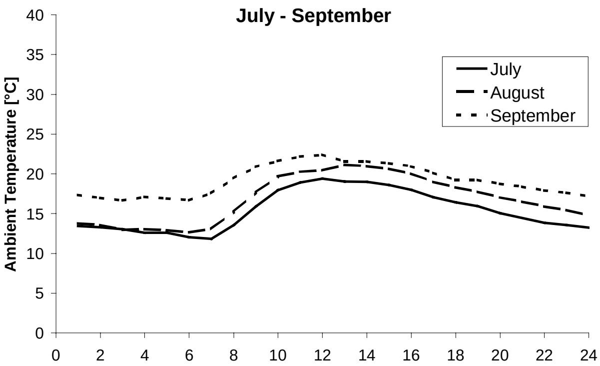
2.3 Monthly data

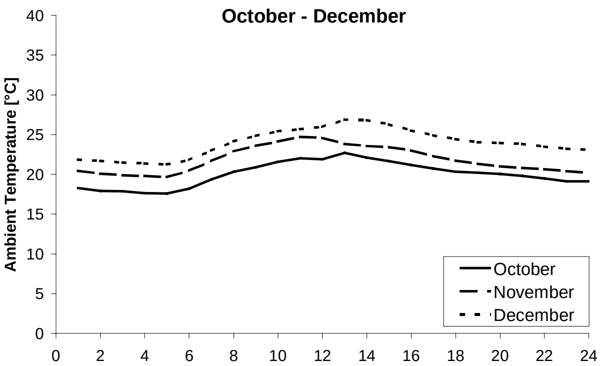
Mabibi Region

(Monthly average per hour of the day)



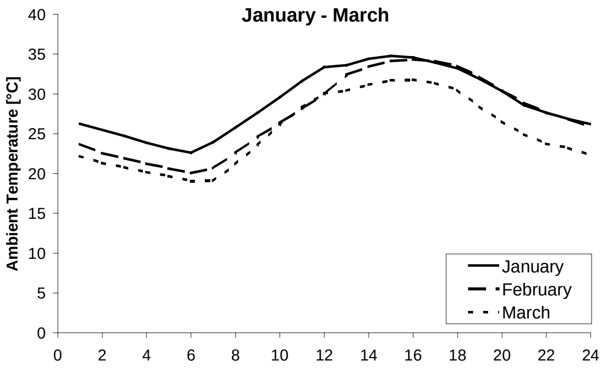


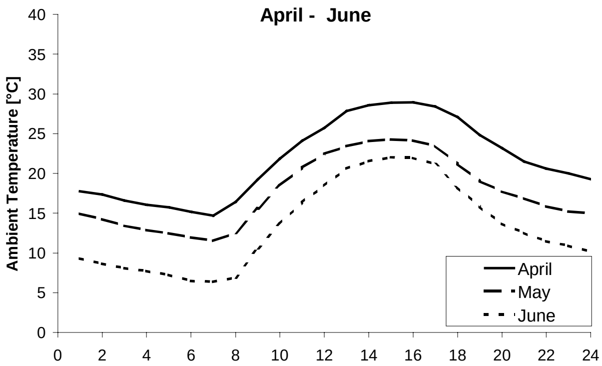


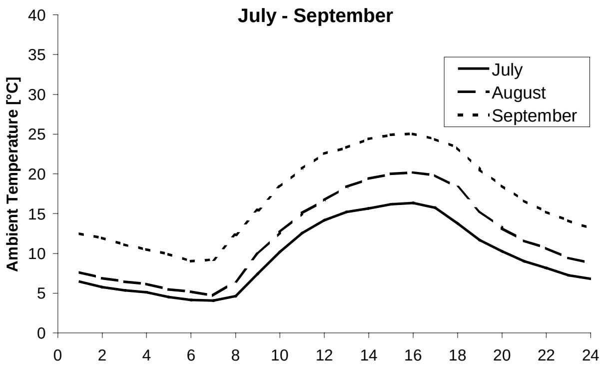


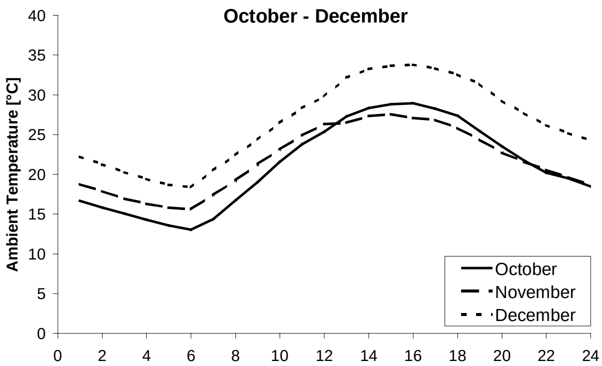
Upington Region

(Monthly average per hour of the day)









APPENDIX B

DESIGN SIMULATIONS FOR UPINGTON

Sizes and LCC, Upington

For both system configurations with a parallel inverter and a normal inverter, the life cycle costs per kWh are highest for the irregular profile with a daytime peak, D2 (Figure A 1, Figure A 2). Irregularity in demand is more expensive than designing a system for a regular demand pattern. This is partly due to additionally required redundancy in the component sizing. In addition, diesel generator operation costs per kWh and fuel costs per kWh are highest for the irregular peak demand profile, D2, regardless of the type of inverter installed. For the irregular demand profile D2 a large PV array is utilised in both the switched and parallel configurations. It seems that mainly using a diesel generator to cover the many peaks and low loads in profile D2 would not be cost-efficient and increased use of renewable energy sources reduces costs for a highly peaky profile.

Overall life cycle costs per kWh are lower for the parallel inverter configuration. This should be due to the fact that diesel generator and battery sizes and their operation can be reduced in the parallel configuration as the DC and AC busses can add their energy outputs. In the switched system configuration (normal inverter configuration) only either the DC or AC bus output can supply the AC load.

The diesel generator in the normal inverter configuration is sized to meet peak demands for all three demand profiles, and is larger in size for D2, the irregular profile with the higher peaks. The diesel generator size in the parallel inverter configuration is for all three demand profiles sized smaller than peak demand. For this reason, for all demand profiles the fuel costs per kWh are lower for the parallel inverter configuration (Figure A 3, Figure A 4). The diesel generator operation costs per kWh are higher in the parallel configuration. This can be due to the fact that the smaller diesel generators in the parallel configuration are used more at lower levels than in the normal inverter configuration (Figure A 21, Figure A 23, Figure A 25, Figure A 27, Figure A 29, Figure A 31).

In addition, in the parallel configuration, the diesel generator is sized smaller for the daytime peak profiles, D2 and D3, than for the evening peak profile (D1), with a slightly bigger diesel generator for demand profile D2 to cover the high irregular peaks. The day-time peak profiles D2 and D3 make correspondingly more use of the renewable energy sources by using bigger renewable energy components than in the normal inverter configuration.

The battery size is 50% larger in the switched configuration than in the parallel configuration due to higher storage requirements in the switched configuration in which the DC bus needs to have sufficient energy to supply the AC load as otherwise the diesel generator is used.

The life cycle costs are lowest, with either a parallel or normal inverter, for the evening peak demand pattern, D1. This can be due to the fact that the diesel generator needs to run in the evening at any case (which is confirmed by Figure A 21, Figure A 27) and can supply the load more efficiently than using day-time renewable energies cycled through a battery. In addition, the PV sources cover on average the day-time demand of the evening peak profile D1 (Figure A 21, Figure A 27).

For the same evening peak demand profile D1, battery costs per kWh in the normal inverter configuration are higher than for the other demand profiles. This should be due to increased cycling of daytime renewable energy for discharge during the evening. It is interesting that in the parallel inverter configuration the battery costs per kWh are lower, indicating the advantage in adding renewable energies directly on to the AC bus output instead of storing them until the combined DC bus energy is large enough to substitute the diesel generator output.

Amongst the regular profiles, D1 and D3, the daytime peak profile (D3) makes very little use of the PV sources (see also Figure A 25, Figure A 31), regardless of inverter type used. This might be due to the fact that as the diesel generator is anyway covering high demand levels and lower demand levels suitable for PV coverage are few.

Wind turbine sizes stay the same and at a very low value in the parallel inverter and normal inverter configuration.

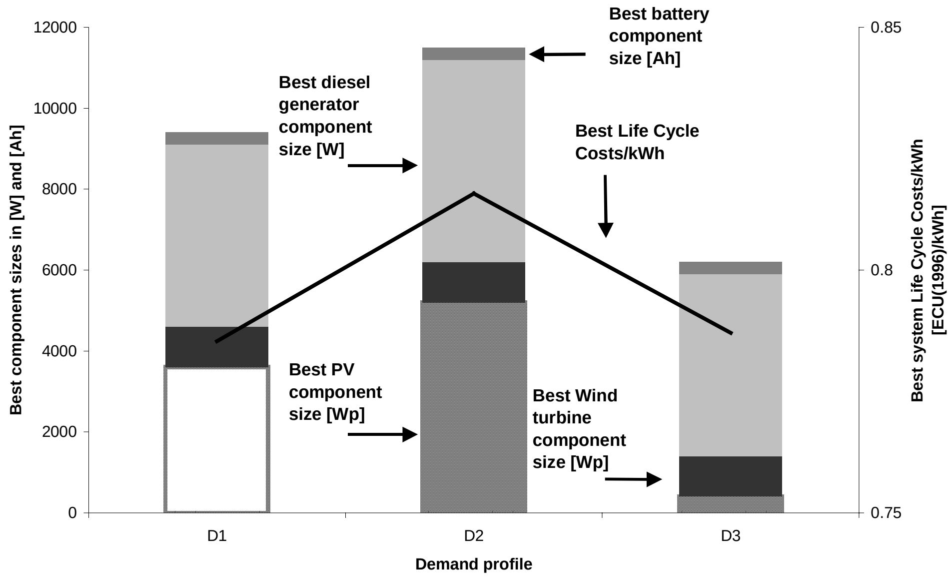


Figure A 1: Best sizing and life cycle costs per kWh for demand profiles D1-D3, normal inverter, Upington

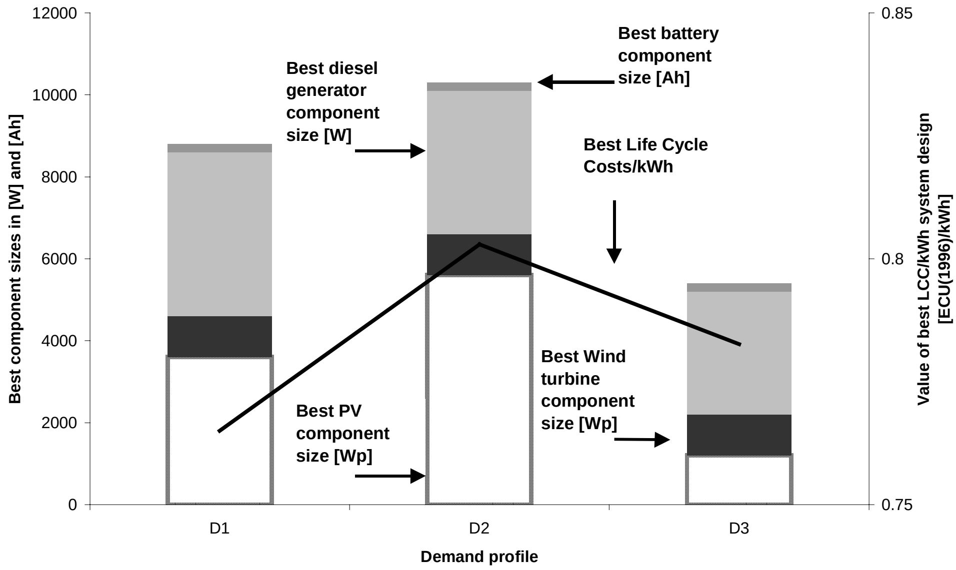


Figure A 2: Best sizing and life cycle costs per kWh for demand profiles D1-D3, parallel inverter, Upington

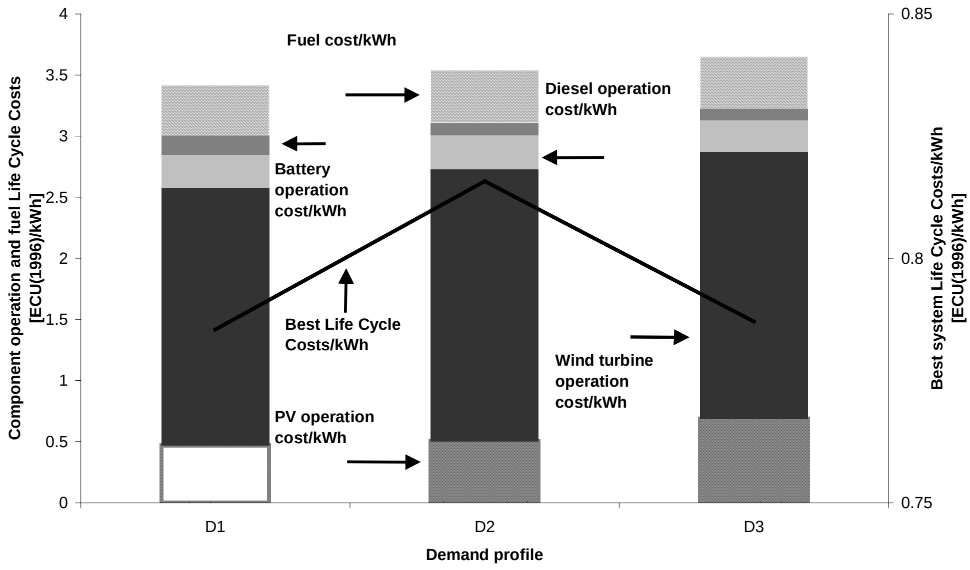


Figure A 3: Operation costs for 3 designs, normal inverter, Upington

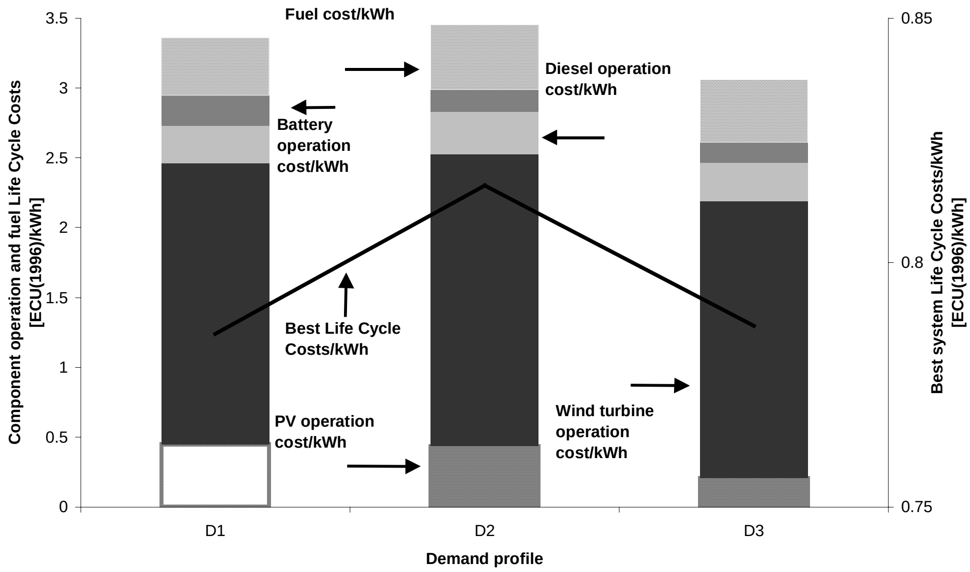


Figure A 4: Operation costs for 3 designs, parallel inverter, Upington

Control settings and fuel costs Upington

Battery discharge and renewable energy outputs cover the load instead of the diesel generator if the battery's state of charge is higher than 80% for the normal inverter configuration and 85% for the parallel inverter configuration (see control setting 1 in Figure A 5, Figure A 6). For this reason, if there is a choice in that both the inverter output and the diesel generator output can cover the load, extensive use is made of the DC bus energy in all designs, regardless of type of inverter used. In the parallel inverter configuration, a slightly higher use of the DC bus energy is made. This corresponds to the higher PV sizes in the parallel configuration designs.

However, it needs to be mentioned that whether the DC bus is sufficient to cover the load depends on the sizing of the DC energy sources and battery storage.

If a normal inverter is used, the diesel generator can route energy onto the DC bus which then can supply the load with the other DC energy through the inverter, if the battery state of charge is less than control setting 2 (Figure A 5). Therefore for the regular demand profiles D1 and D3, the designs allow the diesel generator supply through the inverter to cover the load if the battery state of charge is less than 82% (246Ah) and 96% (288Ah) respectively, i.e. quite often. How often does the battery's state of charge go below this value on average (Figure A 22, Figure A 26)? For demand profile D1, the evening peak, it does so on average twice a day, around midnight and in the evening. For demand profile D3, the daytime peak, the battery state of charge on average is always below that value and correspondingly the diesel generator plus battery discharge cover the AC demand quite often (Figure A 21, Figure A 25). This corresponds with the low installed renewable energy capacity.

For the irregular demand profile D2 with the daytime peak, the diesel generator is nearly never allowed through the DC bus (Figure A 23) to cover the AC load with the DC sources (at 53% or 159Ah, Figure A 24). If the inverter output is covering the load, the diesel generator is only allowed to charge the batteries. Still, due to the highly irregular and very peaky demand profile, fuel costs per kWh are highest for D2. The findings also correspond with the fact that D2 has the highest renewable energy share for all three demand profiles.

If a parallel inverter is installed and neither the inverter output nor the diesel generator output alone can cover the load, the diesel generator output is preferred to cover the load if the battery state of charge is smaller than control setting 2 (Figure A 6); additional energy needed to cover the load is then taken from the inverter. In case of the regular evening peak demand profile D1 and the daytime peak profile D3, the diesel generator is always preferred to cover the load, whereby additional energy is taken from the inverter output, if neither inverter output nor diesel generator output can cover the load alone. Correspondingly, the diesel generator is running a large proportion of the time (Figure A 27, Figure A 31), even more though in the design for demand profile D3, because the renewable energy resources are quite small. For demand profile D2, the irregular daytime peak, if the battery's state of charge is above 95% (190Ah), the inverter output is taken first to cover the load and any energy needed in addition is taken from the diesel generator. This is on average the case around noon, where renewable energy production is very high, and at night for ca an hour (Figure A 30). The fuel costs per kWh are again highest for the irregular demand profile D2, and lowest for the regular demand profiles.

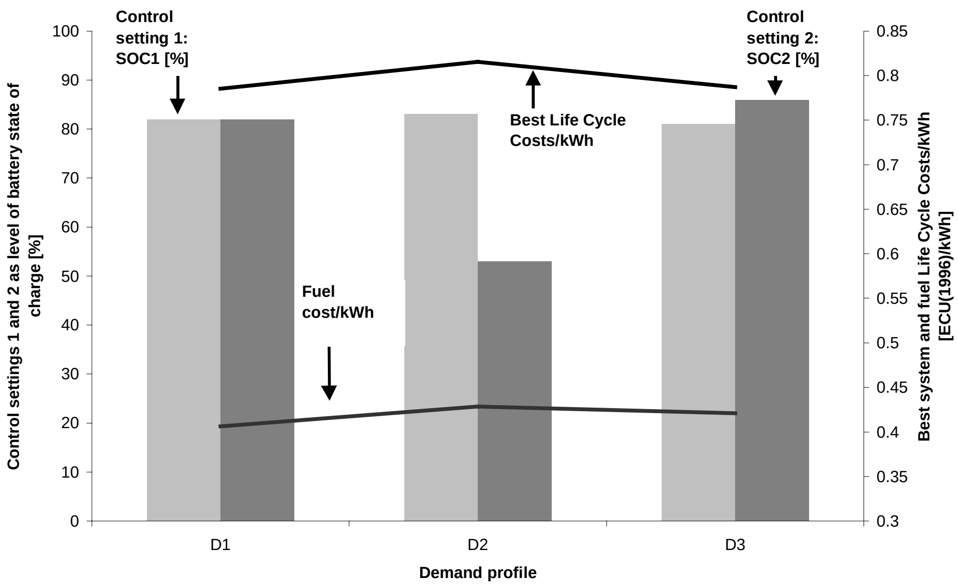


Figure A 5: Control settings and life cycle costs for 3 designs, normal inverter, Upington

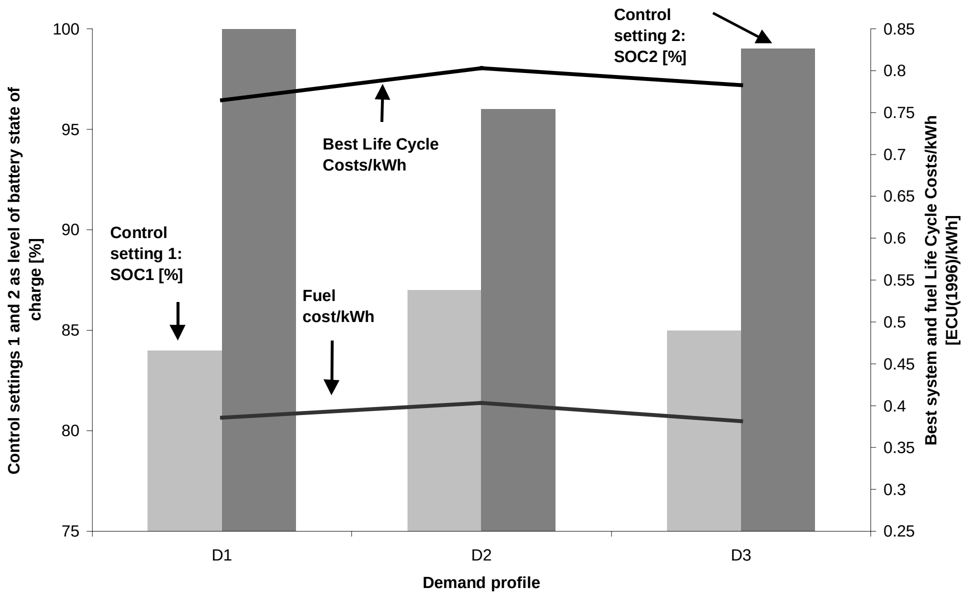


Figure A 6: Control settings and life cycle costs for 3 designs, parallel inverter, Upington

System efficiencies, Upington

In the normal inverter configuration, for all three demand profiles and obtained system designs, the system efficiency (Equation 121) is nearly 60% (Figure A 7), D3 being slightly lower than D2 and D2 being slightly lower than D1. On average the generator is running at maximum capacity for the regular profiles D1 and D3, and somewhat below full loading for the irregular profile D2. The average battery SOC is highest for the evening peak profile D1 at around 88% average SOC and lowest for the daytime peak profile D3 at around 80% average SOC.

