A Primer on Hybrid Electricity Systems for Managers: The Gobabeb Case

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Abstract
This document provides decision-makers in the Namibian electricity sector with a succinct overview of the Gobabeb hybrid electricity system, and describes the key managerial, financial and operational issues and requirements of this unique off-grid electricity supply system.

1. INTRODUCTION

This document was compiled by the Desert Research Foundation of Namibia as part of sub-project 2.6 of the Danida-funded "Renewable Energy and Energy Efficiency Capacity Building Project".

1.1 Purpose and overview

The purpose of this document is to provide decision-makers and managers with an overview of the Gobabeb diesel-solar hybrid electricity system, and to provide readers with a primer on the costs, managerial and operational issues and requirements relating to such off-grid hybrid electricity systems.

Figure 1: An aerial view of the Gobabeb Centre in the central Namib

The remainder of this chapter describes the background of the Gobabeb electricity supply system and the historical sizing and cost projections.

Chapter 2 focuses on the social aspects of energy efficiency, occupancy rates and considerations of implementation of such systems.

In chapter 3, the current system as implemented at Gobabeb will be described in more detail, and an analysis of the system output will be made, using data collected since the installation of the system in 2004. Chapter 4 presents a cost-benefit analysis, while chapter 5 summarises the lessons learnt in the Gobabeb hybrid electricity system.

1.2 Background

The Gobabeb Centre is a research station in the unique environment of the central Namib. Gobabeb is located on the edge of the Namib sand sea and gravel plains, right along the Kuiseb River, some 70 km east of Walvis Bay. In this remote area, researchers have accumulated knowledge in various scientific fields for decades. Since independence in 1991, Gobabeb has also focused on community development, in addition to its work in the pure sciences. The Centre also offers training courses, and facilitates memorable conferences.

Gobabeb was first electrified in 1972, by means of two diesel generators supplied and maintained by the Ministry of Works. In 1998, Gobabeb took over the responsibility of operating the diesel generators, while the Ministry of Works continues servicing the units. When the hybrid system was installed in 2004, the diesel generators were completely renovated by the Ministry, and have not required major servicing since. (Scholle, 2000; Henschel, 2007).

In the 1990's, a number of studies were conducted to explore the potential energy supply options for Gobabeb. Scholle (2000) summarised various electrification options, and identified a diesel-photovoltaic hybrid electricity system as most cost-effective under the prevailing circumstances.

In 2004, the Danish Government funded the DEGREEE (Demonstration at Gobabeb of Renewable Energy and Energy Efficiency) project, which aimed at demonstrating *"energy technology, energy efficiency and energy management with the purpose of inspiring others to apply these, and by that contribute to the supply of energy to remote, isolated locations in Namibia and SADC"*. The project also provided the necessary funds to establish the modern hybrid electricity system as is in use in Gobabeb since then, i.e. a photovoltaic generator of 26 kW_{peak}, a battery bank of 200 kWh capacity, as well as associated power conversion technology. These components were integrated with the two existing diesel-powered generators of 50 kVA each into the present day diesel-solar hybrid system.

1.3 Electrification options for Gobabeb: diesel, grid, PV, hybrid

In a GTZ-funded study for the Desert Research Foundation of Namibia, Scholle presents four electricity generating options for Gobabeb, namely diesel, grid-connection, a complete photovoltaic solution, and a hybrid diesel-photovoltaic option. The options are compared on a life-cycle costing basis using the parameters summarised in Table 1 below. The key distinguishing factors of these four options are summarised in this sub-section.

Parameter	
project life	20 years
real discount rate real loan rate real diesel fuel escalation rate real gas fuel escalation rate inflation rate	5% 5% 5% 2% 10%

Parameter	
salvage rate of diesel generator	5%

Table 1: Life cycle costing parameters (Scholle, 2000, p. 35)

1.3.1 Diesel

Diesel-powered generators were used in Gobabeb since 1972, and met all daily energy needs and requirements between 06:00 and 22:00. Electrical energy was unavailable outside these periods.