In the parallel inverter configuration, average system efficiencies are slightly higher than for the normal inverter configuration (Figure A 8). The system efficiency is highest for demand profile D2, but the difference to the system efficiencies of D1 and D3 is not very significant. The average diesel capacity factor is around 90% for D1 and D2, around 100% for the regular daytime peak demand profile D3 that uses little renewable energies. The average battery state of charge is around 90%.

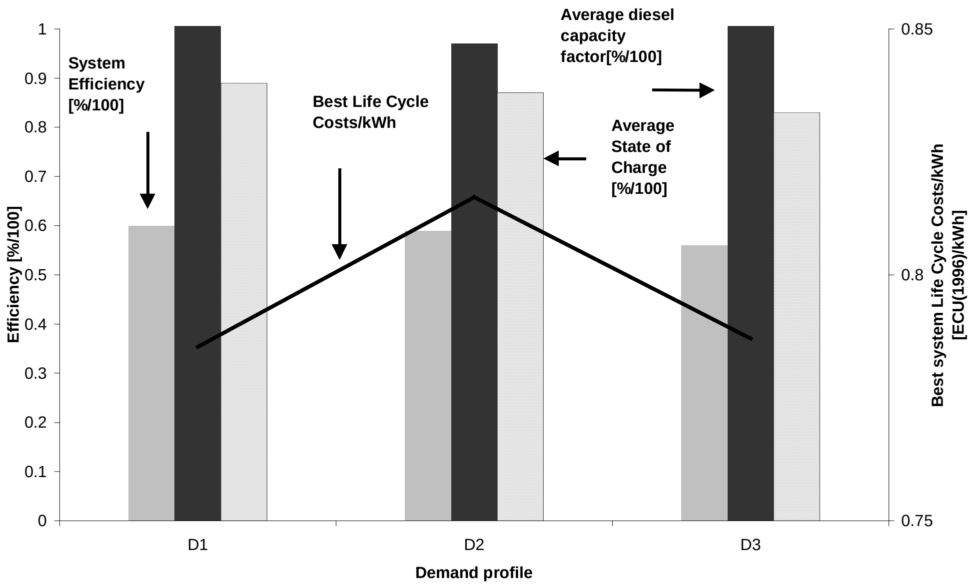


Figure A 7: System efficiency and component loading for 3 designs, normal inverter, Upington

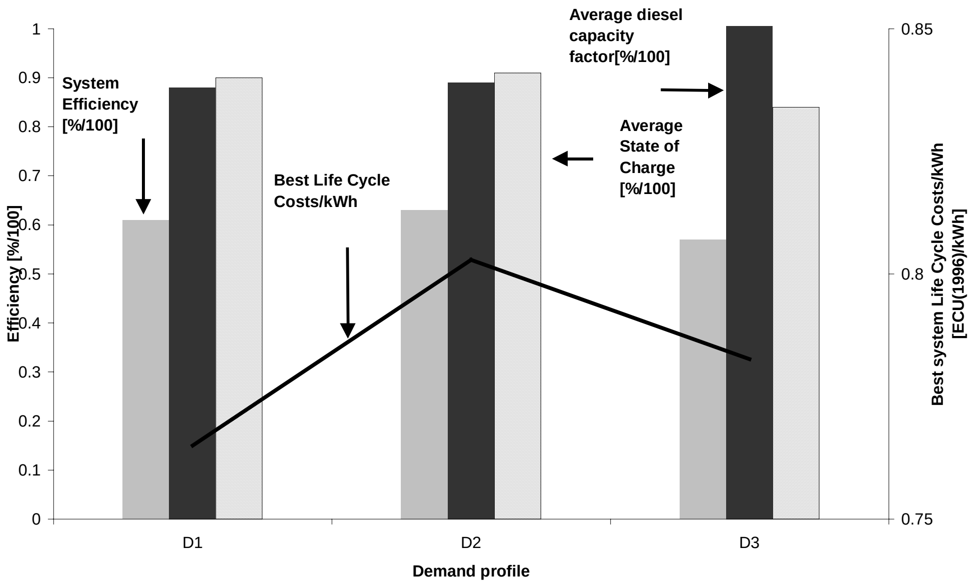


Figure A 8: System efficiency and component loading for 3 designs, parallel inverter, Upington

Losses, Upington

In the normal inverter configuration, the system losses are smallest for evening demand profile D1, and highest for the irregular demand profile D2 (Figure A 9). It can be seen that the inverter losses are the highest in the system for D2, probably due to increased use of renewable energy for demand profile D2. The battery charger losses are highest and inverter losses are smallest in the system for regular daytime profile D3.

In the parallel inverter configuration (Figure A 10), the system for demand profile D2 has again the highest losses, and the system for the demand profile D3 the lowest. In the system for D2 the inverter losses are the major losses similarly to the normal inverter configuration. Storage losses are highest and inverter losses smallest in the system for D3

Both set-ups with the normal and parallel inverter use a very high diesel generator percentage in energy production for the regular daytime peak profile D3. The highest renewable share was recommended for D2. Losses are a bit lower in the parallel inverter system. The highest loss forms are battery charger and inverter losses.

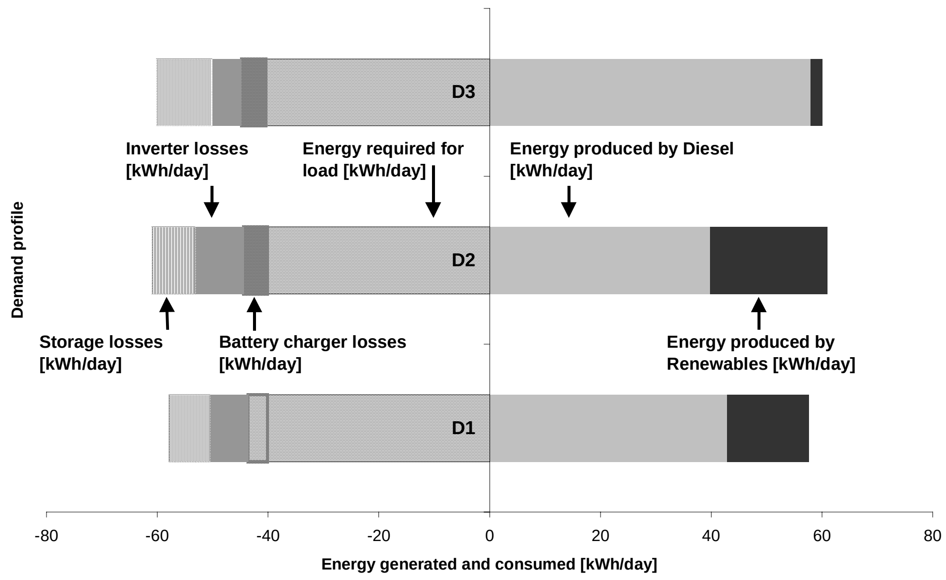


Figure A 9: Energy generation and losses for 3 designs, normal inverter, Upington

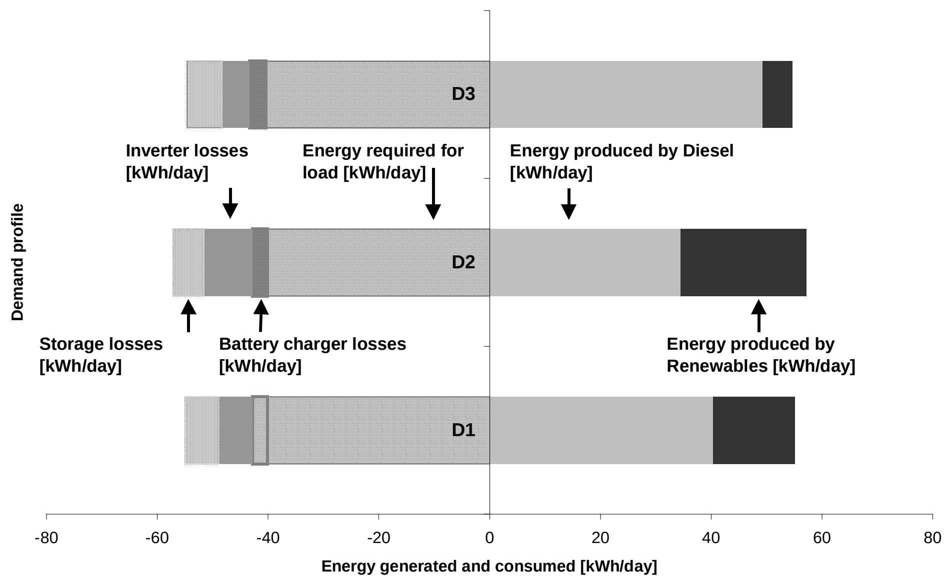


Figure A 10: Energy generation and losses for 3 designs, parallel inverter, Upington

APPENDIX C

DESIGN SIMULATIONS FOR MABIBI

Sizes and LCC, Mabibi

For both configurations, the life cycle costs are highest for demand profile D2 (irregular daytime peak profile), second highest for demand profile D1 (evening peak profile) and smallest for demand profile D3 (regular daytime peak profile), see Figure A 11 and Figure A 12. The difference in cost for the system designed for demand profile D3 between the normal and parallel inverter configuration can be neglected.

The PV share in all three systems is the same and very small for both configurations reflecting the lower radiation as compared to the Upington site. It is interesting to note that for Upington, with good PV resources, the evening peak profile is lowest in costs, whereas in Mabibi with good wind resources, the lowest cost system can designed for daytime peak loading due to the different availability time-wise of wind and PV resources.

Wind turbine in the normal configuration is sized smallest for the regular daytime peak profile D3 and highest for regular evening peak profile D1. In the parallel configuration, the wind turbine array size is largest for demand profile D1, and smallest for demand profiles D2 and D3 for which the wind turbine size is the same. This corresponds with the fact that the wind turbine operation costs are highest in the systems designed for the daytime peak profiles D2 and D3, regardless of inverter type used (Figure A 13, Figure A 14).

When a normal inverter is used, the size of the diesel generator is designed to meet peak demand and therefore is largest for the irregular daytime peak demand profile D2. In the parallel inverter configuration, the diesel generator sized smaller than required to cover peak loads. It is interesting to note that for the irregular daytime peak demand profile in the parallel inverter configuration the diesel generator is sized smallest compared to the designs for demand profiles D1 and D3.

In the parallel configuration, the fuel costs per kWh are highest for the system designed for evening peak demand profile D3, whereas when a normal inverter is installed, the fuel costs per kWh are highest for the irregular demand peak profile D2. In both configurations, they are smallest for the system designed for demand profile D1.

Regardless of the configuration, the battery operation costs per kWh are lowest for the systems designed for daytime peak profiles D2 and D3 for both configurations, even though the battery sizes for these profiles is slightly higher. The smaller battery is size for the evening peak profile D1 can be due to the fact most of the wind energy is used directly.

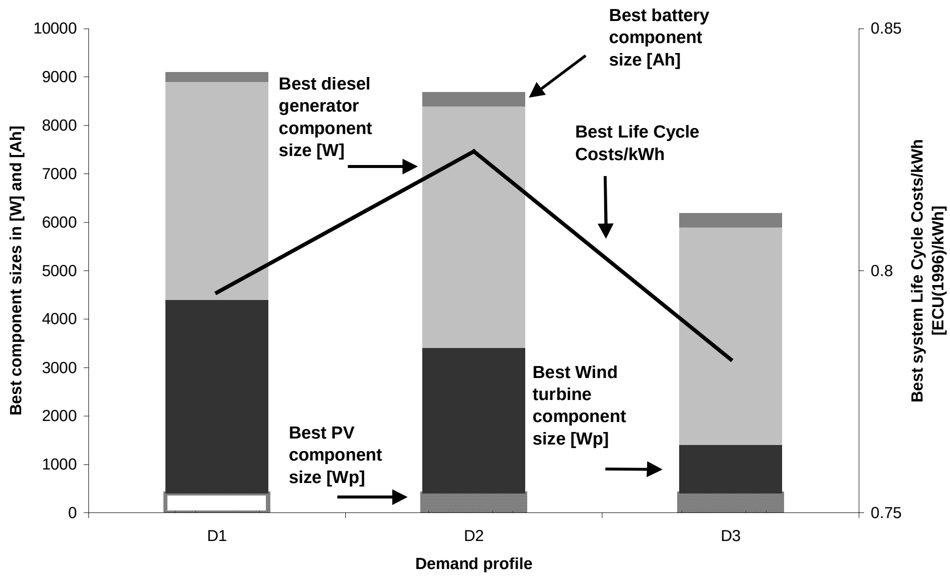


Figure A 11: Sizing and life cycle costs for 3 designs, normal inverter, Mabibi

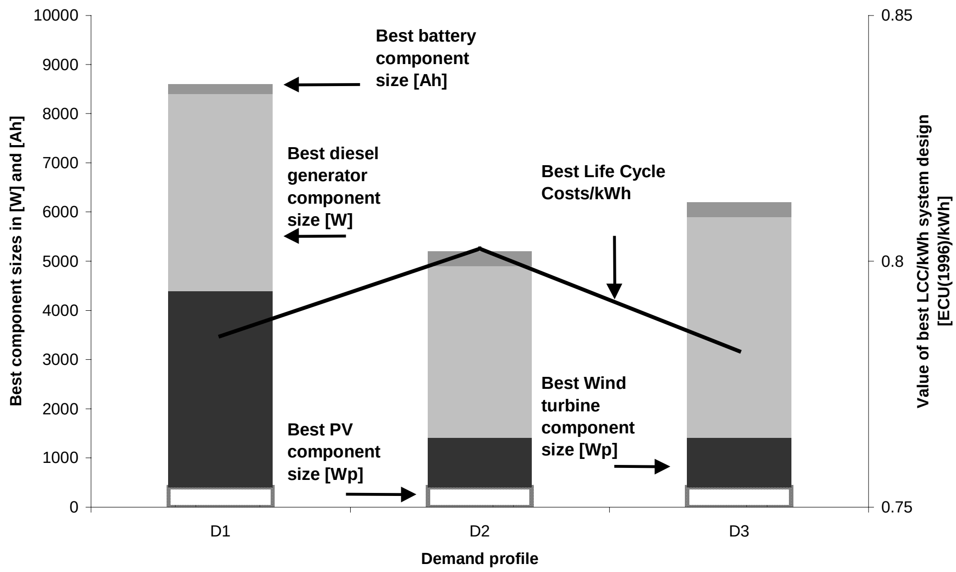


Figure A 12: Sizing and life cycle costs for 3 designs, parallel inverter, Mabibi

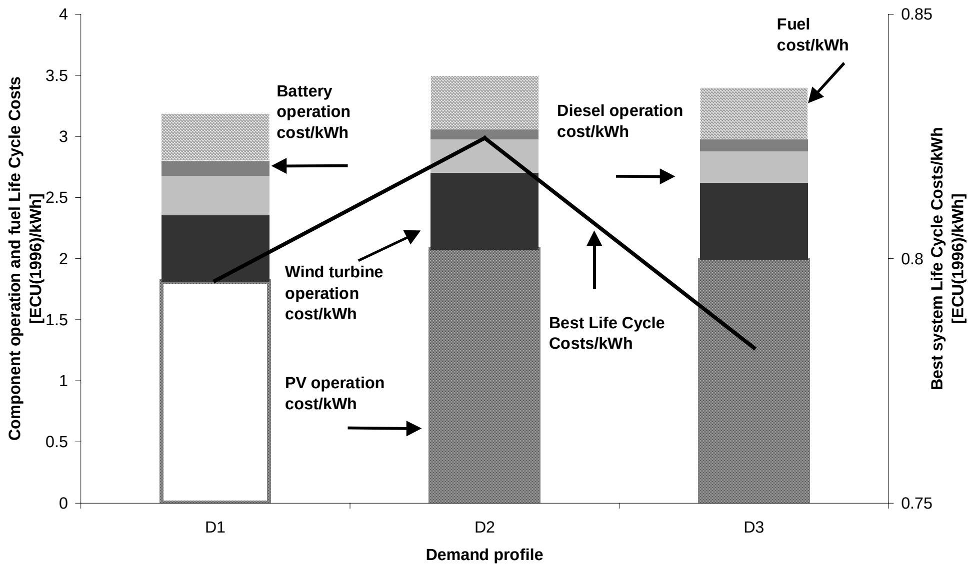


Figure A 13: Operation costs for 3 designs, normal inverter, Mabibi

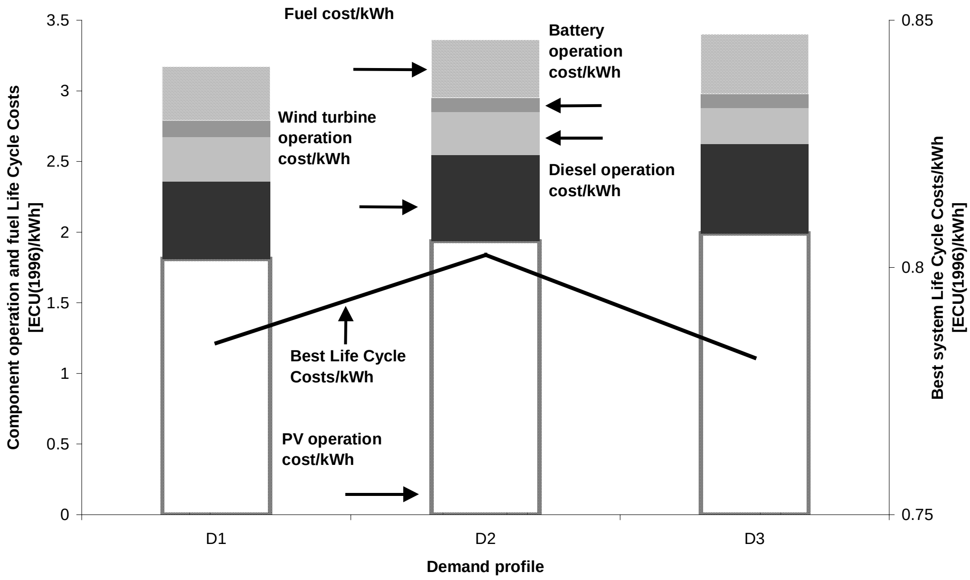


Figure A 14: Operation costs for 3 designs, parallel inverter, Mabibi

Control settings, Mabibi

In the normal inverter configuration, if the battery discharge and renewable energy sources are sufficient to cover the load, they are allowed to do so whenever the battery state of charge is above 54% (108Ah) for demand profile D1 (control setting 1 in Figure A 15), 84% (252Ah) for demand profile D2 and 79% (237Ah) for demand profile D3. According to Figure A 34, Figure A 36, Figure A 38 this is always the case for the evening peak demand profile D1, for the irregular daytime peak profiles D2 this is possible in the morning, and for the regular daytime peak profile the inverter output can supply the load instead of the diesel generator for around 5 hours distributed over the whole day. That means that the evening load profile makes extensive use of covering the load with the inverter output.

In case neither the inverter output nor the diesel generator can cover the load, the diesel generator output is allowed to cover the load together with the DC energy sources through the inverter if the battery state of charge is below around 60% for the systems designed for demand profiles D1 and D2 and below 80% for demand profile D3 (control setting 2 in Figure A 15). The fuel costs are lowest for D1 and highest for D3 in both configurations. That means for the evening peak profile D1 and the irregular daytime peak demand, the diesel generator can nearly never cover the load through the inverter due to the controller settings, whereas for the regular daytime peak profile this is quite often possible.

In the parallel inverter configuration, for evening peak demand profile D1 the battery and renewable energy sources are almost always allowed to supply the load instead of the diesel generator, if they can cover the load. In the systems designed for demand profiles D2 and D3, the diesel generator can cover the load if the battery's state of charge is below around 80% (260Ah), even if the battery and renewable energy sources would be sufficient to cover the load.

In case neither the inverter output nor the diesel generator can fully cover the load in the parallel inverter configuration, for the evening peak profile D1 the diesel generator output is nearly always taken first to satisfy the load and the inverter outputs tops up the rest of any additionally needed energy to cover the load. This is also the case for demand profile D2 if the battery is below 92% (276Ah), and for demand profile D3 if the battery state of charge is below 80% (240Ah).

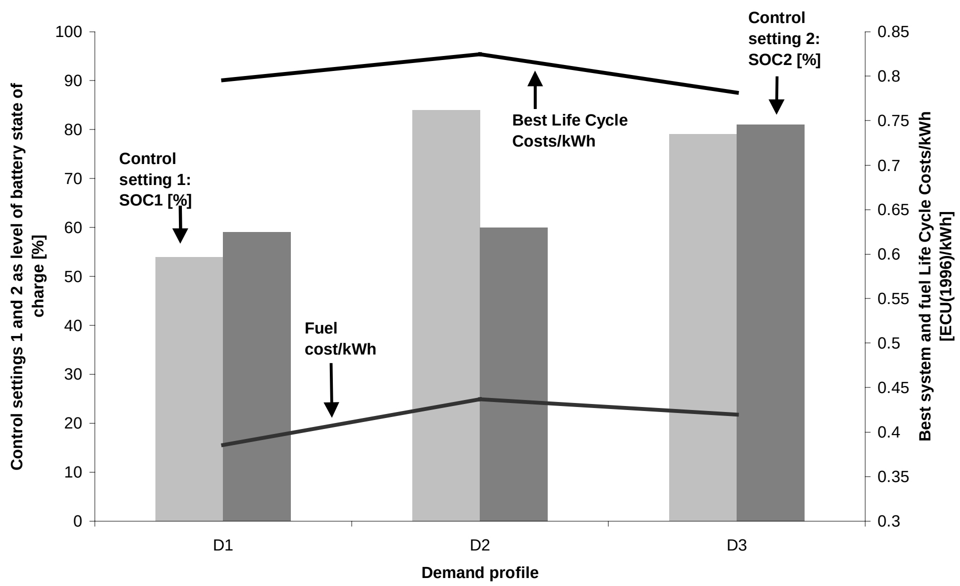


Figure A 15: Control settings and life cycle costs for 3 designs, normal inverter, Mabibi

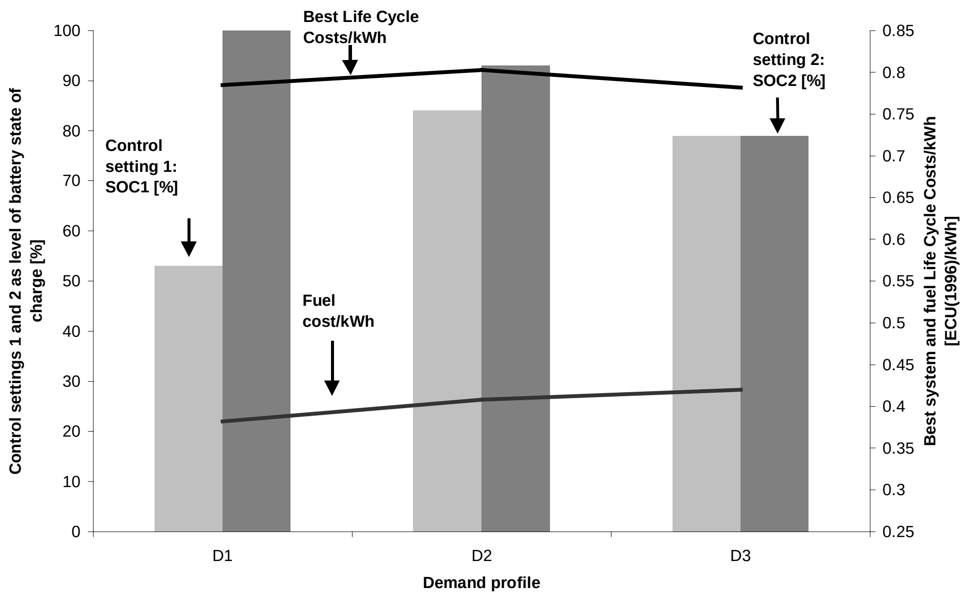


Figure A 16: Control settings and life cycle costs for 3 designs, parallel inverter, Mabibi

Efficiencies, Mabibi

The average overall system efficiency in both configurations are around 60% (Figure A 17, Figure A 18), slightly higher for the system designed for demand profile D1, and slightly lower for the two others. The average battery's state of charge for both configurations and all designs is around 80%, being somewhat higher for demand profiles D2 and D3.

In both the configurations, the average diesel capacity factor is close to full loading for the systems designed for demand profiles D2 and D3. It is just below 80% for demand profile D1 in the normal inverter configuration and just below 90% in the parallel inverter configuration.

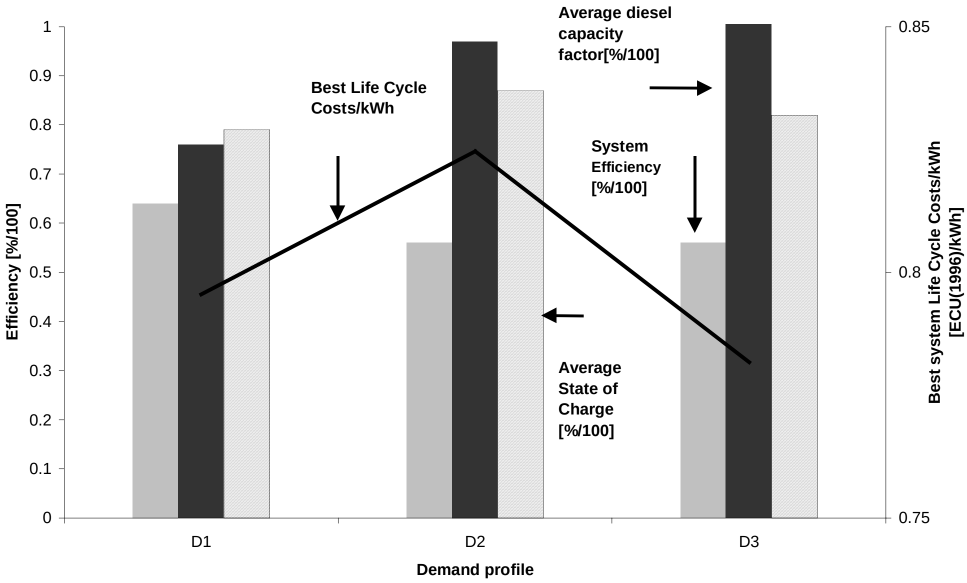


Figure A 17: System efficiency and component loading for 3 designs, normal inverter, Mabibi

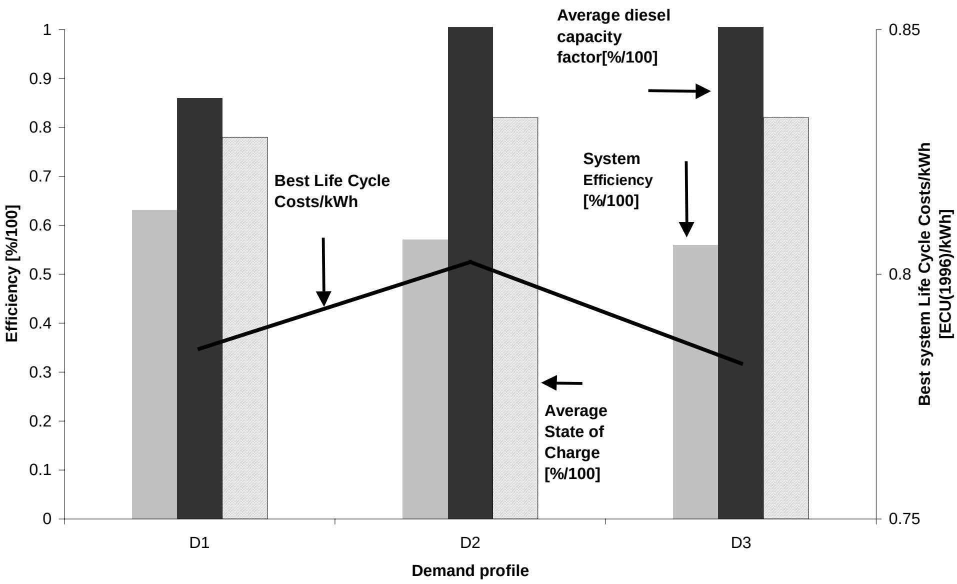


Figure A 18: System efficiency and component loading for 3 designs, parallel inverter, Mabibi

Losses, Mabibi

In the normal inverter configuration, the losses are lowest for the system designed for evening peak demand profile D1, which also has the highest renewable share in its energy production compared to the irregular and regular daytime peak profiles, D2 and D3 respectively (Figure A 19). The losses are highest for the system designed for demand profile D2, where the renewable energy share is second highest. The major part of losses for demand profile D2 consists of battery charging losses followed by inverter losses. The high losses for the irregular daytime peak demand profile are maybe due to the fact that the wind energy produced cannot be used directly in many cases and then has to be stored. In addition, the diesel generator might have to route a lot of energy onto the DC bus to charge the batteries and to supply the load through the inverter. Whereas for the evening peak demand profile most of the produced wind energy might be used directly to supply the load, thus decreasing losses. In addition, less of the diesel generator energy might be needed to be routed onto the DC bus.

In the parallel inverter configuration, the renewable energy share is again highest for the system designed for demand profile D1, which also has, as in the normal inverter configuration, the lowest losses even though inverter losses are higher than for demand profiles D2 and D3 (Figure A 20). The highest losses occur in the system for demand profile D3, where battery charging losses are highest compared to the demand profiles D1 and D2. The system designed for D2 has a lower renewable energy share than in the normal inverter configuration.

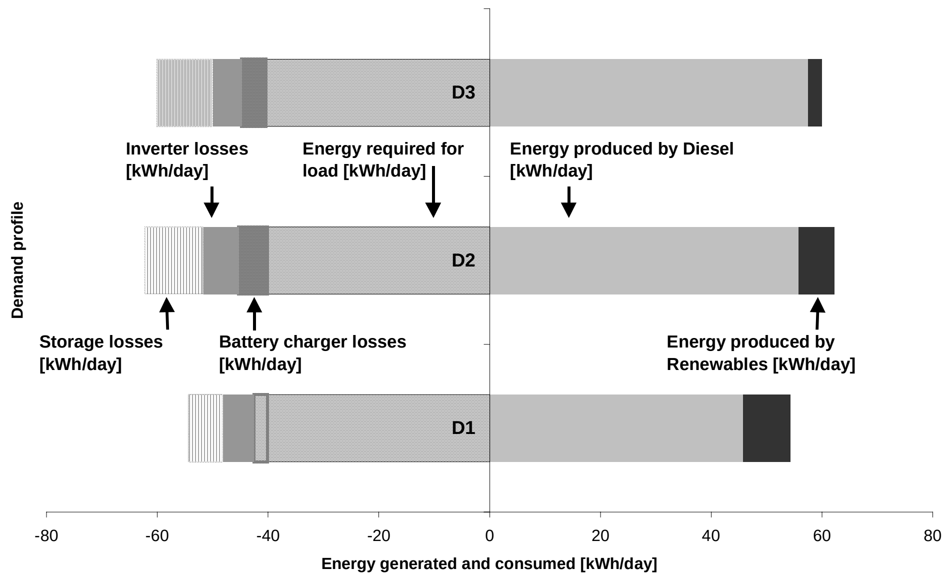


Figure A 19: Energy generation and losses for 3 designs, normal inverter, Mabibi

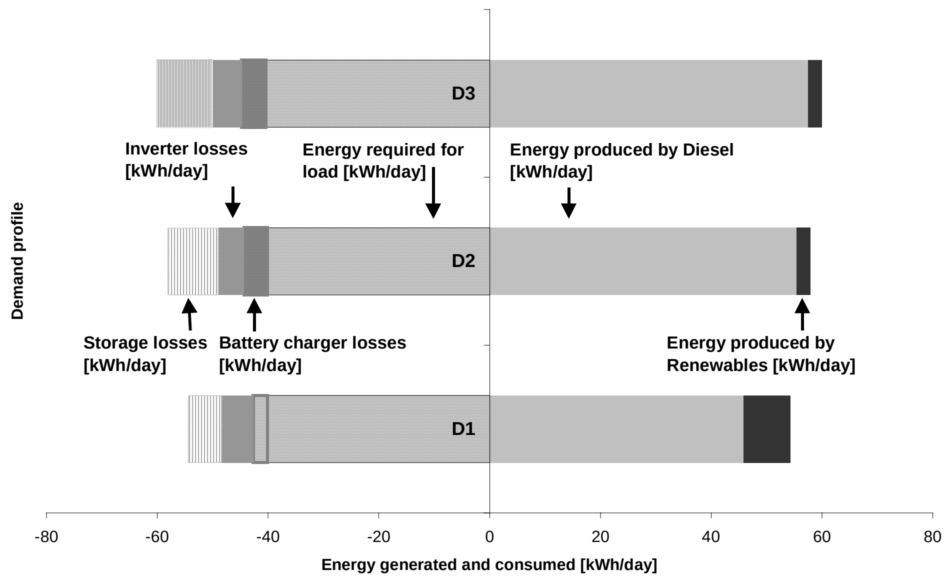


Figure A 20: Energy generation and losses for 3 designs, parallel inverter, Mabibi

APPENDIX D

TIME SERIES FOR UPINGTON AND MABIBI

The averaged time series for one day of the Upington and Mabibi designs are displayed in Figure A 27-Figure A 32 for the Upington designs and in Figure A 33-Figure A 44, for the Mabibi designs. For each design case one diagram shows the averaged levels of demand and component energy outputs and inputs, whereas another diagram depicts the average battery's state of charge level and the average energy cycled through it.

D1, Upington, Normal inverter

On average, the diesel generator is running mainly in the evening and less often in the morning. The diesel generator still supports the renewable energy output on a few rare occasions during midday. Wind energy is a very minor contribution. The battery is heavily cycled in the evening and to some extent in the morning.

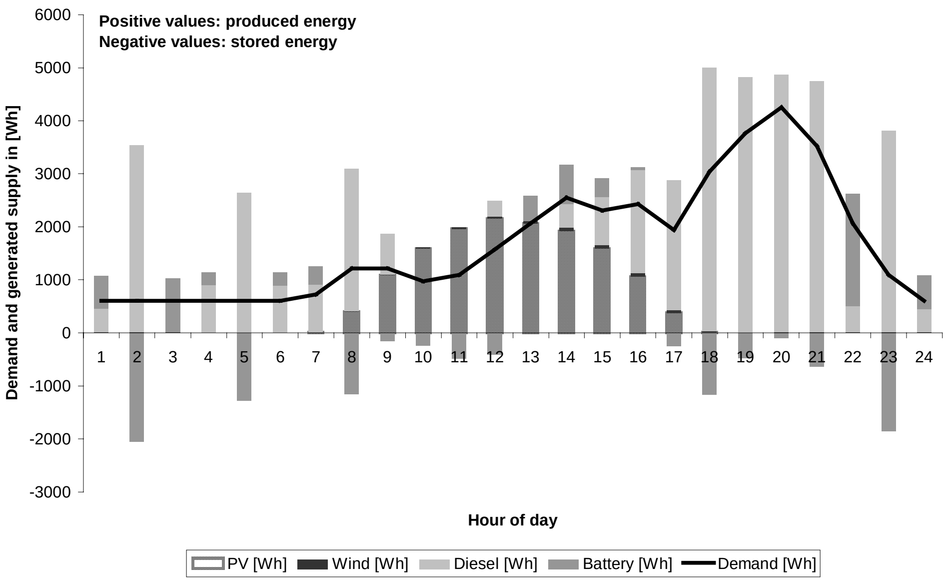


Figure A 21: Average hourly energy produced/demanded for demand D1, normal inverter, Upington

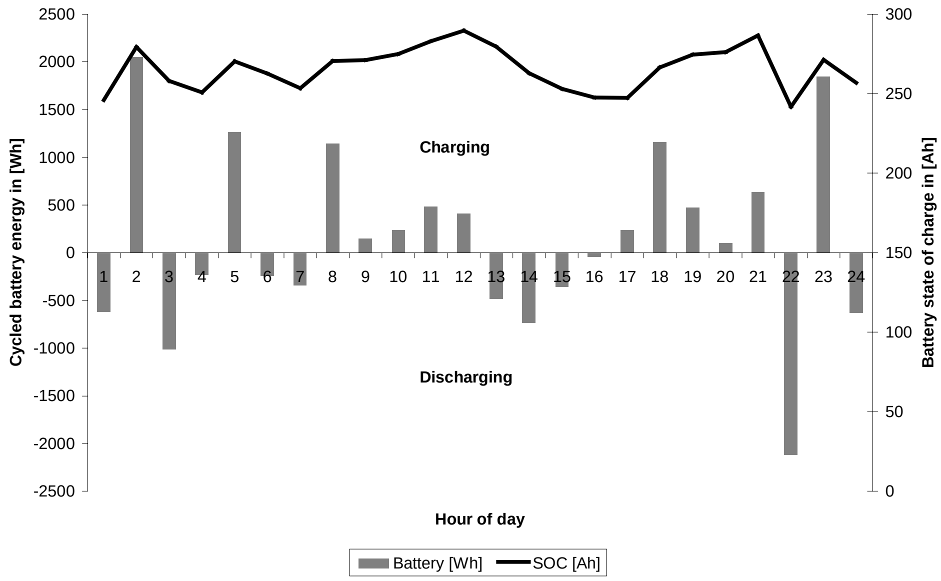


Figure A 22: Average hourly battery energy and SOC for demand D1, normal inverter, Upington

D2, Upington, Normal inverter

The diesel generator is on average running in the morning and evening. The diesel generator contributes very rarely energy during some midday hours. The battery is cycled less on average than for demand profile D1.

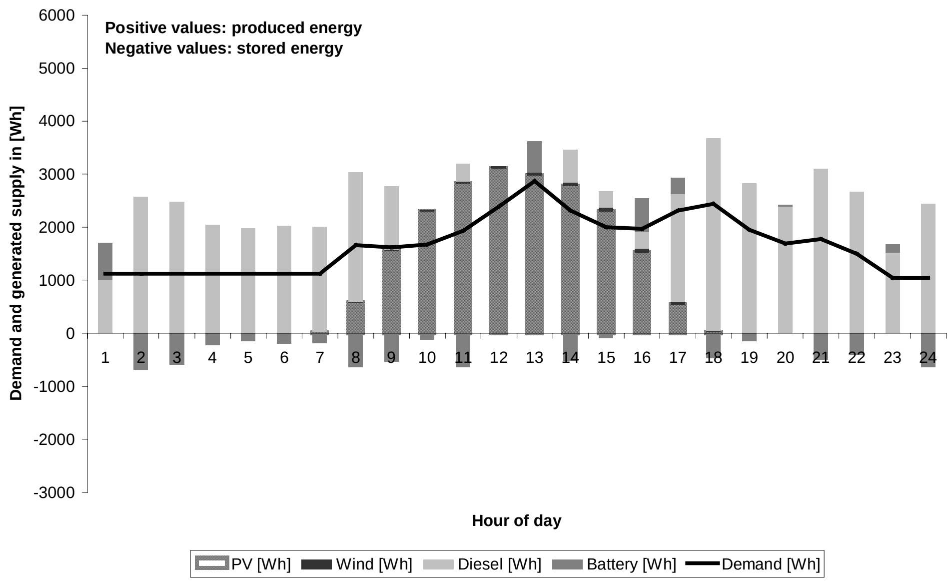


Figure A 23: Average hourly energy produced/demanded for demand D2, normal inverter, Upington

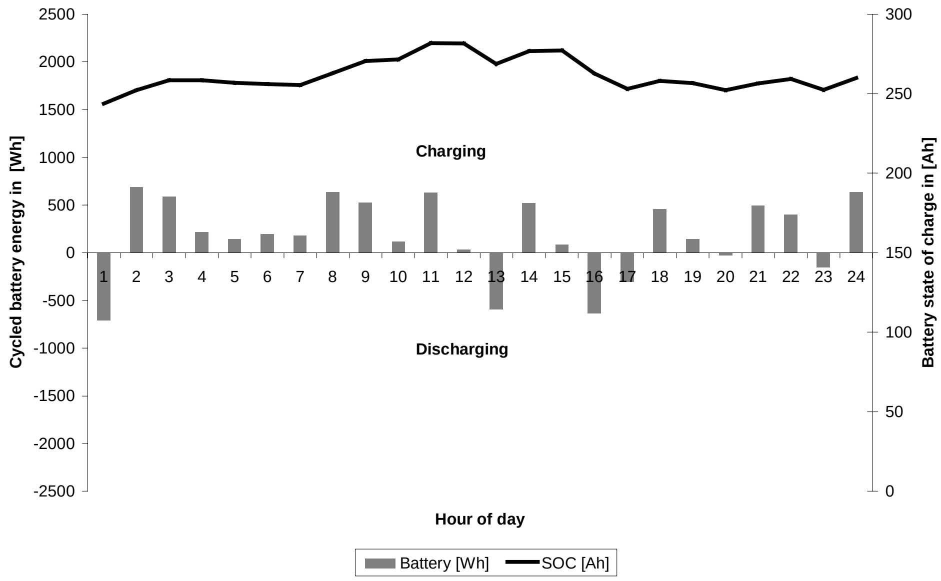


Figure A 24: Average hourly battery energy and SOC for demand D2, normal inverter, Upington

D3, Upington, Normal inverter

On average, the diesel generator is on mainly during the daytime, and less often in the morning or evening. Renewable energy output forms a small contribution. The battery is cycled intensively.