The advantages of this option were:

- Initially high reliability of the generators, however it should be noted that the system suffered from voltage fluctuations and cut-out as the gensets and the installation aged
- no need for significant energy management
- abundant power, on demand availability.

The disadvantages were:

- poor efficiency of the diesel generators, due to the generally low loads and consequently low capacity factors
- no electrical energy available during non-operating times
- increasing costs of fuel for the same service output
- air and noise pollution
- high ongoing maintenance requirements.

A life-cycle analysis determined the annual costs of this option to be N$ 247,000 (value of N$ in year 2000). As this analysis was seen from the perspective of Gobabeb, it did not include the capital costs of the diesel generators, as these were already installed, while the costs of a complete overhaul of the generators and the electrical control system at the time are included.

1.3.2 Grid connection

Connecting Gobabeb to the national electricity grid would require a transmission line from Ruby substation near Walvis Bay, some 70 kilometres from Gobabeb.

The advantages of this option would have been:

- high reliability
- 24-hour power on demand
- no on-site maintenance or significant energy management required.

The disadvantages would have been:

- vulnerability to power failures
- dependence on power utility to provide service
- corrosion of power lines and pylons in the desert, possibly resulting in unexpected maintenance costs

- high probability of substantial upfront costs due to Gobabeb's non-inclusion in the Namibian electricity distribution master plan.

The all inclusive life-cycle analysis determined the annual costs of this option to be N$305,000 (in 2000).

1.3.3 Total photovoltaic option

The envisaged total photovoltaic option would have consisted of a PV generator of 42.3 kW_{peak}, a battery storage system of 288 kWh, and inverters to change from DC to AC power.

The advantages of this option would have been:

- 24-hour power supply
- low maintenance
- renewable energy source, in line with the GTRC's vision and image.

The disadvantages would have been:

- high upfront costs
- power and energy is capped
- peak demand, as is typical for Gobabeb, requires an uneconomical system size which implies even higher upfront costs.

The all inclusive life-cycle analysis determined the annual costs of this option to be N$258,000 in 2000.

1.3.4 Diesel-PV hybrid

This option consisted of a hybrid electricity system, using one of the existing diesel-powered generators, a new PV generator of 11.8 kW_{peak}, an inverter, and batteries with a storage capacity of 253 kWh.

The advantages of this option are:

- 24-hour power supply
- ability to supply a varying load
- renewable energy source to supply the Centre's base load
- system concept is inherently more efficient, i.e. the renewable resource can be fully utilised and the diesel generators can be operated at full load at and when required (often pre-determined times).

The disadvantages are:

- regular maintenance and maintenance budgets required for diesel system, although significantly lower in such a system configuration in comparison with a diesel-only system
- energy management to become integrated into all station activities
- occasional noise and air pollution
- diesel-fuel needs to be available.

A life-cycle analysis determined the annual costs of this option to be N$243,000 (in 2000) which includes all the capital, operating, maintenance and replacement costs but excludes the capital costs of the diesel generators

1.3.5 Summary of life-cycle costs for different electrification options

Table 2 summarises the projected 20-year life-cycle costs for the different electrification options for Gobabeb, expressed in N$ of 2000.

	Diesel [N$]	Grid [N$]	Solar PV [N$]	PV hybrid [N$]
Initial costs				
System:	86,000	1,925,000	2,375,000	1,200,000
Upgrade:	none	none	50,000	50,000
Conversions:	none	none	14,000	14,000
Total initial capital costs:	**86,000**	**1,925,000**	**2,439,000**	**1,264,000**
Future expenses:				
Operating, maintenance & replacements:	2,773,000	1,655,000	190,000	1,189,000
Gas:	224,000	224,000	581,000	581,000
Total future expenses:	**2,997,000**	**1,879,000**	**771,000**	**1,770,000**
Life cycle costs:	3,083,000	3,804,000	3,210,000	3,034,000
Annual costs:	247,000	305,000	258,000	243,000

Table 2: Life-cycle costing analysis of the four electrification options for Gobabeb in 2000

As can be seen from Table 2, the initial capital expenditure for the diesel option is low, because this infrastructure was already in place at the time. However, future costs associated with this electrification option were expected to be significant, mainly due to high maintenance and fuel costs.