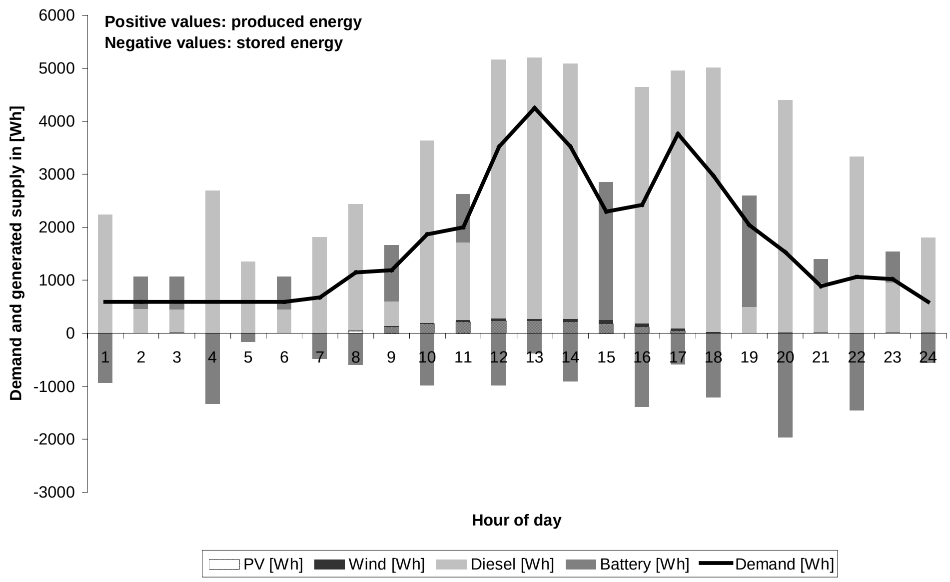


Figure A 25: Average hourly energy produced/demanded for demand D3, normal inverter, Upington

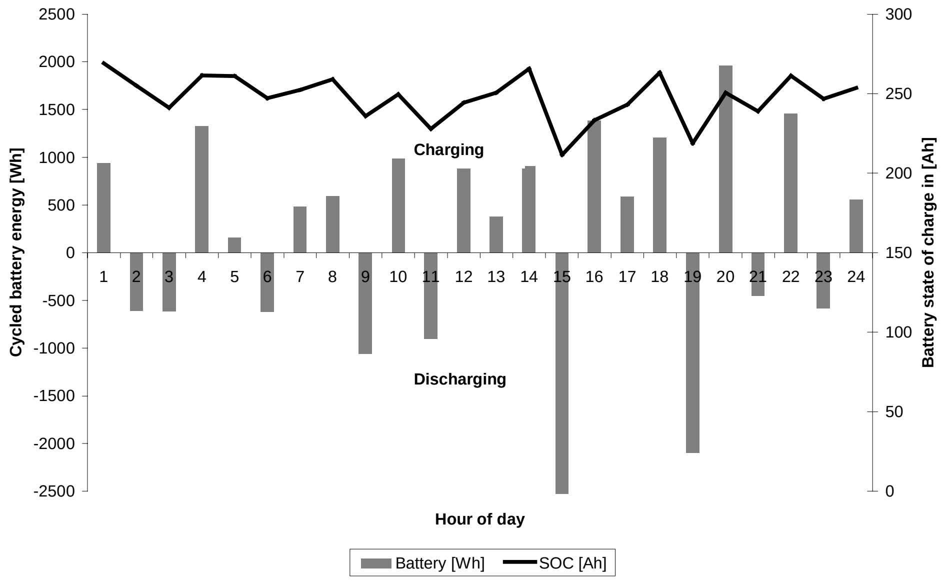


Figure A 26: Average hourly battery energy and SOC for demand D3, normal inverter, Upington

D1, Upington, Parallel inverter

The diesel generator on average runs mainly during the evening and sometimes in the morning. During midday the diesel generator is only sometimes supplying energy. The battery is cycled on average similarly to the normal inverter configuration.

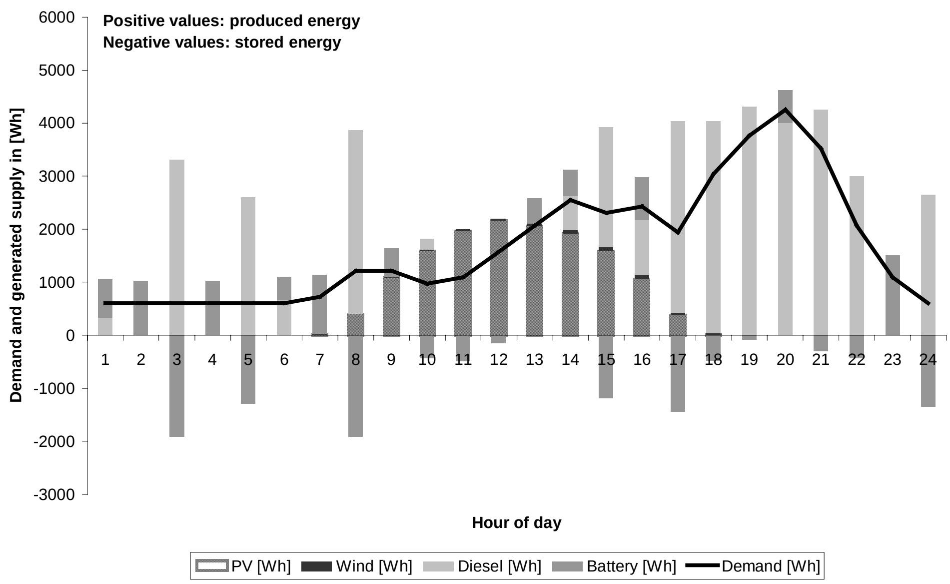


Figure A 27: Average hourly energy produced/demanded for demand D1, parallel inverter, Upington

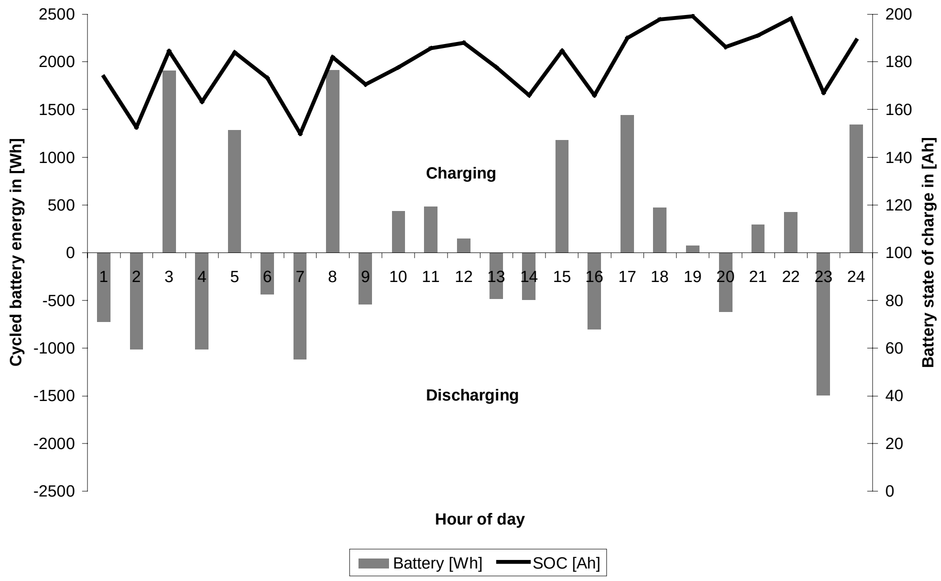


Figure A 28: Average hourly battery energy and SOC for demand D1, parallel inverter, Upington

D2, Upington, Parallel inverter

The diesel generator is on average switched on mainly during the morning and evening. The battery is cycled evenly.

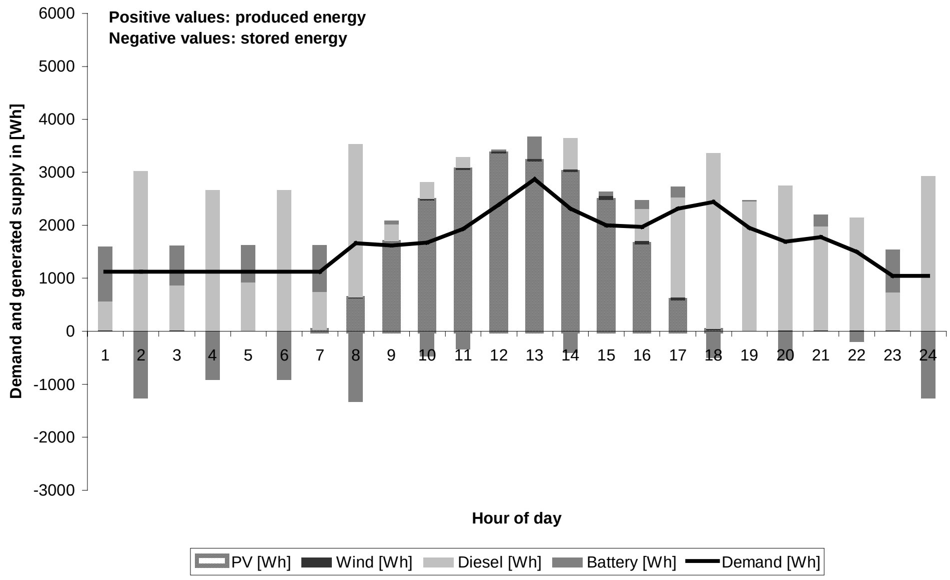


Figure A 29: Average hourly energy produced/demanded for demand D2, parallel inverter, Upington

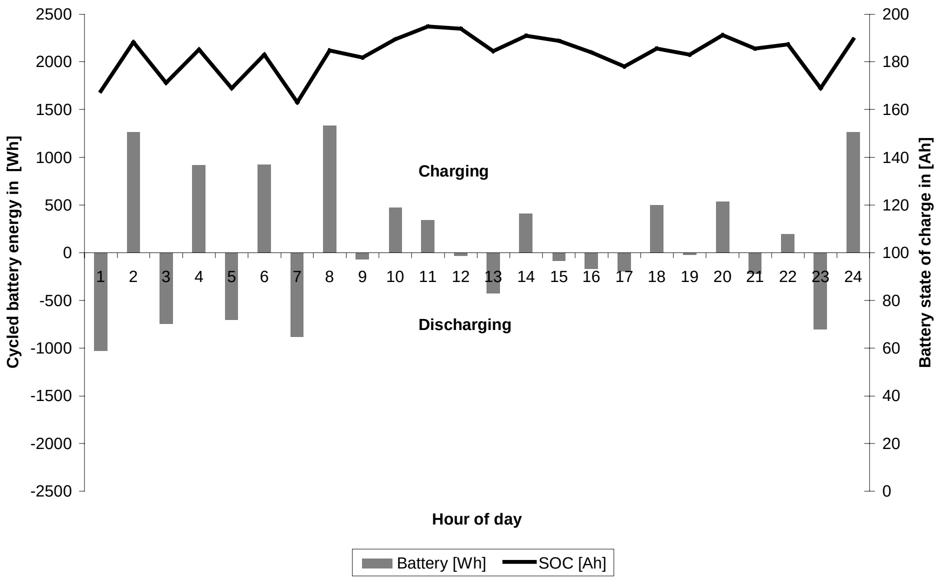


Figure A 30: Average hourly battery energy and SOC for demand D2, parallel inverter, Upington

D3, Upington, Parallel inverter

The diesel generator runs on average around midday or afternoon. It runs less often in the morning, The battery is often discharged in the evening. This is similar to the normal inverter situation.

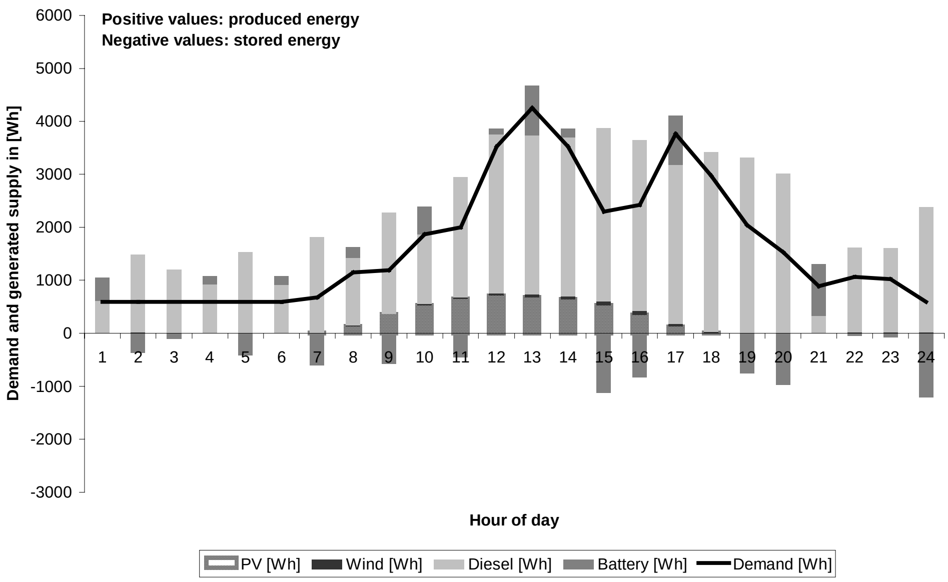


Figure A 31: Average hourly energy produced/demanded for demand D3, parallel inverter, Upington

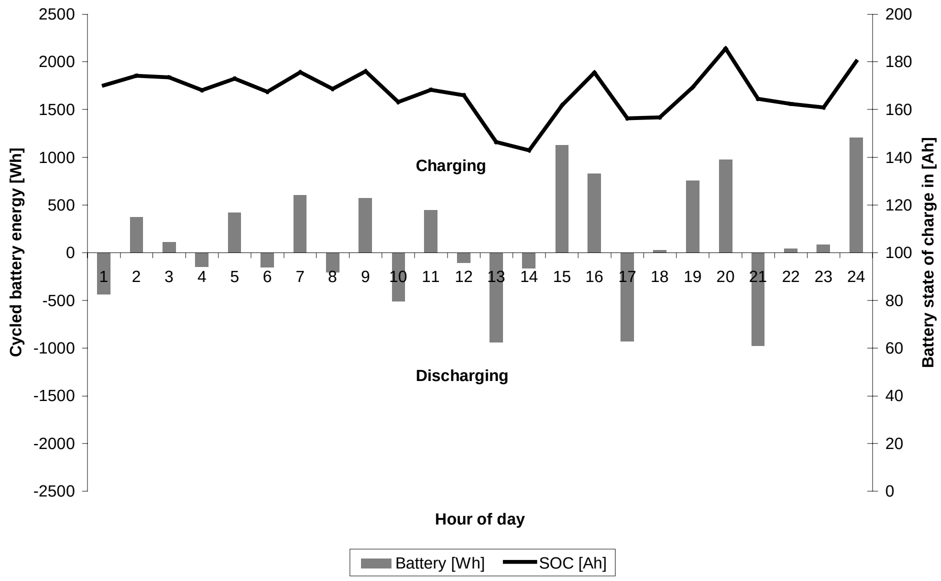


Figure A 32: Average hourly battery energy and SOC for demand D3, parallel inverter, Upington

D1, Mabibi, Normal inverter

The diesel generator on average is running mainly during the evening/late afternoon hours. It is seldom on during the morning. The battery is mainly discharged during the evening and only rarely during the morning.

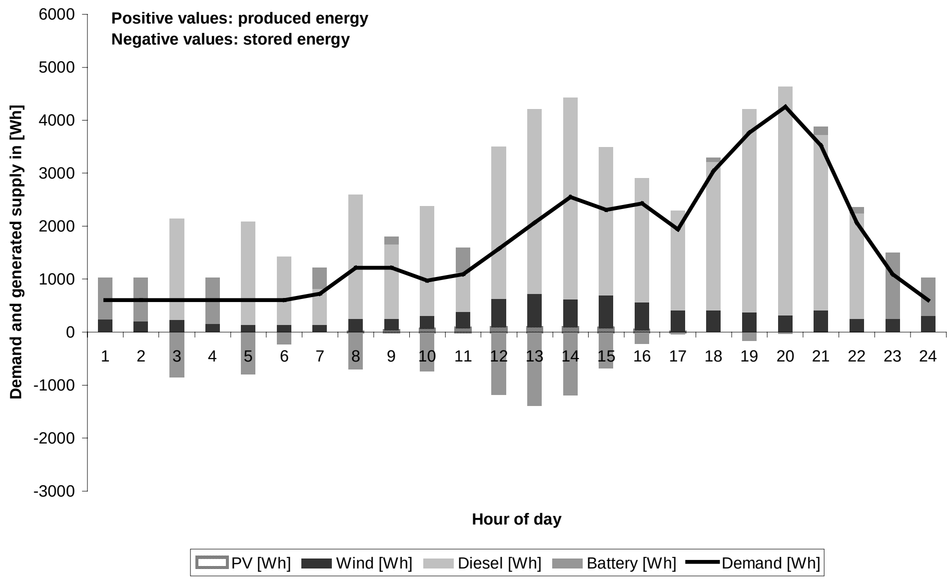


Figure A 33: Average hourly energy produced/demanded for demand D1, normal inverter, Mabibi

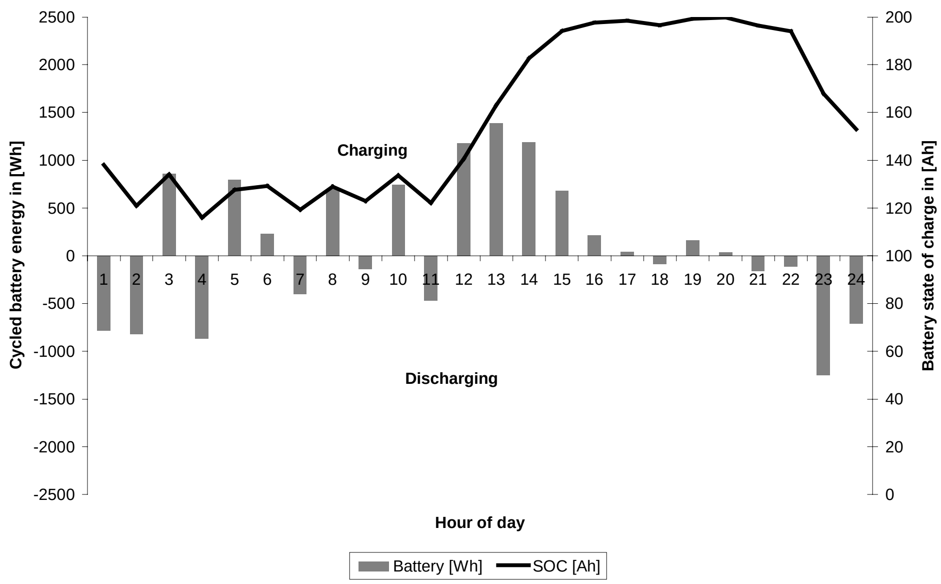


Figure A 34: Average hourly battery energy and SOC for demand D1, normal inverter, Mabibi

D2, Mabibi, Normal inverter

The diesel generator is on average likely to be on mainly during midday and sometimes during the evening and morning. The wind turbine energy contributions are substantially higher than for the system designed for demand profile D2 in Upington. The battery is on average mainly cycled during the morning, and is likely to charge from midday until late afternoon and discharge later in the evening.

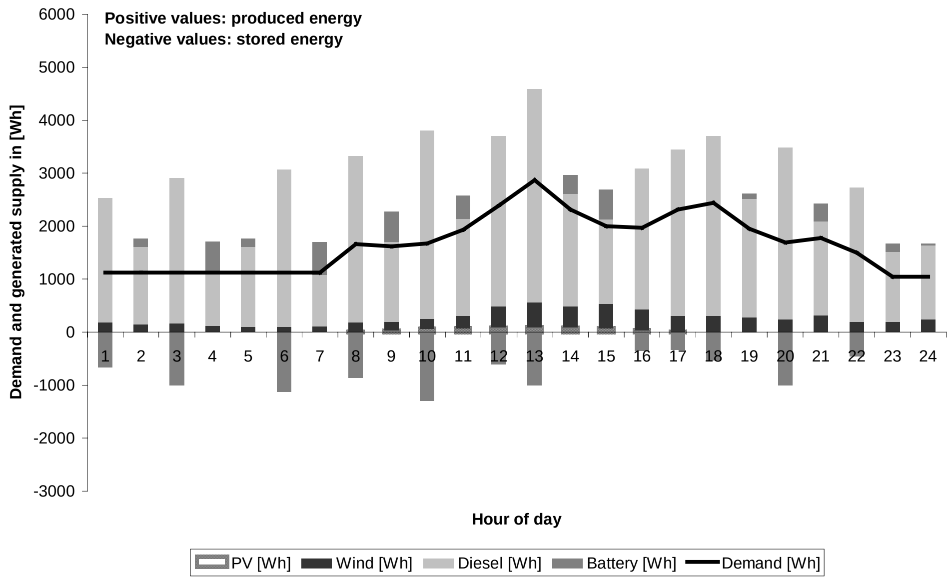


Figure A 35: Average hourly energy produced/demanded for demand D2, normal inverter, Mabibi

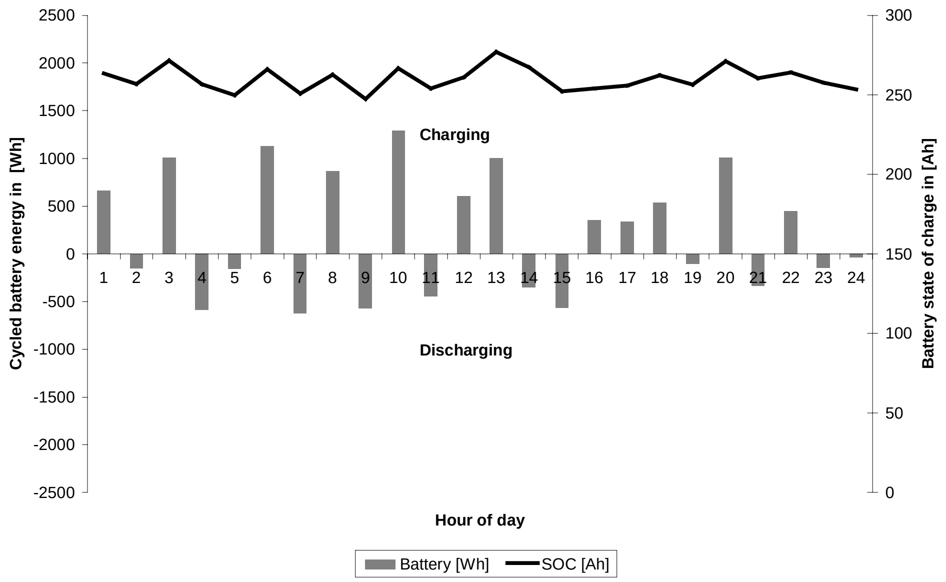


Figure A 36: Average hourly battery energy and SOC for demand D2, normal inverter, Mabibi

D3, Mabibi, Normal inverter

The wind turbine energy contributions are on average again higher than for the system designed for the same demand profile in Upington. The diesel generator is running in the evening, and is also sometimes switched on during the morning. The battery is on average mainly charged during the late afternoon, sometimes even early morning, and discharged late at night. The battery is also sometimes discharged in the morning.

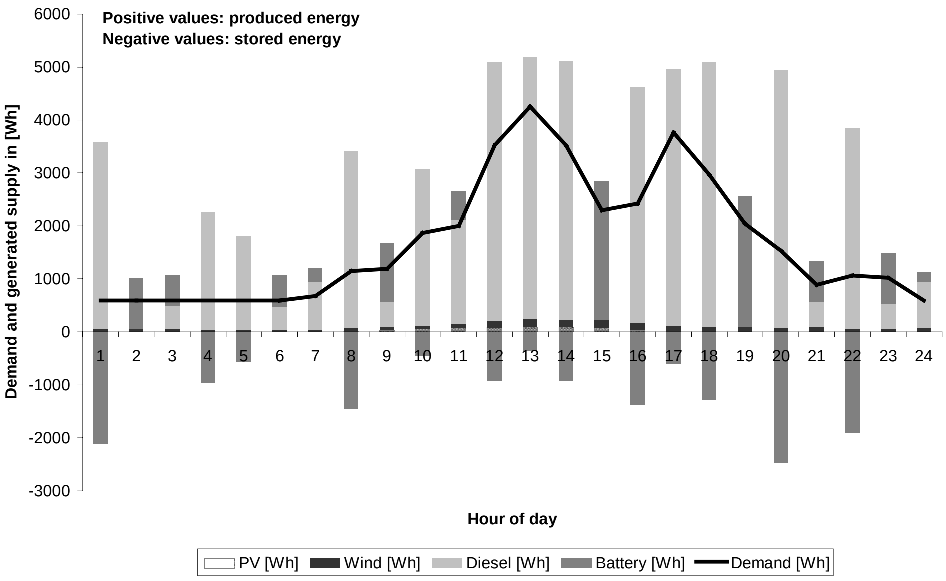


Figure A 37: Average hourly energy produced/demanded for demand D3, normal inverter, Mabibi

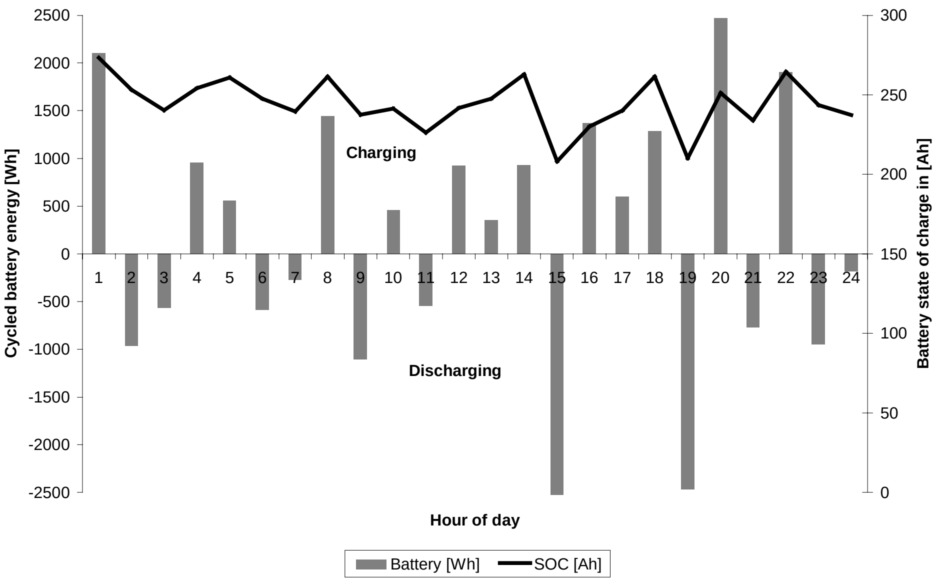


Figure A 38: Average hourly battery energy and SOC for demand D3, normal inverter, Mabibi

D1, Mabibi, Parallel inverter

The diesel generator operates on average mainly around midday and late evening. The diesel generator is less often on in the morning. The wind turbine contributions are quite high. The battery is on average charged during midday and during afternoon and discharged later at night. Some charging and discharging occurs in the morning as well. This is in principle similar to the system designed for the normal inverter configuration, only that the wind turbine contributions are higher than for the normal inverter configuration.

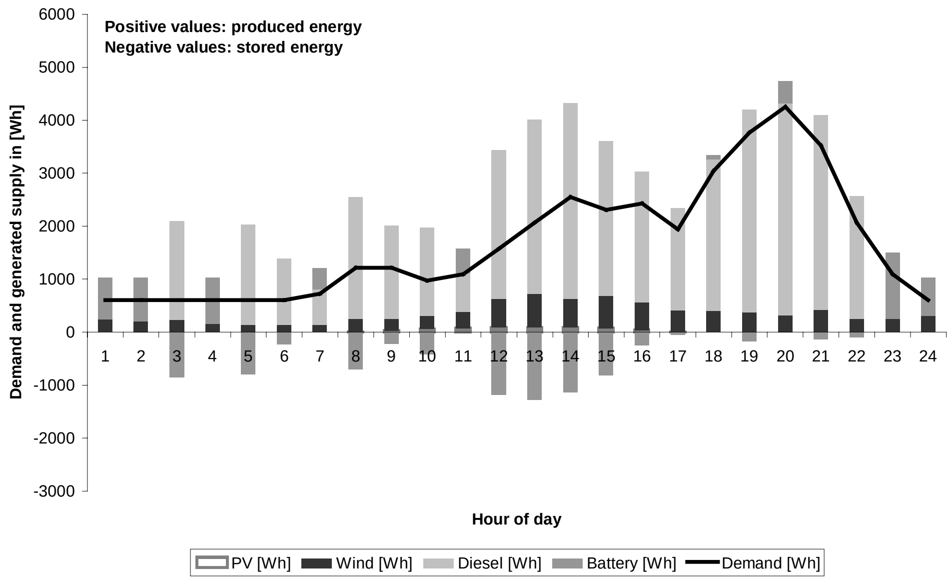


Figure A 39: Average hourly energy produced/demanded for demand D1, parallel inverter, Mabibi

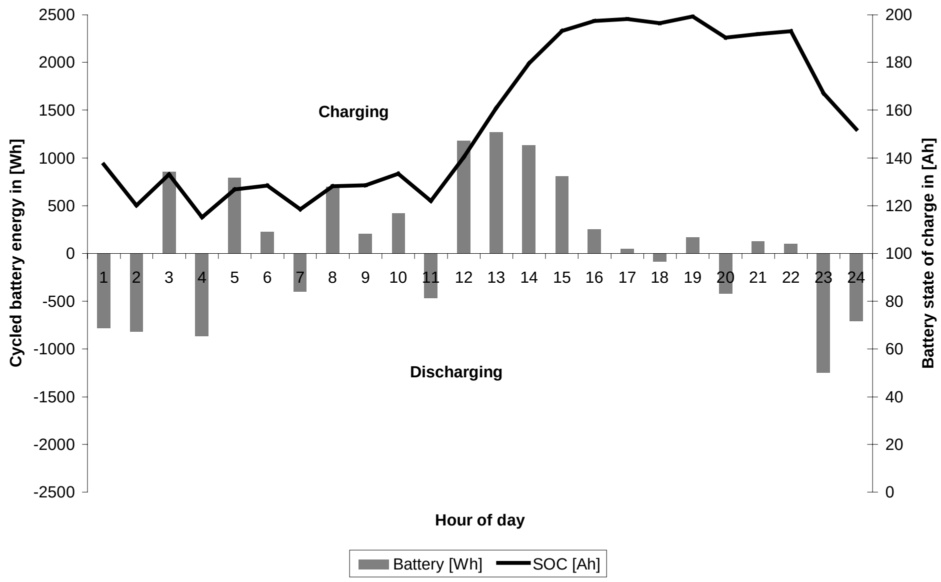


Figure A 40: Average hourly battery energy and SOC for demand D1, parallel inverter, Mabibi

D2, Mabibi, Parallel inverter

The diesel generator capacity is on average running mainly during midday and during the evening. The wind turbine contributions are smaller as compared to the normal inverter configuration for the same demand profile. The battery is on average mainly discharged during the afternoon and evening, where also most of the charging occurs, next to some other early morning charging.

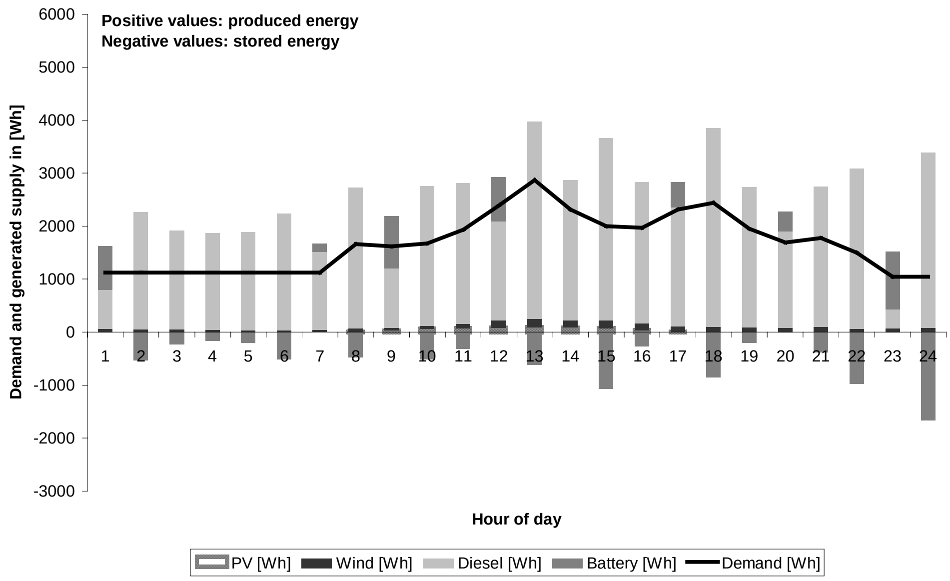


Figure A 41: Average hourly energy produced/demanded for demand D2, parallel inverter, Mabibi

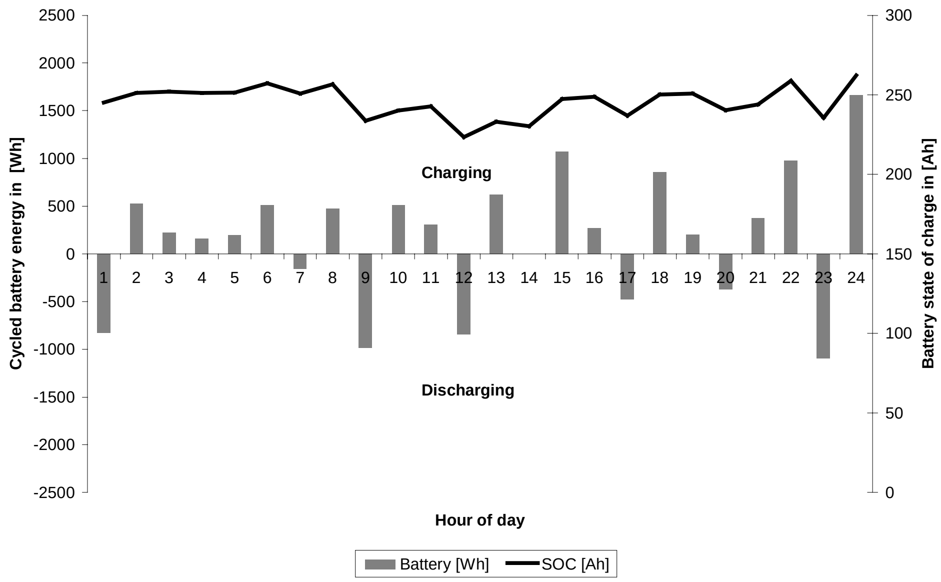


Figure A 42: Average hourly battery energy and SOC for demand D2, parallel inverter, Mabibi

D3, Mabibi, Parallel inverter

The diesel generator is on average mainly running during midday and evening, less often during the morning. The energy contributions from the wind turbines are on average small. In the normal inverter configuration, the wind energy contributions are higher. The battery is charged mainly in the morning and in the evening and discharged most often during the late afternoon. With the normal inverter, the battery is cycled more evenly for the same demand profile.

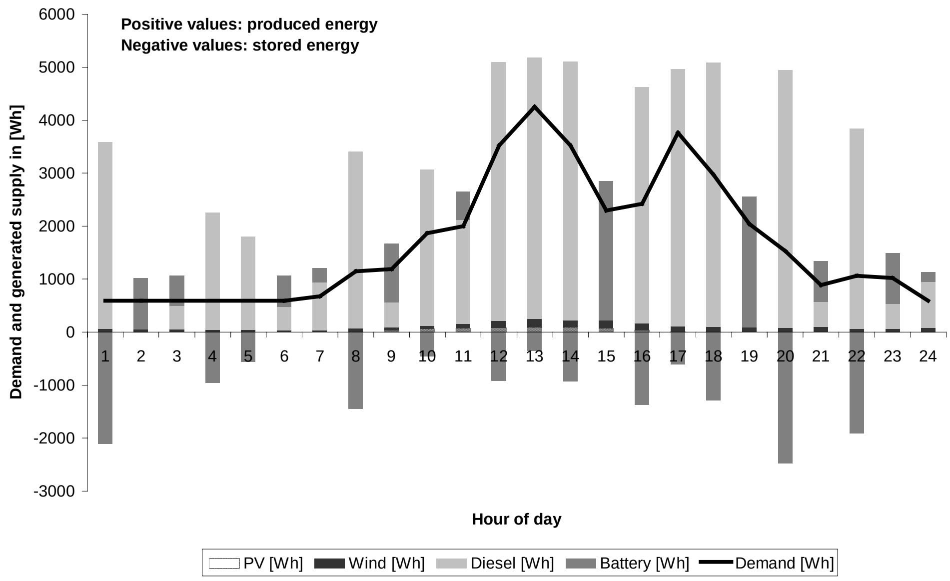


Figure A 43: Average hourly energy produced/demanded for demand D3, parallel inverter, Mabibi

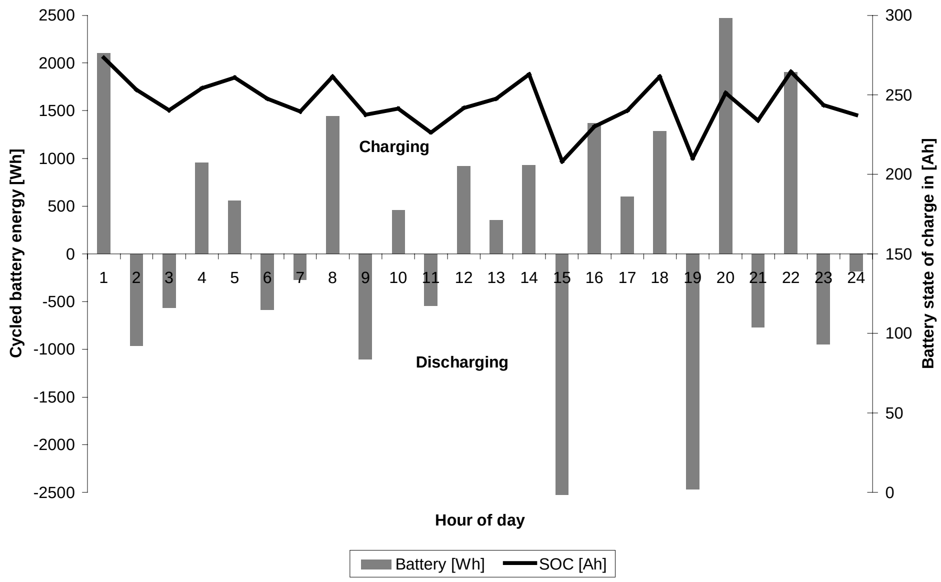


Figure A 44: Average hourly battery energy and SOC for demand D3, parallel inverter, Mabibi

APPENDIX E

SENSITIVITY ANALYSIS

Diesel generator capital costs

The life cycle costs per kWh decrease 1.6% and 3.3% when the diesel generator capital costs decrease 20% and 40% respectively (Figure A 45). This is a nearly parabolic pattern. Surprisingly, the diesel generator size stays the same for different levels of diesel generator capital cost.

As can be seen in Table 1, the control setting number two is not strongly affected by the change in capital costs for the generators: it stays around 80% battery state of charge below which the diesel generator can supply the load together with the DC sources through the inverter, in case neither the inverter output nor the diesel generator can cover the load.

The change in control setting number one indicates that with decreasing diesel generator capital costs, the inverter should increasingly cover the load if it can, instead of the diesel generator. This corresponds to the increase in PV array size, which be due to the fact that the design solution with this larger PV array size is in the proximity of recommendable solutions and is helped being selected through the dropped price for a diesel generator.

The lower the diesel generator costs are, the lower become the diesel replacement costs and the diesel generator operation costs decrease. With decreasing diesel generator capital costs the diesel generator is run more leading to increased fuel costs. On the other hand, with decreasing diesel generator capital cost scenario, an increase in the size of the PV array is likely to contribute to the decreased fuel use costs. This might explain the parabolic shape of the decrease in life cycle cost per kWh as the diesel generator capital costs decrease.

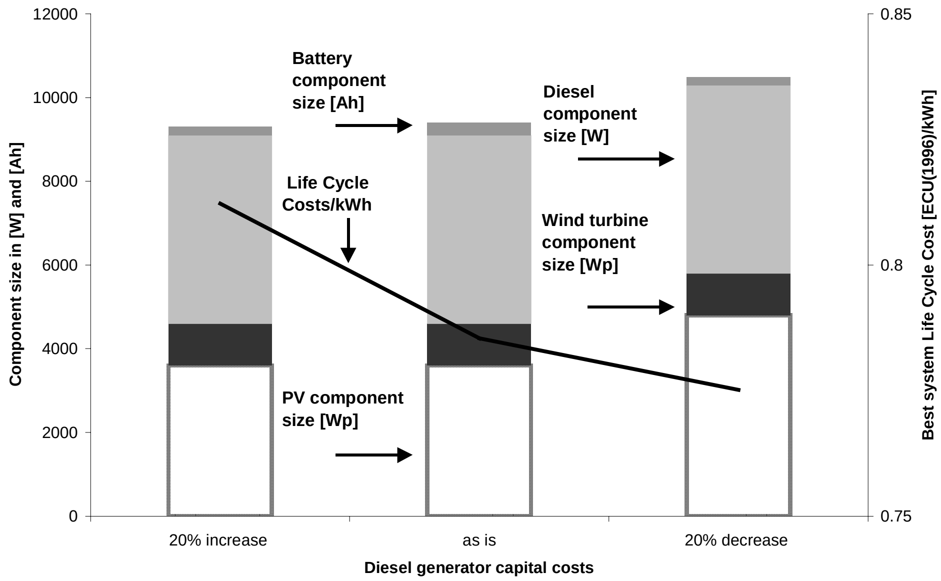


Figure A 45: Sensitivity of diesel generator capital costs

PV capital costs

A decrease in PV capital costs by 20% and 40% lowers the life cycle costs per kWh nearly parabolically by 1.5% and 6.7% respectively (Figure A 46) and similarly leads to the use of bigger PV array sizes.

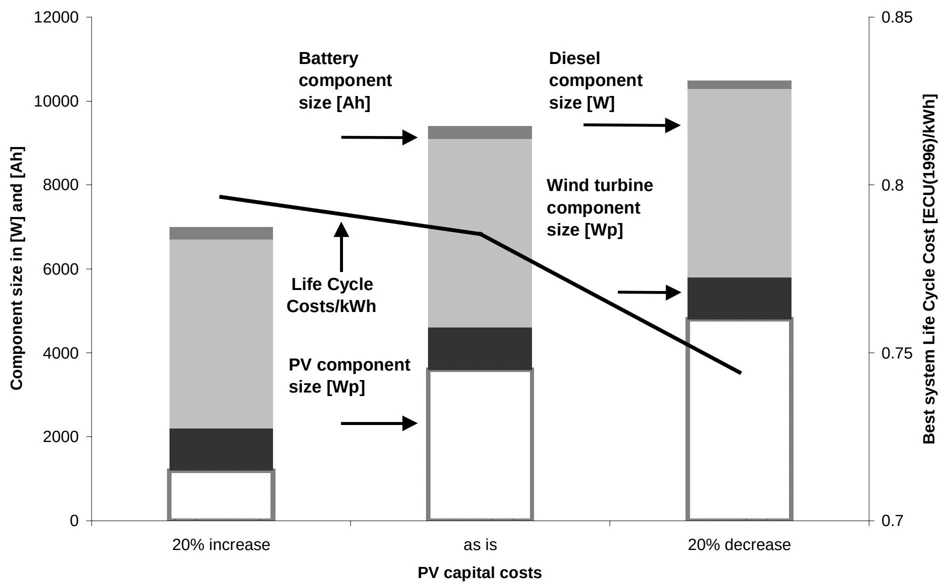


Figure A 46: Sensitivity of PV capital costs

Wind turbine capital costs

The decrease in wind turbine capital costs lowers the life cycle costs, however, it does not affect the size of wind turbine array which remains small.