For the grid-connection option, the upfront capital expenditures were significant as well, because of the long transmission lines needed to connect Gobabeb to the sub-station near Walvis Bay. Moreover, these power lines would have required some ongoing maintenance, which again would have been costly.

The 42kW$_{peak}$ total photovoltaic option would have required a large initial investment, but would have had minor future expenses, as no fuel would be needed, and such a system generally requires low maintenance inputs. As will be shown below, the battery replacement costs are the most significant future costs.

The upfront costs for the diesel-PV hybrid option are half of those of the solar only option, but still significant. The future costs are moderate, mainly due to the diesel generator maintenance and diesel fuel.

It should be noted that the complete energisation of Gobabeb required two additional energy sources, namely liquid petroleum gas for cooking and tea water, as well as solar water heating for bulk hot water supply. Therefore, gas costs need to be taken into account for the total costs of the solar and hybrid options. The use of gas for heating is cost effective since the installed capacity of the power converter and battery storage can be significantly smaller when not catering for such thermal needs by means of electrical heating.

Similarly, solar water heating presents an attractive alternative to gas or electrically heated water, due to the excellent and consistent local solar resource at Gobabeb. It can be seen that the full life-cycle costs are lowest for the hybrid system (for a life-span of twenty years), which is also reflected in the low annual costs of this option.

2. RECENT DEVELOPMENTS OF THE GOBABEB HYBRID SYSTEM

2.1 Introduction

This section provides an overview of the considerations for the Gobabeb hybrid electricity system design, as well as the historical developments that occurred as a result of the DEGREEE project. First, the original system sizing and cost considerations will be discussed, then the energy efficiency and occupancy changes will be discussed, and lastly, some lessons learned from the DEGREEE project will be summarised.

2.2 Energy demand and generation considerations

The average daily electricity consumption amounted to 230 kWh in 2000. To ensure the viability of the envisaged hybrid electricity system, such consumption levels had to be reduced significantly. It was anticipated that - by means of introducing energy efficiency technologies and user education - the Centre's electricity consumption could be reduced to about 100 kWh per day, leaving a spare capacity of about 35 kWh/day for future growth and expansions (Scholle, 2000).

The hybrid system was designed anticipating an increase in permanent residents, visiting researchers and tourists, from an average of around 40 people in 2000, to around 60 people in the medium term. According to the Gobabeb occupancy log of 2006 (Helen Kolb, 2006), there were 30 permanent residents (15 residents, including workers and on average 15 interns), while the average number of overnight visitors was about 10 visitors per day, resulting in a total occupancy rate of just over 40 people per night, i.e. almost as in 2000.

On this basis, a system was proposed consisting of a photovoltaic (PV) generator of 16 kW_{peak}, resulting in a projected annual contribution of approximately 40% through PV (40kWh per day) and 60% diesel-powered generator (the hybrid system sizing was based on an average diesel generator contribution of 4 generating hours per day, with an effective output of 95kWh per day) based on a 135kWh day. However, because of the availability of additional funds towards the end of the DEGREEE project, the PV generator could be expanded to its present day size of 26 $kW_{peak.}$

The present system size allowed the Centre to rely on 99% PV generated power during April to November 2006, with the diesel generator only being operated to equalise the batteries, and in occasional peak-demand times. This performance was achieved due to the rigorous energy efficiency improvements and active energy management, which resulted in lower than anticipated overall consumption levels.

2.3 Energy efficiency

In order to make the hybrid electricity system a viable option, Gobabeb's total energy consumption had to be reduced significantly. Table 4 shows the energy consumption before 2000, indicating an average energy consumption of 230 kWh per day, as well as the projected energy consumption with a hybrid system delivering some 135kWh/day.