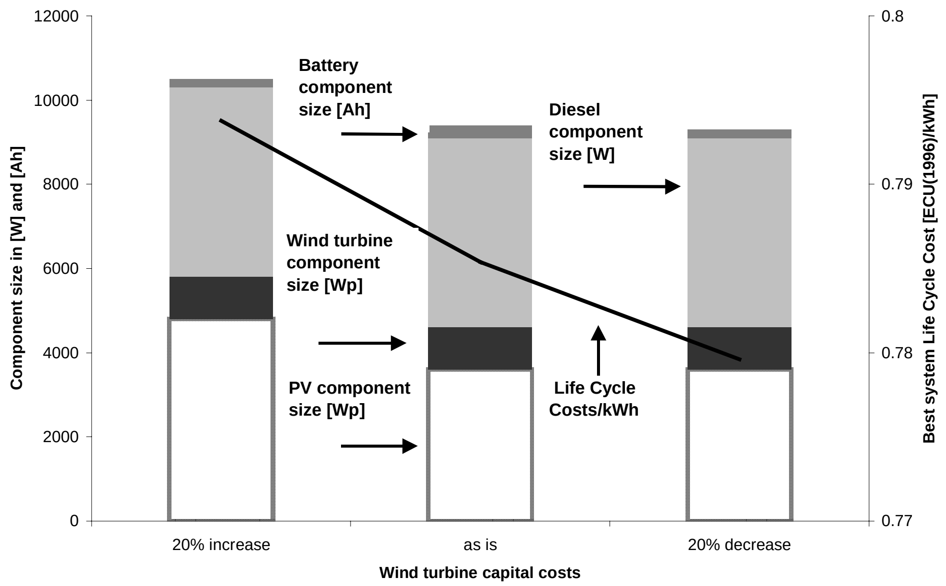


Figure A 47: Sensitivity of wind turbine capital costs

Battery capital costs

Lower battery capital costs increase the use of batteries with larger capacity and lower their operation costs. System life cycle costs per kWh are therefore decreased while storage potential of renewable energy increases which favours enlarged renewable energy array sizes.

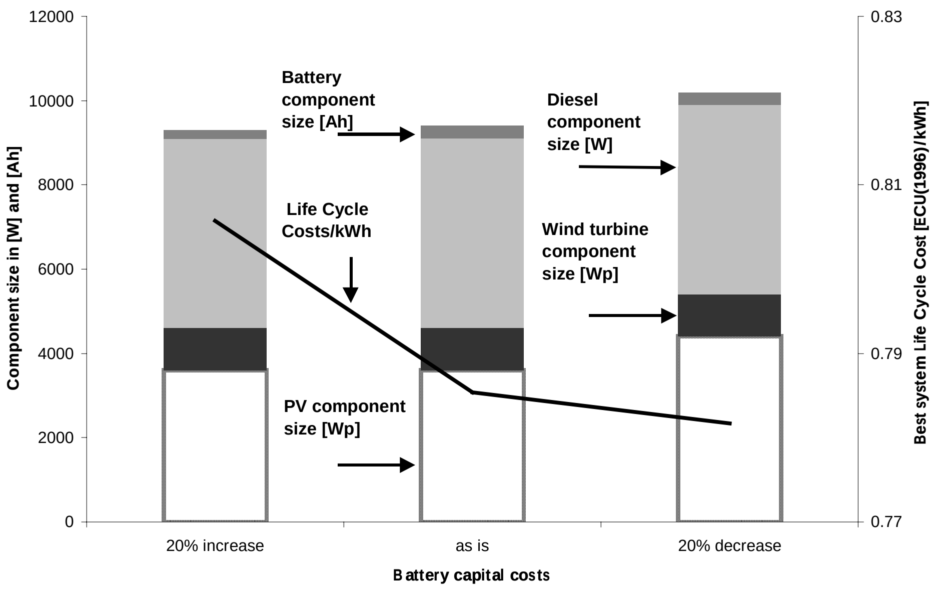


Figure A 48: Sensitivity of battery capital costs

O&M costs for renewable energy sources

As depicted in Figure A 49, the drop in the operation and maintenance costs for the renewable energy sources decreases life cycle costs.

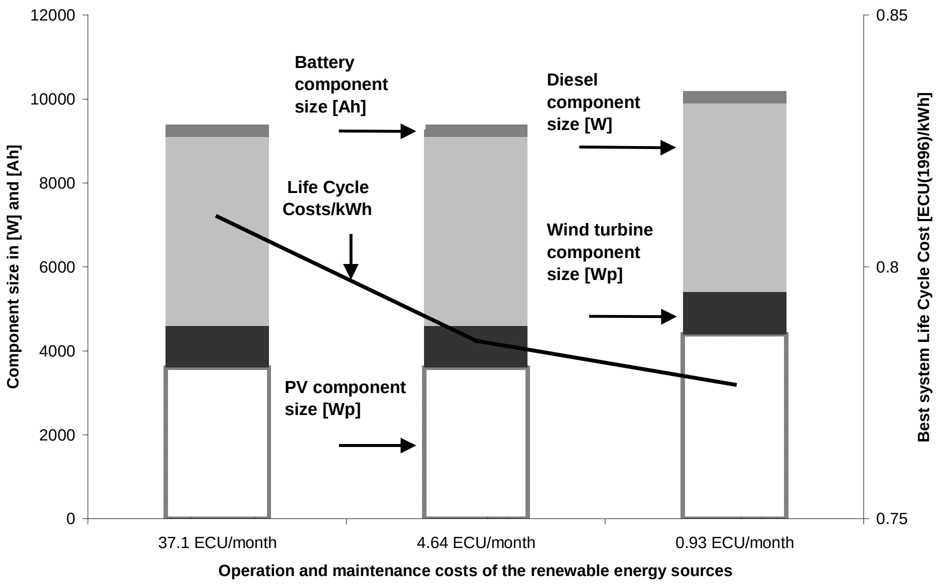


Figure A 49: Sensitivity of operation and maintenance costs for renewable energy sources

O&M costs for the diesel generator

The cheaper the diesel generator operation, the more the system tends towards a diesel generator only system with battery back up.

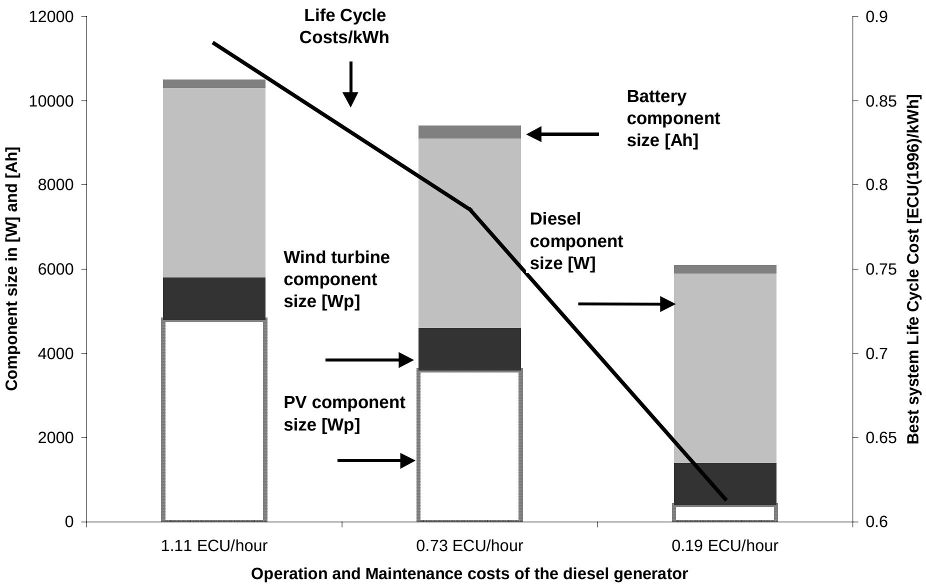


Figure A 50: Sensitivity of operation and maintenance costs for diesel generator

Diesel generator lifetime

Reducing the diesel generator lifetime increases life cycle costs and supports the increase of the size of the renewable energy sources.

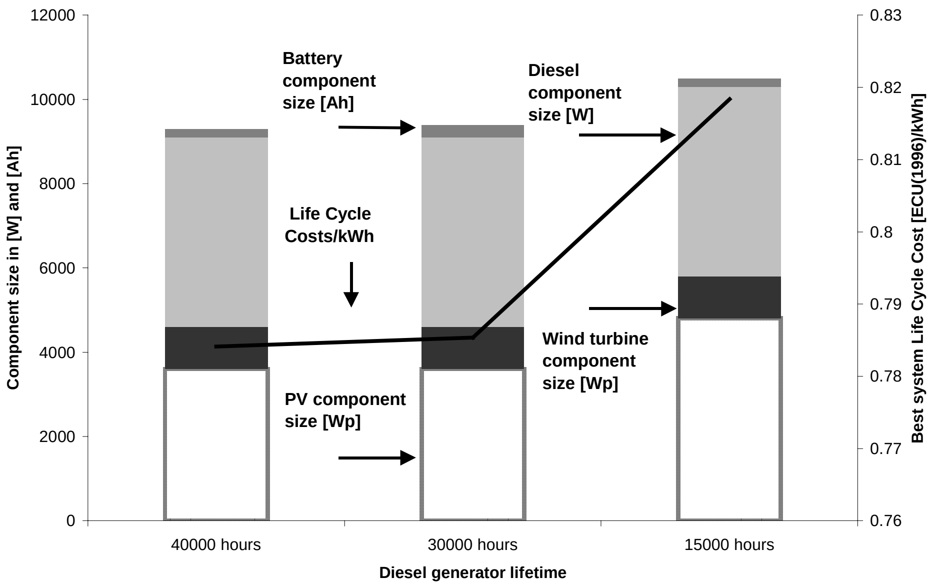


Figure A 51: Sensitivity of diesel generator lifetime

Battery lifetime

A shorter battery lifetime, in terms of a decrease in the number of times the battery can be cycled before replacement, increases life cycle costs of a hybrid system as can be seen in Figure A 52. The shorter battery lifetime also leads a smaller battery size. It is interesting to note that due to the shorter battery life and its decreased size in the “half as many cycles” scenarios, the size of the PV array increases.

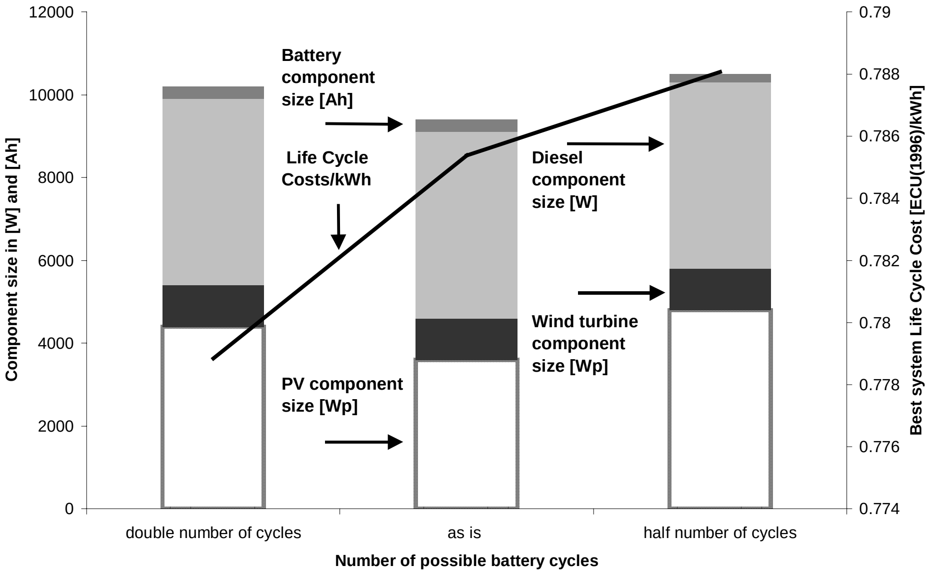


Figure A 52: Sensitivity of battery lifetime

Discount rate

The higher the discount rate the smaller the net present value of future costs becomes. Therefore the diesel generator is the preferred component in case of higher discount rates, as the majority of costs associated with diesel generator operation occur in the future. The decrease in the amount of future costs also lowers the life cycle costs. Smaller discount rates increase the value of future expenses, thereby supporting the increased use of renewable energy sources that are initial cost intensive but do not incur high future costs.

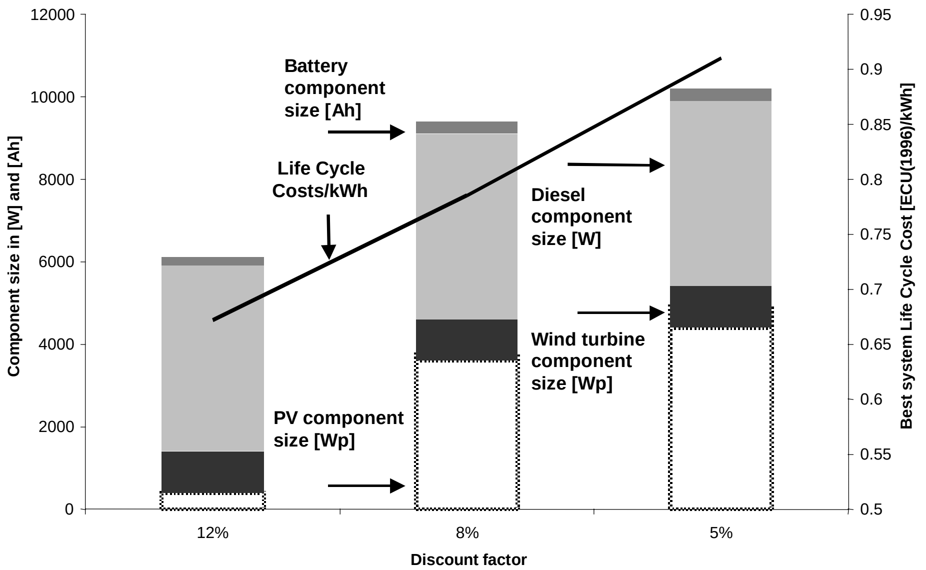


Figure A 53: Sensitivity of discount factor

Length of project life

Counting the life cycle costs over less than 20 years increases the overall cost count and leads to a preference in diesel generator use. This is due to the fact that renewable energy sources have high initial costs but low operation costs, therefore they show more cost effectiveness the longer the project life over which costs are calculated. Diesel generator costing on the other hand benefits from a short project life, as initial costs are small and the majority of diesel generator costs are operation and replacement costs occurring in the future. Therefore a diesel generator will be deceivingly preferred if the life cycle costing is carried out using a short project life, even though a higher percentage of renewable energy sources would be more cost effective when life cycle costs are calculated over a longer project life (Figure A 54).

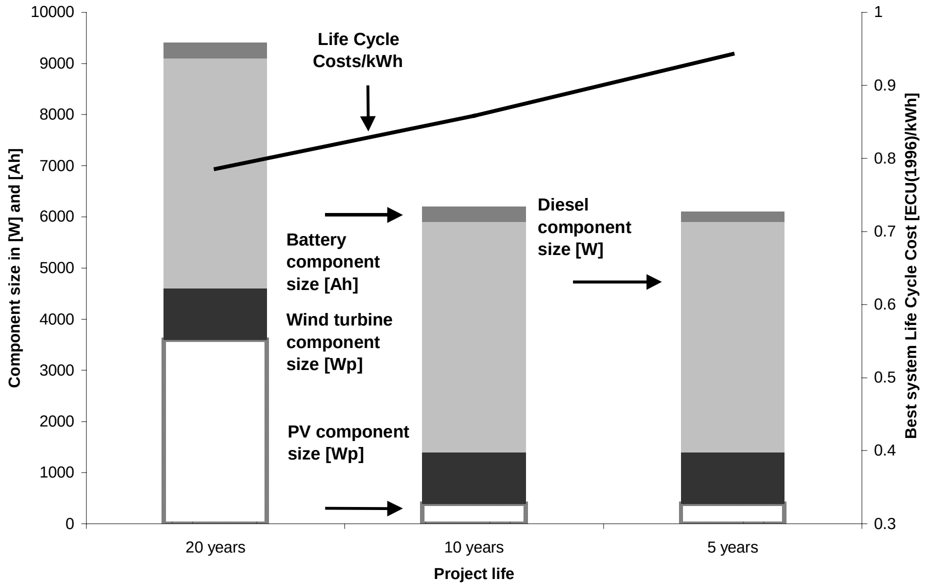


Figure A 54: Sensitivity of project life

Fuel costs

The lower the cost of fuel for a diesel generator, the lower are the life cycle costs and the more the system tends towards a diesel generator and battery system only. The higher the cost for fuel the larger is the recommended size of renewable energy sources.

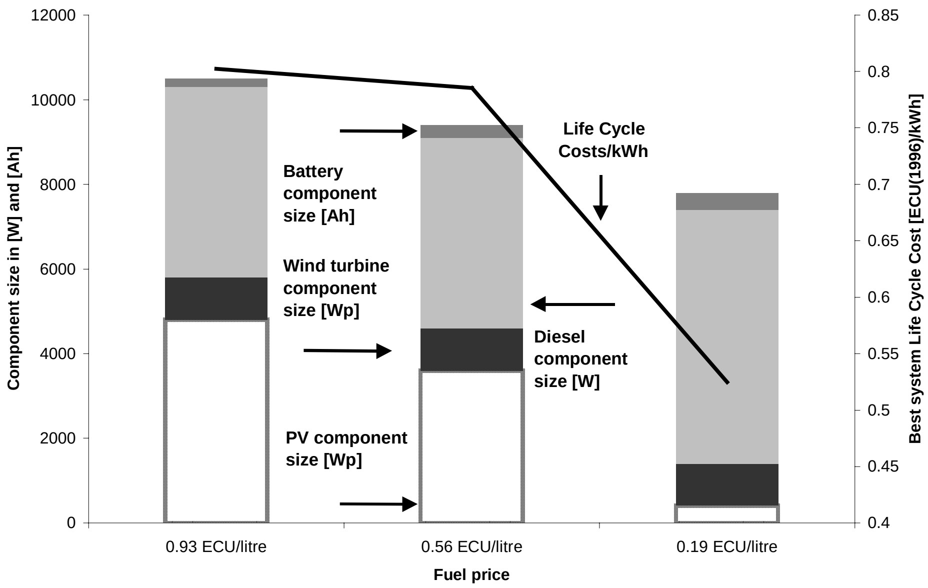


Figure A 55: Sensitivity of fuel price

Reliability required

In case the reliability required from the system can be reduced, the life cycle costs can be decreased due to being able to size component smaller. The cost reduction is more significant amongst the first few percent of reducing reliability from 100%.

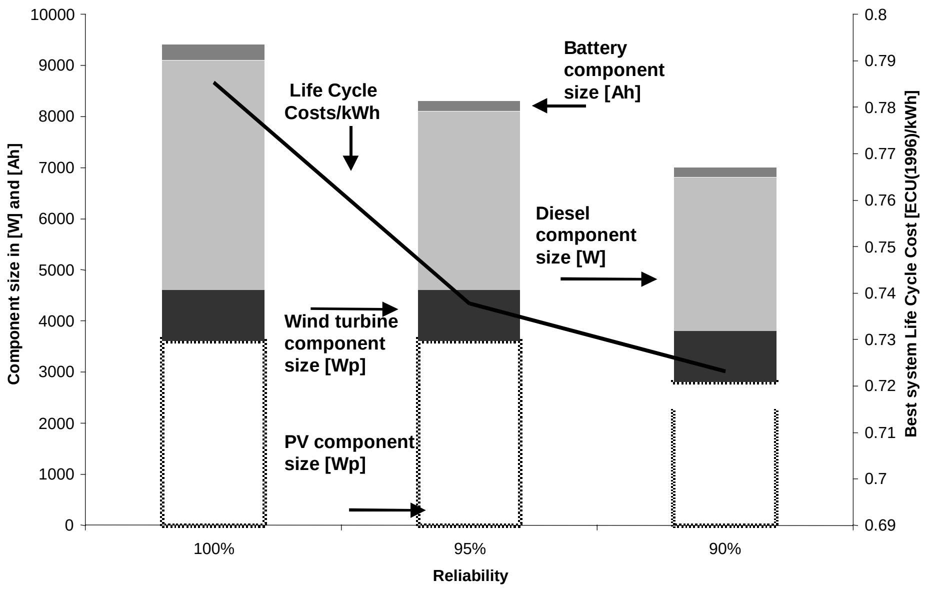


Figure A 56: Sensitivity of reliability requirement

DC bus voltage

If it is possible to find suitable devices and appliances then the DC bus voltage should be chosen as high as possible as life cycle costs are decreased. The smaller the DC bus voltage, the more battery capacity is required to yield the required energy storage size. To limit the increase in storage requirements, the size of the renewable energy arrays can increase to limit storage needs.

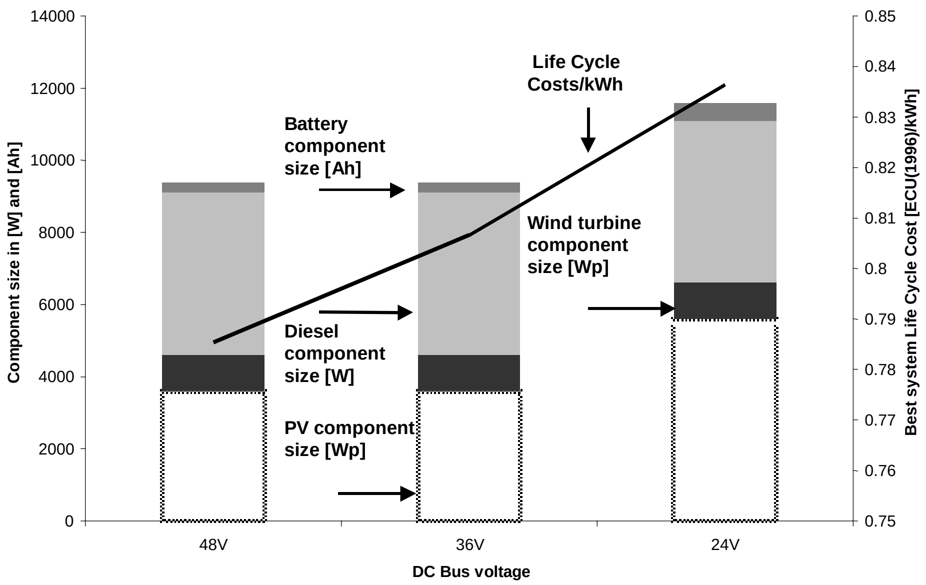


Figure A 57: Sensitivity of DC bus voltage

Level of demand

Load levels can be different to originally anticipated levels or can change after some time of system operation. It is obvious that the lower the demand to be placed on the system, the higher will be the life cycle costs per kWh, as less use can be made of economies of scale.

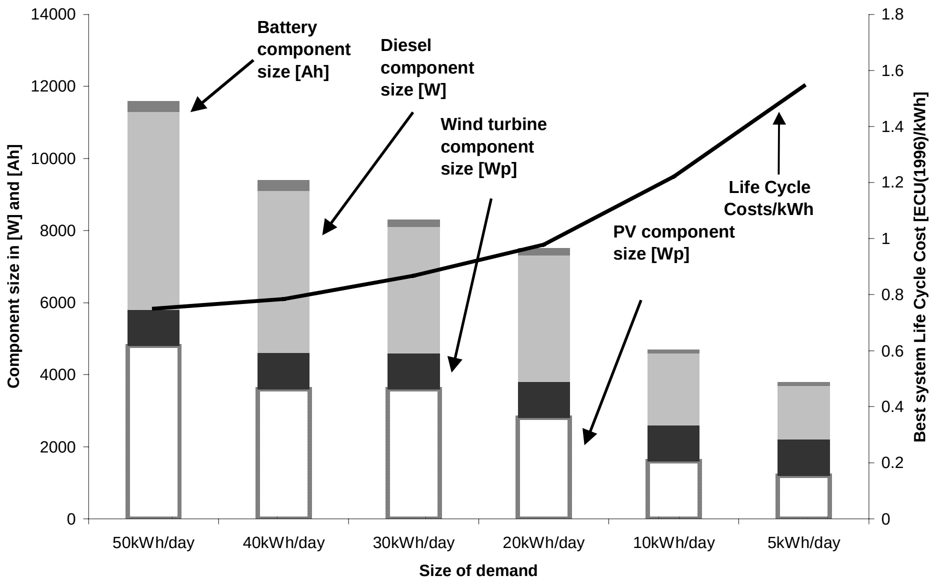


Figure A 58: Sensitivity of level of demand

System configuration

The different types of possible single-source systems and hybrid system combinations were simulated with the developed prototype, and their costing and sizing is compared in Figure A 59 with the one recommended by the prototype for a PV/wind/diesel/battery system. It can be seen that no renewable-only system, PV/battery, wind/PV/battery or wind/battery, can meet the demand requirements cost-effectively. The wind/battery system does not meet the demand requirements reliably even at very high costs - the costs are so high that they lie far above the scale shown in Figure A 59. For the high demand level of 40kWh/day, a diesel generator only system is more reasonable in cost than a renewable only system. However the life cycle costing of a diesel generator only system can be improved by adding a battery, and can be a bit more improved by also adding PV. Even though Upington is not a windy area at all and the wind turbine size of 1000W was due to the prototype program adding the lowest possible wind turbine size to the system configuration, it can be seen that the PV/wind/battery/diesel systems has the lowest overall life cycle costs.

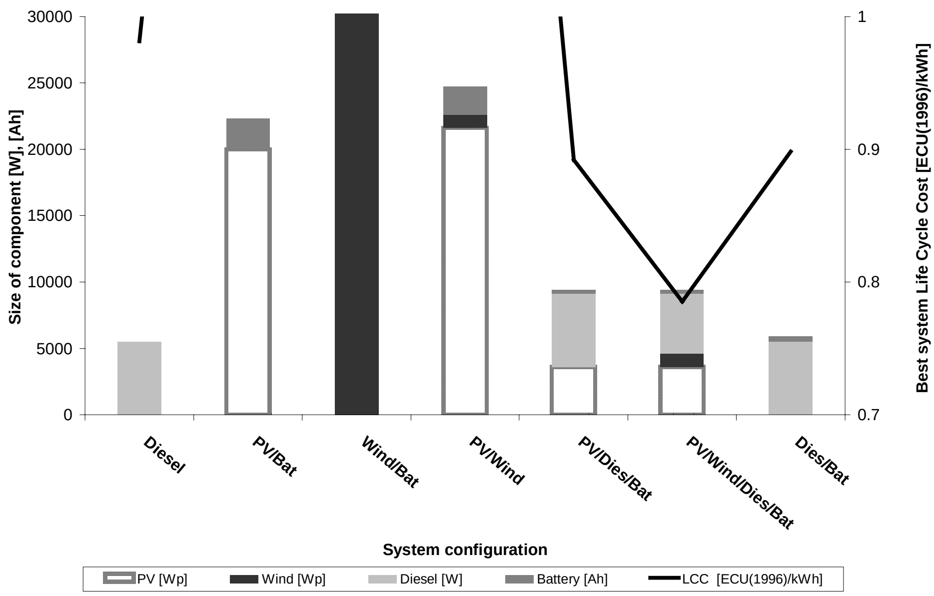


Figure A 59: Sensitivity of different system configurations for Upington

In case of the Mabibi design, a comparison with the different possible system types (Figure A 60) show that a PV only system would not be cost-effective at all. A diesel generator individual system is more cost effective but still expensive. The life cycle costs of the diesel generator are improved by adding a battery. It can be seen that the diesel generator/battery system is more cost effective than the PV/wind/diesel/battery, the PV/diesel/battery or the wind/PV/battery systems. The last three systems are arranged in order of descending costs. The lowest cost system configuration is a wind/battery system, which is even cheaper than the diesel/battery system. The algorithm would have found this particular wind/battery system to be the most cost-effective system if the implemented prototype would not have the feature of not setting any system component to zero by itself. It should be no problem to adjust this feature, so that the algorithm is considering zero component sizes as well.

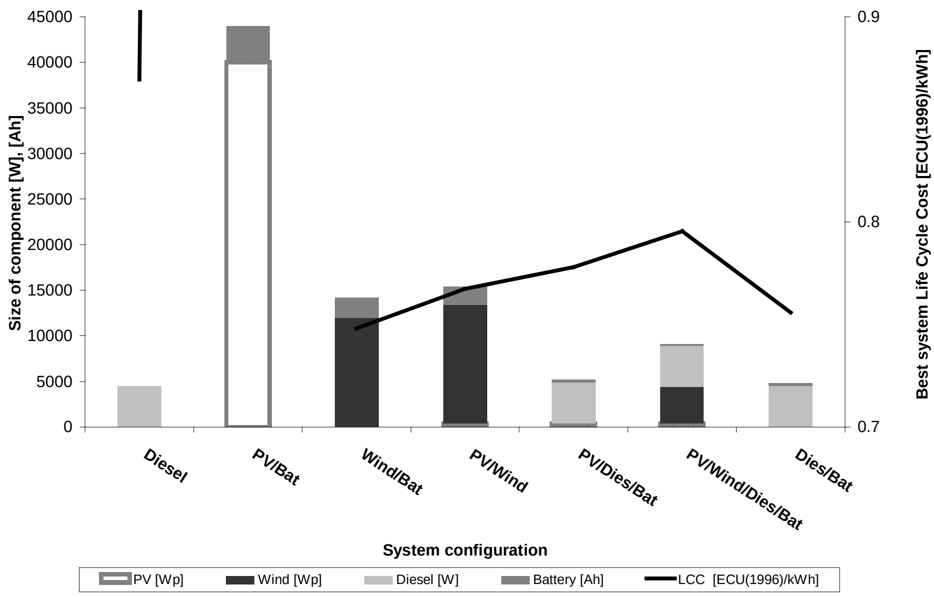


Figure A 60: Sensitivity analysis for various system configurations at Mabibi

Summary sensitivity analysis

It seems the diesel generator is chosen at peak power demand level except for very cheap fuel, lowered reliability standards and certain levels of demand. The wind turbine size is in all cases chosen at the lowest possible turbine size allowed by the prototype algorithm. This indicates that it is worth exploring smaller sizes than 1000W_p and no wind turbines. The battery size shifts between 200Ah and 300Ah, again with the exception of very low fuel prices and differing levels in demand and in addition in case of lower DC bus voltages. The size of the PV array varies considerably between its lowest possible size in the prototype algorithm of 400W_p and 5.6kW_p for the hybrid configurations and up to around 20kW_p for the individual component configurations. In case of the Mabibi site with lower radiation but much better wind speeds, the cases for the PV and wind turbine components are reversed: the PV size is stable at its lowest possible size, and the wind turbine sizing changes with differently valued input parameters.

Parameters whose changes can impact most on the life cycle costs are diesel generator O&M costs, discount rate, length of project life, fuel prices, reliability requirements, DC bus voltages and demand level.

System efficiencies generally were around 60%. The chosen control settings in each case guaranteed average capacity factors between 90% to 100%. For higher diesel generator and battery capital costs, lowered diesel generator O&M costs, increased diesel generator lifetime, a higher discount rate, and a short project life period, the load factors were lower at around 70-80%. In the diesel generator only system the average capacity factor drops to 40%. The average battery state of charge ranges between 71% and 93%.

If both inverter and diesel generator can cover the load, the control setting allowing the inverter output to cover the load instead of the AC bus output if the battery state of charge is greater than "$\%_1$", is 70% SOC to 86% SOC in most cases. In addition to that, the inverter output is nearly always preferred to supply the load in cases where i) PV is cheaper and can therefore be used more, and ii) where the diesel generator is cheaper and might not have to be operated in its best interest all the time. The inverter output is also preferred if the diesel generator O&M costs are high and system operation costs are increasing, therefore more use is made of renewable energy sources and the battery storage. Decreasing system lifetimes means operating the diesel generator less and using the inverter energy more. Decreasing battery lifetime might call for an increased use of renewable energy sources and less storage of energy produced by the diesel generator. An increase in fuel prices also calls for a more intense use of the DC bus renewable energy sources. If the DC bus voltage decreases, the conversion of energy between buses becomes less efficient. Probably therefore the inverter output is used whenever possible, in order to use the DC energy as much as possible and to avoid running the diesel generator and thereby charging the battery with high energy losses. In case of lower demand levels, the renewable energy sources and battery storage might operate more cost effectively thereby stimulating their increased use.

The control setting allowing the diesel generator to supply the load through the inverter if the battery state of charge is lower than "$\%_2$" is generally 70%SOC- 98%SOC. It is 54%SOC – 69%SOC for an increase in PV capital costs, an increase in diesel generator and battery lifetime, and lowered reliability requirements. That means the wasteful use of diesel generator energy after it passed through the battery charger and the inverter with their corresponding efficiency losses is increasingly allowed if PV panels get expensive and more energy is required from the diesel generator. If the component lifetimes of the diesel generator and battery are prolonged, thus reducing operation costs, it seems extra costs due to efficiency losses are allowed. In case the reliability requirements are lowered, the diesel generator has to supply the load less often through the inverter, as the load can stay unmet in such instances. Therefore the diesel generator is allowed to supply the load through the inverter as this will only rarely happen.

Table 1: Overview over results from the sensitivity analysis

Results	LCC	PV	Wind	Diesel	Bat.	$\%_1$	$\%_2$	η_{sys}	CF_{av}	SOC_{av}
Unit	ECU_{1996}/kWh	kW_p	kW_p	kW	Ah	%	%	%	%	%
'as is' CASE	0.785	3.6	1	4.5	300	82%	82%	60%	100%	89%
20%↑ Dies CC	0.81	3.6	1	4.5	200	85%	79%	62%	78%	90%
20%↓ Dies CC	0.77	4.8	1	4.5	200	52%	82%	60%	92%	74%
20%↑PV CC	0.80	1.2	1	4.5	300	82%	56%	57%	100%	84%
20%↓ PV CC	0.74	4.8	1	4.5	200	55%	93%	60%	92%	74%
20%↑ Wind CC	0.79	4.8	1	4.5	200	54%	98%	60%	92%	74%
20%↓ Wind CC	0.785	3.6	1	4.5	200	85%	57%	62%	78%	90%
20%↑ Bat CC	0.806	3.6	1	4.5	200	85%	93%	62%	78%	90%
20%↓ Bat CC	0.782	4.4	1	4.5	300	77%	91%	59%	100%	83%
570%↑ $O\&M_{RE}$	0.81	3.6	1	4.5	300	82%	79%	60%	100%	89%
86%↓ $O\&M_{RE}$	0.79	4.4	1	4.5	300	78%	85%	59%	100%	84%
51%↑ $O\&M_{Dies}$	0.88	4.8	1	4.5	200	55%	86%	60%	92%	74%
75%↓ $O\&M_{Dies}$	0.61	0.4	1	4.5	200	86%	88%	64%	72%	93%
33%↑ Dies Life	0.79	3.6	1	4.5	200	85%	59%	62%	78%	90%
50%↓ Dies Life	0.82	4.8	1	4.5	200	55%	84%	60%	92%	74%
100%↑ Bat life	0.778	4.4	1	4.5	300	77%	54%	59%	100%	83%
50%↓ Bat life	0.788	4.8	1	4.5	200	52%	72%	60%	92%	74%
50%[1]↑ dis fact	0.67	0.4	1	4.5	200	86%	98%	64%	72%	93%
38%[2]↓ dis fact	0.91	4.4	1	4.5	300	77%	75%	59%	100%	83%
50%↓ proj life	0.86	0.4	1	4.5	300	76%	87%	56%	100%	79%
75%↓ proj life	0.94	0.4	1	4.5	200	86%	73%	64%	72%	93%
66%↑ fuel cost	0.80	4.8	1	4.5	200	54%	94%	60%	92%	74%
66%↓ fuel cost	0.52	0.4	1	6	400	82%	72%	56%	100%	86%
5%↓ reliability	0.74	3.6	1	3.5	200	70%	70%	63%	92%	90%
10%↓reliability	0.72	2.8	1	3	200	86%	69%	65%	95%	91%
33%↓ DC V	0.81	3.6	1	4.5	300	86%	73%	60%	91%	90%
66%↓ DC V	0.84	5.6	1	4.5	500	54%	87%	59%	100%	75%
25%↑ load	0.75	4.8	1	5.5	300	87%	82%	61%	89%	91%
25%↓ load	0.87	3.6	1	3.5	200	54%	85%	60%	100%	71%
50%↓ load	0.98	2.8	1	3.5	200	74%	97%	58%	98%	83%
75%↓ load	1.22	1.6	1	2	100	53%	74%	58%	94%	74%
87.5%↓ load	1.54	1.2	1	1.5	100	51%	85%	56%	100%	74%
Diesel only	0.98	0	0	5.5	0	100%	50%	100%	38%	0%
PV/Bat	1.74	20	0	0	2300	50%	50%	57%	0%	77%
Wind/Bat	256.97	0	100[3]	0	4000	50%	50%	48%	0%	68%
PV/Wind/Bat	1.77	21.6	1	0	2100	50%	50%	58%	0%	78%
PV/Dies/Bat	0.89	3.6	0	5.5	300	86%	82%	60%	93%	89%
Dies/Bat	0.90	0	0	5.5	400	80%	53%	56%	100%	82%

[1] equivalent to an additional 4% in actual discount rate

[2] equivalent to minus 3% in actual discount rate

[3] The wind/battery system still has a high percentage of uncovered load

APPENDIX F

VERIFICATION OF THE SIMULATION RESULTS WITH HYBRID 2[1]

1 NORMAL INVERTER 2

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N.B.: All currencies in this document are in South African Rand

[1] An improved and updated version of HYBRID2 has become available since the time of writing

1 Normal Inverter

1.1 Summary

****
*   RESULTS OF THE SIMULATION: OVERALL PERFORMANCE
****

Summary File created with Hybrid2 Version 1.1
Executable Software Date: August 1997
Simulation run on: Tuesday, January 6, 1998 at 8:28:50 AM

* Project
Upington is in the Northern Cape of South Africa, very high radiation

* General
- date of run 01-06-1998
- Time of run 08:28:51

* Run specifications
- start value of the simulation period (h) 1
- duration of the simulation period (h) 8784
- simulation time step (min) 60

* HYBRID SYSTEM

ENERGY FLOWS	kWh	% load demand		kWh	% load demand
Total production	26674.27	181.9	Total sinks	26649.02	181.7
Load demand	14666.29	100	Load coverage	14637.58	99.8
AC primary load	14666.29	100	AC primary load	14637.58	99.8
AC deferrable load	0	0	AC deferrable load	0	0
DC primary load	0	0	DC primary load	0	0
DC deferrable load	0	0	DC deferrable load	0	0
			Unmet load	28.7	.2
Production			Optional load	0	0
- from wind (AC)	0	0	- AC optional load	0	0
- from wind (DC)	1204.27	8.2	- DC optional load	0	0
- from PV (AC/DC)	4264.01	29.1			
- from diesel (AC/DC)	16910.4	115.3			
Storage			Excess energy	28.45	.2
- into storage	6259.59	42.7	- spilled	0	0
- from storage	4266.88	29.1	- dump load	0	0
			- excess dump load	28.45	.2
Energy losses	5694.69	38.8			
Fuel consumed (liters)	8455.2				

* RESULTS OF THE SIMULATION: PERFORMANCE PER COMPONENT *************************

* AC primary load
(scale factor of 1 included)
- average (kW) 1.67
- standard deviation (kW) 1.1
- minimum (kW) .61
- maximum (kW) 4.25

* Wind speed
(scale factor of 1 included)
- air density correction 1

at height of	anemo-meter	hub turbine 1
- height (m)	10	13
- hub height correction	-	1.038
- average (m/s)	3.93	4.07934
- standard deviation (m/s)	2.35	2.4393
- minimum (m/s)	0	0
- maximum (m/s)	0	15.8814

```
* Solar insolation at horizontal array plane
- average (W/m2)       307.71
- maximum (W/m2)       1336.11

* Solar insolation at real array plane
- average (W/m2)       289.38

* Ambient temperature
- average day temp ( C)        20.2
- minimum ( C) -4.3
- maximum ( C)  41.8

* HYBRID SYSTEM

* AC diesel
diesel # 1 ( 4.5 kW)
       - on time (h)   4936
       - number of starts     855

PROJECT: OVERVIEW ************************************************************

* NOTES
Upington is in the Northern Cape of South Africa, very high radiation

* LOAD

AC primary load: Notes: Yearly data
AC primary load scale factor   1

DC wind turbines
Total power:    1  kW
- number and type of specified wind turbines:
        1 1000W SA WT wind turbine ( 1  kw)
- DC wind power scale factor   1

DC PV Panel
Peak power:     2.3 kW
Peak voltage:   63.6 V
- number and type of specified PV panels:
        4  series by  12  parallel of 75 W Siemens SA PV panels

AC diesel
Total power:    4.5  kW
- number and type of specified diesels:
        1 4.5 kW generic diesel generator ( 4.5  kW)

Battery bank
Battery notes: Trojan L-16, 350 Ah, 6 VDC Deep Cycle Lead-Acid battery, Trojan Battery Company,
12380 Clark St., Santa Fe Springs, CA 90670.  Phone (310) 946-8381
- total capacity (scaled)   24.2 kWh[2]  (accessible capacity  12.1  kWh)
- number and type of batteries        8 350Ah SA battery 6V batteries
- battery bank scale factor    1
- nominal voltage      6  V

Inverter:      5kW Inv SA
- rated power:         5  kW

Rectifier:     Battery charger Upington
- rated power :        4.5  kW

Dispatch strategy : Hard Cycle Charge
The batteries are used to cover any deficit in renewable power to keep a diesel from being
started.  Once the batteries have been discharged, the diesel is started and run to cover the
load and charge the batteries at the maximum rate possible.  Dispatch strategy B.1.9 in Users
Manual.

       Battery control
       - minimum level (fraction)     .5
       - battery discharge code:     all or part of average load
       - boost charge:               if diesels are already on

       Diesel control
       - minimum run time (h):        1
```

[2] Battery capacity for 48V nominal bus voltage is 16.8kWh. 24.2kWh calculated for 69V peak PV panel voltage

```
        - Netload offset for diesel start (kW):       0
        - allowed shutdown:   all
        - period of forced shutoff:    0  hrs
        - dispatch order:     minimum fuel use

        Operating Power level:        at or near maximum power

        Diesel starts:        to charge batteries

        Diesel stops:         when battery is charged

* Economics on separate economics file

* PROJECT: DETAIL**************************************************

* RESOURCE/SITE

Wind speed
- power law exponent    .143
- turbulence length scale (m)  100
- reference wind velocity for
   turbulence calculations (m/s)       10
- nominal turbulence intensity         .15
- air density model:  density ratio
- nominal ambient temperature ( C)     20.16687

Solar insolation
- ground reflectivity   .2

* POWER SYSTEM
DC wind turbines
- spacing between DC wind turbines (m)        10
- DC wind farm power fluctuation reduc. factor        1
- DC wind power response factor       1.5

DC PV array
- number of PV panels in series       4
- number of PV panels in parallel     12
- tracking code:      1 (fixed slope)
- PV array slope (deg):       30
- PV array azimuth (deg):     0
- PV rack or tracker capital cost (SA Rand):  0
- PV array installation cost (SA Rand):       0
- Max. power point tracker:   present
- PV MPPT Loss Factor         .98
- MPPT capital cost (SA Rand):        0

Battery bank
- number of batteries in series:          8
- number of battery banks in parallel:    1
- initial capacity of battery bank (kWh):  24.2
- battery bank installation cost (SA Rand):      1440

General system cost
- balance of system capital cost (SA Rand):   0
- system O&M Cost (fraction/y):       0
- administrative Cost (fraction/y):   0
- wind turbine O&M Cost (fraction/y):        .08333
- diesel O&M Cost (fraction/y):       0

* OVERVIEW OF FILES************************************************************

File name                              Date

OUTPUT
C:\HYBRID2\UP_SA_05.SUM                1/6/98
```