Section	Per unit [kWh/day]	Qty	Energy [kWh/day]
Main Station	69.0	1	69.0
Bungalow and old house	3.3	5	16.5
Staff houses	9.0	3	27.0
Slums	16.0	1	16.0
Pool, water & sewage pumps	8.0	1	8.0
Workers houses	8.0	3	24.0
Future developments:			
Training centre	3.3	1	3.3
Library	3.0	1	3.0
Offices	1.2	5	6.0
Staff houses	4.0	5	20.0
Reserve capacity: 20%	39.0	1	39.0
Total energy for the diesel generator configuration [kWh/day]			230.0

Table 4: Energy consumption for the diesel only option

	Per unit [kWh/day]	Qty	Days per week	Energy [kWh/day]
Main Station	37.0	1	6	31.7
Bungalow and old house	1.0	5	4	2.9
Staff houses	6.0	3	7	18.0
Slums	8.0	1	7	8.0
Pool, water & sewage pumps	8.0	1	7	8.0
Workers houses	4.0	3	7	12.0
Future developments:				
Training centre	3.3	1	6	2.8
Library	3.0	1	6	2.6
Offices	1.2	5	6	5.1
Staff houses	4.0	5	7	22.5
Reserve capacity: 20%	21.4	1	7	22.0
Total energy for the PV solar configuration [kWh/day]				135.0

Table 3: Projected energy consumption with the hybrid

In order to achieve the reduction in daily electricity demand from the previous diesel-only era (230 kWh/day) to the hybrid output of 135kWh/day, energy efficient technology and usage changes were introduced, in particular

- the replacement of electric stoves/kettles with gas stoves for cooking and tea water
- the replacement of incandescent with compact fluorescent lights
- using energy efficient refrigerators
- replacing the seals on the remaining refrigerators
- behavioural changes such as using lighting appropriately
- activating energy saving settings on computers, and
- making users aware of system constraints and usage tips.

2.4 Lessons learnt during the hybrid implementation

The implementation of the hybrid electricity system at Gobabeb has three important areas in which lessons can be summarised, namely energy and power supply, energy efficiency, and revenue collection.

2.4.1 Energy and power supply

Overall, the introduction of the hybrid electricity system has not decreased the availability of power, if the diesel generators remain on stand-by. However, seeing that all users are aware of the limitations of the 'solar only option', and in view of the active Gobabeb policy of minimising the use of the diesel generators, end-users have changed demand levels and usage patterns, which limit the amount of electricity used per person per day. This was and still is achieved by reminder notes throughout the Centre, for example that plugs cannot be used for devices drawing more than 4 Amperes, and awareness materials on fridges and in kitchens, explaining the importance of using electricity sparingly. Users know that substantive power-consuming activities, such as welding, need to be coordinated with the systems energy manager, as these require that a diesel generator is switched on.

The above illustrates that it is essential that usage norms are communicated to all beneficiaries of the electricity system. In the case of Gobabeb, this is done by the energy manager, supported by the notification signs posted on most power outlets and in kitchens. This strategy ensures that users are aware of what devices can be used, and limits the misuse of the system. Because of a changing visitor population, awareness raising and usage monitoring need to be undertaken on an almost continuous basis. They need to be undertaken by a person who can communicate the usage requirements with authority, underpinned by a good understanding of the workings and system requirements. This activity necessitates the presence of at least one full-time person, for example the system's energy manager, or could be undertaken by another suitably trained person.

2.4.2 Energy efficiency

The transition from the diesel-only operation to the hybrid system required the significant reduction of the daily energy consumption. This was achieved by introducing technology and usage changes, i.e. the replacement of electric stoves/kettles with gas stoves, the replacement of incandescent with compact fluorescent lights, using energy efficient refrigerators, replacing the seals on the remaining refrigerators.

Conversion to cooking with gas was not well received by all members of the Gobabeb community, for reasons of safety as well as concerns about the cost of gas (cooking on electricity was free before DEGREEE). This required a number of meetings with members of staff to develop different perceptions about cooking services through gas as well as resolve the financial implications of such a conversion.