1.2 Economic Analysis

```
HYBRID2 ECONOMIC ANALYSIS
***********************************
01-06-1998    10:10:44
ECONOMIC DATA FILE = C:\HYBRID2\UP_SA_05.ECS
***********************************

ECONOMIC FIGURES OF MERIT
```

```
Calculations Are For A New System:

Basic Project Feasibility Indicators For Hybrid System:
 Simple Payback Period Years   -4.61
 Discounted Payback Period    Years   0

System Economic Indicators:          Hybrid  Diesel Only
 Net Present Value of System Costs    SA Rand  564795        0
 Net Present Value     SA Rand -521978.22      0
 Annualized Worth      SA Rand -53164.63      N/A
 Internal Rate of Return of Project   %      Not Calculated N/A
 Levelized Cost of Energy, Primary    SA Rand/kWh     3.94   0
 Levelized Cost of Energy, Total      SA Rand/kWh     3.94[3]   0
 Net Present Value of Optional Load   SA Rand  0      N/A

Levelized Annual Economic Figures:           Hybrid  Diesel Only
 Debt Costs,   SA Rand  0      0
 Fuel Costs,   SA Rand  16864   0
 O & M Costs,  SA Rand  26378   0
 System Replacement & Overhaul Costs, SA Rand  14284   0
 Gross Revenue,        SA Rand  0      0
 Net Revenue/Gross Income,    SA Rand -53165   0
 Net After Tax Income, SA Rand -53165   0

HYBRID2 PERFORMANCE PREDICTIONS
Power System:         Hybrid  Diesel Only
 Total energy produced,       kWh      14629.2       0
 Primary energy delivered,    kWh      14629.2      0.0
 Deferrable energy delivered, kWh      0      Inc. in Primary
 Optional energy delivered,   kWh      0      Not Included
 Annual fuel consumed, Fuel Units      8432.099       0

SYSTEM LEVELIZED COSTS
Power System:         Hybrid  Diesel Only
 Total installed system capacity,    kW      37      0
 Total system installed cost, SA Rand  244999        0
    Equipment capital cost,   SA Rand  150700        0
    System installation cost, SA Rand  22090  0
    Balance of installation cost,    SA Rand  70000   0
    System installation overhead,    SA Rand  2209    0
 System cost down payment,    SA Rand  0      0

 System cost yearly payment,  SA Rand  0      0
 First year administration cost,     SA Rand  0      0
 First year system O&M cost,  SA Rand  26378  0
 First year system income,    SA Rand  0      0
 Equipment salvage value,     SA Rand  0      0

INPUTS
ECONOMIC ANALYSIS PARAMETERS
 Fuel Cost,    SA Rand/unit    2
 Installation overhead,       %       10
 Total cost of optional load, SA Rand  0
 Useful system life,  Years   20
 Salvage value of project equipment,  %       0
 General inflation rate,      %       0
 Discount rate,       %       8
 Fuel inflation rate,  %       0
 Loan Interest rate,   %       0
 Loan period,  Years   0
 Grace period for loan payback,      Years   0
 Down payment fraction,       %       0
 Price of regular power,      SA Rand/kWh     0
 Price of deferrable power,   SA Rand/kWh     0
 Price of optional power,     SA Rand/kWh     0
 Corporate tax rate,  %       0
 Renewable energy tax incentive,     SA Rand/kWh     0
 Equipment deprecation life,  Years   1

SYSTEM SPECIFICATIONS
Balance of system cost,       SA Rand  70000
Capital cost of optional load equipment (Hybrid only),      SA Rand  0
Capital Cost of the Grid Extension to Consumer,      SA Rand  0
```

[3] that is equivalent to 0.73 ECU_{1996}/kWh

```
Total Importation tariffs (Hybrid only),     SA Rand  0
Total shipping costs (Hybrid only),  SA Rand  0
System administration cost (Hybrid),  SA Rand  0
System general O&M cost (Hybrid),     SA Rand  420
System administration cost (Diesel),  SA Rand  0
System general O&M cost (Diesel),     SA Rand  0

EQUIPMENT SPECIFICATIONS
Wind turbine(s):
 Total capacity on AC bus,    kW       0
 Total capacity on DC bus,    kW       1
 AC turbine scale factor used,                1
 DC turbine scale factor used,                1
 Capital cost, SA Rand  15000
 Total installation cost,     SA Rand  3000
 Wind turbine O&M rate,       SA Rand/kWh     .0833
 Wind turbine overhaul specifications:       Cost; SA Rand  Time; Years
 Wind turbine  1       3000    1

PV:
 Rated power,  kW       2.304864
 Capital cost, SA Rand  86400
Maximum power point tracker cost,     SA Rand  0
 Cost of module rack or tracking system,     SA Rand  0
 PV array installation cost,  SA Rand  8640

Diesel(s):
 Hybrid system total diesel rated capacity,  kW       4.5
 Base case system total diesel rated capacity,       kW       0
 Capital cost of hybrid system diesels,      SA Rand  27600
 Hybrid system diesel installation cost,     SA Rand  8280
 Capital cost of all diesel system,  SA Rand  0
 Diesel system diesel installation cost,     SA Rand  0
 Diesel O&M rate,      SA Rand/hr      4.96
 Diesel overhaul specifications:     Cost, SA Rand  Time, hours
 Hybrid Diesel  1       5520    15000

Battery:
 Rated capacity,       kWh      24.20422
 Storage scale factor used,           1
 Capital cost (including scale factor),      SA Rand  14400
 Installation cost,    SA Rand  1440
 O&M rate, % of initial capital cost per year,               10
 Life of batteries,    Years    1.4

Converter:
 Rated capacity,       kW       4.75
 Capital cost, SA Rand  7300
 Installation cost,    SA Rand  730
 Life of power converter,     Years    20

SYSTEM CASH FLOW
                      Hybrid  Diesel only
        1      0       0
        2     -60642.02       0
        3     -60642.02       0
        4     -51762.02       0
        5     -60642.02       0
        6     -60642.02       0
        7     -66162.02       0
        8     -46242.02       0
        9     -60642.02       0
        10    -66162.02       0
        11    -60642.02       0
        12    -46242.02       0
        13    -66162.02       0
        14    -60642.02       0
        15    -60642.02       0
        16    -51762.02       0
        17    -60642.02       0
        18    -60642.02       0
        19    -66162.02       0
        20    -43242.02       0
```

1.3 Economics

```
1             "Number of wind turbines"
 0             "Total rated power of wind turbines on AC bus; kW"
 1             "Total rated power of wind turbines on DC bus; kW"
 1.67          "Average primary load per hour; kW/h"
 .14           "Average wind power per hour; kW/h"
 0             "Average deferrable load per hour; kW/h"
 0             "Average optional Load per hour; kW/h"
 .485429       "Average PV Power per hour; kW/h"
1              "PV system includes a maximum power point tracker"
 1.925137
"Average Diesel Power in Hybrid; kW/h"
 1.67
"Average Diesel Power in Base case); kW/h"
 0
"Average diesel only case overload power; kW/h"
 3.267633E-03
"Average hybrid system overload power; kW/h"
 0             "Average hourly diesel only fuel use; units/h"
 .9625683      "Average hourly fuel use in hybrid system; units/h"
 8784          "Hours in simulation"
 2.304864      "Rated PV power; kW"
 4.75          "Average convertor rated power; kW"
 24.20422      "Nominal battery capacity (kwh)"
 1.356049      "Battery life; years"
 1             "Battery size scale factor"
 1             "AC wind turbine size scale factor"
 1             "DC wind turbine size scale factor"
 0             "Rated dump power, kW"
 0             "Number of diesels (base case)"
 1             "Number of diesels hybrid case"
 4.5           "Rated diesel power, hybrid system"
 4936          "Diesel hours on, hybrid system"
```

2 Parallel Inverter

2.1 Summary

```
**************************************************
*    RESULTS OF THE SIMULATION: OVERALL PERFORMANCE
**************************************************

Summary File created with Hybrid2 Version 1.1
Executable Software Date: August 1997
Simulation run on:          Tuesday, January 6, 1998     at           10:54:38 AM


* Project
Upington is in the Northern Cape of South Africa, very high radiation

* General
- date of run  01-06-1998
- Time of run  10:54:38

* Run specifications
- start value of the simulation period (h)    1
- duration of the simulation period (h)       8784
- simulation time step (min)   60

* HYBRID SYSTEM

ENERGY FLOWS          kWh       % load                    kWh       % load
                                demand                              demand

Total production       23697.26  161.6 Total sinks         23697.59  161.6

Load demand            14666.29  100   Load coverage       14654.91  99.9
AC primary load        14666.29  100   AC primary load     14654.91  99.9
AC deferrable load     0         0     AC deferrable load  0         0
DC primary load        0         0     DC primary load     0         0
DC deferrable load     0         0     DC deferrable load  0         0
                                       Unmet load          11.38     .1

Production                             Optional load       0         0
- from wind (AC)       0         0     - AC optional load  0         0
- from wind (DC)       1204.27   8.2   - DC optional load  0         0
- from PV (AC/DC)      4264.01   29.1
- from diesel (AC/DC)  14751.58  100.6

Storage                                Excess energy       23.36     .2
- into storage         4975.79   33.9  - spilled           0         0
- from storage         3466.02   23.6  - dump load         0         0
                                       - excess dump load  23.36     .2

Energy losses          4032.15   27.5

Fuel consumed (liters) 7375.79

* RESULTS OF THE SIMULATION: PERFORMANCE PER COMPONENT *************************

* AC primary load
(scale factor of  1  included)
- average (kW)  1.67
- standard deviation (kW)      1.1
- minimum (kW)  .61
- maximum (kW)  4.25

* Wind speed
(scale factor of  1  included)
- air density correction       1
at height of               anemo-  hub
                           meter   turbine 1
- height (m)                10      13
- hub height correction     -       1.038
- average (m/s)             3.93    4.07934
- standard deviation (m/s)  2.35    2.4393
- minimum (m/s)             0       0
- maximum (m/s)             0       15.8814
```

```
* Solar insolation at horizontal array plane
- average (W/m2)       307.71
- maximum (W/m2)       1336.11

* Solar insolation at real array plane
- average (W/m2)       289.38

* Ambient temperature
- average day temp ( C)       20.2
- minimum ( C) -4.3
- maximum ( C)  41.8

* HYBRID SYSTEM

* AC diesel
diesel # 1 ( 4 kW)
       - on time (h)   4322
       - number of starts     697

PROJECT: OVERVIEW ************************************************************

* NOTES
Upington is in the Northern Cape of South Africa, very high radiation

* LOAD

AC primary load: Notes: Yearly data
AC primary load scale factor   1

DC wind turbines
Total power:    1  kW
- number and type of specified wind turbines:
        1 1000W SA WT wind turbine ( 1  kw)
- DC wind power scale factor   1

DC PV Panel
Peak power:     2.3 kW
Peak voltage:   63.6 V
- number and type of specified PV panels:
        4  series by  12  parallel of 75 W Siemens SA PV panels

AC diesel
Total power:    4  kW
- number and type of specified diesels:
        1 4 kW generic diesel generator ( 4  kW)

Battery bank
Battery notes: Trojan L-16, 350 Ah, 6 VDC Deep Cycle Lead-Acid battery, Trojan Battery Company,
12380 Clark St., Santa Fe Springs, CA 90670.  Phone (310) 946-8381
- total capacity (scaled)   24.2 kWh  (accessible capacity  12.1  kWh)
- number and type of batteries        8 200 Ah Bat SA batteries
- battery bank scale factor    1
- nominal voltage      6  V

Bi-directional convertor:     4kW Bi-Direc Inverter SA
- rated power :        4  kW

Dispatch strategy : Hard Cycle Charge
The batteries are used to cover any deficit in renewable power to keep a diesel from being
started.  Once the batteries have been discharged, the diesel is started and run to cover the
load and charge the batteries at the maximum rate possible.  Dispatch strategy B.1.9 in Users
Manual.

       Battery control
       - minimum level (fraction)     .5
       - battery discharge code:     all or part of average load
       - boost charge:               if diesels are already on

       Diesel control
       - minimum run time (h):        1
       - Netload offset for diesel start (kW):       0
       - allowed shutdown:   all
       - period of forced shutoff:    0  hrs
       - dispatch order:     minimum fuel use

       Operating Power level:        at or near maximum power
```

```
       Diesel starts:         to charge batteries

       Diesel stops:          when battery is charged

* Economics on separate economics file

* PROJECT: DETAIL**************************************************

* RESOURCE/SITE

Wind speed
- power law exponent    .143
- turbulence length scale (m)  100
- reference wind velocity for
   turbulence calculations (m/s)      10
- nominal turbulence intensity        .15
- air density model:   density ratio
- nominal ambient temperature ( C)    20.16687

Solar insolation
- ground reflectivity   .2

* POWER SYSTEM
DC wind turbines
- spacing between DC wind turbines (m)       10
- DC wind farm power fluctuation reduc. factor       1
- DC wind power response factor       1.5

DC PV array
- number of PV panels in series       4
- number of PV panels in parallel     12
- tracking code:      1 (fixed slope)
- PV array slope (deg):        30
- PV array azimuth (deg):      0
- PV rack or tracker capital cost (SA Rand):  0
- PV array installation cost (SA Rand):       0
- Max. power point tracker:   present
- PV MPPT Loss Factor         .98
- MPPT capital cost (SA Rand):        0

Battery bank
- number of batteries in series:          8
- number of battery banks in parallel:    1
- initial capacity of battery bank (kWh):  24.2
- battery bank installation cost (SA Rand):      1440

General system cost
- balance of system capital cost (SA Rand):   0
- system O&M Cost (fraction/y):       0
- administrative Cost (fraction/y):   0
- wind turbine O&M Cost (fraction/y):        .08333
- diesel O&M Cost (fraction/y):       0

* OVERVIEW OF FILES************************************************************

File name                              Date

OUTPUT
C:\HYBRID2\SA_Dem01.SUM                1/6/98
```

2.2 Economic Analysis

```
HYBRID2 ECONOMIC ANALYSIS

***********************************
01-06-1998    11:28:02
ECONOMIC DATA FILE = C:\HYBRID2\SA_Dem01.ECS
***********************************

ECONOMIC FIGURES OF MERIT
Calculations Are For A New System:

Basic Project Feasibility Indicators For Hybrid System:
 Simple Payback Period Years   -5.35
```

```
 Discounted Payback Period    Years   0

System Economic Indicators:          Hybrid  Diesel Only
 Net Present Value of System Costs   SA Rand  464321        0
 Net Present Value     SA Rand -426754        0
 Annualized Worth      SA Rand -43465.84      N/A
 Internal Rate of Return of Project  %       Not Calculated N/A
 Levelized Cost of Energy, Primary   SA Rand/kWh     3.2352         0
 Levelized Cost of Energy, Total     SA Rand/kWh     3.2352[4]      0
 Net Present Value of Optional Load  SA Rand  0     N/A

Levelized Annual Economic Figures:          Hybrid  Diesel Only
 Debt Costs,   SA Rand  0      0
 Fuel Costs,   SA Rand  14711  0
 O & M Costs,  SA Rand  22861  0
 System Replacement & Overhaul Costs, SA Rand  9720   0
 Gross Revenue,        SA Rand  0      0
 Net Revenue/Gross Income,    SA Rand -43466  0
 Net After Tax Income, SA Rand -43466  0

HYBRID2 PERFORMANCE PREDICTIONS
Power System:         Hybrid  Diesel Only
 Total energy produced,       kWh     14629.2       0
 Primary energy delivered,    kWh     14629.2      0.0
 Deferrable energy delivered, kWh     0     Inc. in Primary
 Optional energy delivered,   kWh     0     Not Included
 Annual fuel consumed, Fuel Units     7355.637      0

SYSTEM LEVELIZED COSTS
Power System:         Hybrid  Diesel Only
 Total installed system capacity,    kW      36     0
 Total system installed cost, SA Rand  232330       0
    Equipment capital cost,   SA Rand  140000       0
    System installation cost, SA Rand  20300  0
    Balance of installation cost,    SA Rand  70000  0
    System installation overhead,    SA Rand  2030   0
 System cost down payment,    SA Rand  0      0

 System cost yearly payment,  SA Rand  0      0
 First year administration cost,     SA Rand  0      0
 First year system O&M cost,  SA Rand  22861  0
 First year system income,    SA Rand  0      0
 Equipment salvage value,     SA Rand  0      0

INPUTS
ECONOMIC ANALYSIS PARAMETERS
 Fuel Cost,    SA Rand/unit    2
 Installation overhead,      %      10
 Total cost of optional load, SA Rand  0
 Useful system life,  Years   20
 Salvage value of project equipment,  %      0
 General inflation rate,     %      0
 Discount rate,       %      8
 Fuel inflation rate,  %      0
 Loan Interest rate,  %      0
 Loan period,  Years   0
 Grace period for loan payback,      Years   0
 Down payment fraction,      %      0
 Price of regular power,     SA Rand/kWh     0
 Price of deferrable power,   SA Rand/kWh     0
 Price of optional power,    SA Rand/kWh     0
 Corporate tax rate,  %      0
 Renewable energy tax incentive,     SA Rand/kWh     0
 Equipment deprecation life,  Years   1

SYSTEM SPECIFICATIONS
Balance of system cost,       SA Rand  70000
Capital cost of optional load equipment (Hybrid only),     SA Rand  0
Capital Cost of the Grid Extension to Consumer,     SA Rand  0
Total Importation tariffs (Hybrid only),    SA Rand  0
Total shipping costs (Hybrid only),  SA Rand  0
System administration cost (Hybrid), SA Rand  0
System general O&M cost (Hybrid),    SA Rand  420
```

[4] that is equivalent to 0.6 ECU_{1996}/kWh

```
System administration cost (Diesel),  SA Rand  0
System general O&M cost (Diesel),     SA Rand  0

EQUIPMENT SPECIFICATIONS
Wind turbine(s):
 Total capacity on AC bus,    kW      0
 Total capacity on DC bus,    kW      1
 AC turbine scale factor used,               1
 DC turbine scale factor used,               1
 Capital cost, SA Rand  15000
 Total installation cost,     SA Rand  3000
 Wind turbine O&M rate,       SA Rand/kWh     .0833
 Wind turbine overhaul specifications:       Cost; SA Rand  Time; Years
 Wind turbine  1       3000   1

PV:
 Rated power,  kW      2.304864
 Capital cost, SA Rand  86400
Maximum power point tracker cost,    SA Rand  0
 Cost of module rack or tracking system,     SA Rand  0
 PV array installation cost,  SA Rand  8640

Diesel(s):
 Hybrid system total diesel rated capacity,  kW      4
 Base case system total diesel rated capacity,      kW      0
 Capital cost of hybrid system diesels,      SA Rand  24000
 Hybrid system diesel installation cost,     SA Rand  7200
 Capital cost of all diesel system,  SA Rand  0
 Diesel system diesel installation cost,     SA Rand  0
 Diesel O&M rate,      SA Rand/hr      4.96
 Diesel overhaul specifications:      Cost, SA Rand  Time, hours
 Hybrid Diesel  1      4800   15000

Battery:
 Rated capacity,      kWh      24.20422
 Storage scale factor used,          1
 Capital cost (including scale factor),      SA Rand  9600
 Installation cost,    SA Rand  960
 O&M rate, % of initial capital cost per year,              10
 Life of batteries,    Years    1.5

Converter:
 Rated capacity,      kW      4
 Capital cost, SA Rand  5000
 Installation cost,    SA Rand  500
 Life of power converter,     Years    20

SYSTEM CASH FLOW
                      Hybrid  Diesel only
        1      0      0
        2     -50171.98      0
        3     -40571.98      0
        4     -54971.98      0
        5     -50171.98      0
        6     -40571.98      0
        7     -54971.98      0
        8     -50171.98      0
        9     -40571.98      0
        10    -50171.98      0
        11    -54971.98      0
        12    -40571.98      0
        13    -50171.98      0
        14    -54971.98      0
        15    -40571.98      0
        16    -50171.98      0
        17    -40571.98      0
        18    -54971.98      0
        19    -50171.98      0
        20    -37571.98      0
```

2.3 Economics

```
"economics"
 1            "Number of wind turbines"
 0            "Total rated power of wind turbines on AC bus; kW"
 1            "Total rated power of wind turbines on DC bus; kW"
```

```
 1.67          "Average primary load per hour; kW/h"
 .14           "Average wind power per hour; kW/h"
 0             "Average deferrable load per hour; kW/h"
 0             "Average optional Load per hour; kW/h"
 .485429       "Average PV Power per hour; kW/h"
1              "PV system includes a maximum power point tracker"
 1.679369
"Average Diesel Power in Hybrid; kW/h"
 1.67
"Average Diesel Power in Base case); kW/h"
 0
"Average diesel only case overload power; kW/h"
 1.29535E-03
"Average hybrid system overload power; kW/h"
 0             "Average hourly diesel only fuel use; units/h"
 .8396846      "Average hourly fuel use in hybrid system; units/h"
 8784          "Hours in simulation"
 2.304864      "Rated PV power; kW"
 4             "Average convertor rated power; kW"
 24.20422      "Nominal battery capacity (kwh)"
 1.549693      "Battery life; years"
 1             "Battery size scale factor"
 1             "AC wind turbine size scale factor"
 1             "DC wind turbine size scale factor"
 0             "Rated dump power, kW"
 0             "Number of diesels (base case)"
 1             "Number of diesels hybrid case"
 4             "Rated diesel power, hybrid system"
 4322          "Diesel hours on, hybrid system"
```