Moreover, energy users at Gobabeb had to change their energy consumption behaviours, which required a shared understanding of the system capabilities, and the willingness to accept such changes. In the case of Gobabeb, the transition was effectively managed, and shows that a combination of usage changes and low energy technologies can indeed achieve substantial reductions in day-to-day energy consumption patterns.

It is to be noted that the small number of users at Gobabeb, all involved in the operations of the Centre, simplified the task of making people aware of their energy consumption and introducing energy saving behaviours. Electricity supply systems with a more diverse group of users, on the other hand, may find that users are not necessarily willing to make such changes, especially if they are responsible for the associated costs of technology replacements. This necessitates a carefully crafted approach to user education in the transition to a new electricity regime.

2.4.3 Revenue system

Electricity metering was introduced as part of the introduction of the Gobabeb hybrid system. Users have been made aware of their electricity consumption on a monthly basis, and are charged accordingly. Before the introduction of the hybrid system, people were not aware of their personal consumption patterns, and were not charged for their electricity use.

The fact that users had to pay for their electricity was accepted, because people were aware of the external circumstances that affected Gobabeb's energy situation, i.e. that since 1998, Gobabeb had the responsibility of operating (and therefore paying for) the diesel generators, while the Ministry of Works continues to service them to this day. This is an important aspect that requires considerable preparation, as many users accustomed to 'free electricity' may not readily be convinced that they have to pay for such services. In addition, as soon as users are charged, they will compare their expenditures with friends and colleagues in other localities, and may find that their per-kWh charge is considerably higher than what is paid in, for example, grid-connected areas. Such comparisons, if not adequately communicated, may lead to dissatisfaction and confusion. The introduction of appropriate user charges, and the collection of revenues, therefore necessitates a planned implementation approach, in which users are made aware of the need of collecting revenues, and the rationale of tariffs applied.

In terms of future hybrid system implementations where an existing diesel generator infrastructure is in place, it is preferable that cost-reflective charging for electricity consumption and energy efficiency changes are implemented well-before the hybrid system is implemented. This process avoids that the hybrid system with its solar and/or wind component is blamed for "expensive" energy services. Energy costs would theoretically decrease with the introduction of a hybrid configuration taking current diesel prices into account.

3. TECHNICAL AND OPERATIONAL CHARACTERISTICS OF THE GOBABEB HYBRID SYSTEM

This section presents a brief overview of the various technical components which form part of the Gobabeb hybrid electricity system.

3.1 The system

The hybrid electricity system currently in place in Gobabeb consists of two three-phase 50 kVA diesel generators, four arrays of solar panels totalling $26kW_{peak}$, a battery storage system of 200 kWh, and a 30kVA three-phase bi-directional power converter (i.e. inverter as well as battery charger). Electricity is distributed to all consumers via an armoured three-phase underground cable network installed in 1972.

The system provides electrical energy for 24-hours per day, throughout the year, with the battery system providing for the night-time electricity demand. The system is pre-dominantly powered by solar energy. The diesel generators however provide critical functionality to a hybrid system, including

- power during inclement weather

- power to select high-consumption users
- power during periods of above-normal system use (in case of larger gatherings at Gobabeb)
- ideal charging patterns for the battery during the monthly equalisation charges, which are critical to ensure that the battery set meets its life expectancy target
- system redundancy.

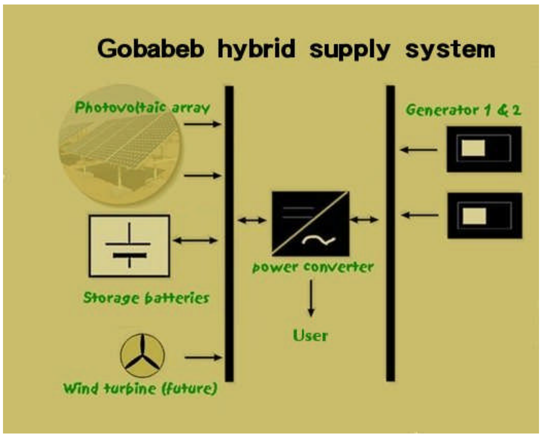

Figure 2: Gobabeb's hybrid electricity supply system

The electricity system is fitted with a series of power and energy meters, indicating instantaneous and daily system performance. These meters present first-line information to the operator, and are essential to assess the system status and current usage.

An electronic monitoring system, consisting of displays of the power supplied and demanded by the different energy sources and user groups, provides more in-depth information on consumption and generation patterns to the operator, and is invaluable for educational and research purposes. Usage data is logged, and available for analysis, mainly to monitor the day-to-day performance of the system, and to ensure that the power supplied matches the electricity requirements of users, and to ensure that the battery system maintains adequate charge levels.

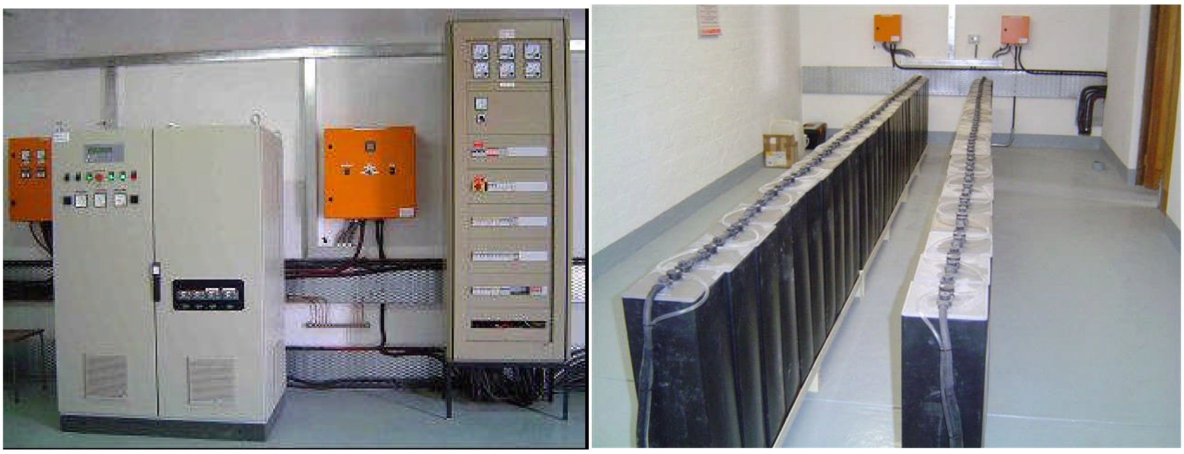

Figure 3: The Gobabeb hybrid electricity system's operation room, and 200 kWh battery bank

3.2 System management

Gobabeb has a facility manager, who is also the hybrid system's energy manager, responsible for the operations and ongoing maintenance of the system. Broadly, the energy manager has a three-tiered control regime that covers daily, weekly and monthly system requirements.

On a day-to-day basis, the energy manager monitors key system indicators, which include the battery state-of-charge, and overall system performance.

Every week the battery water levels are checked, and the batteries are equalised if needed. In order to optimise battery life the system provides power from the battery system as long as the battery charge is above 50% of capacity. If the battery charge drops below this threshold, one of the two diesel-powered generators switches on automatically, and batteries are charged until the battery charge exceeds 70% capacity. Batteries are not brought to full charge by the diesel generator in order to avoid displacing the available and free solar energy. The full charge cycle by means of the diesel generator only takes place for equalisation charges.

Once a month the system is visually inspected, and the solar arrays are cleaned.

The inverter is taken through a load test every four months, while the diesel generators are serviced as required.

The energy manager communicates vital system information to Gobabeb residents. In case user groups show excessive electricity use, these are identified and corrective measures are introduced.

3.3 Performance monitoring and assessment

As described above, the hybrid system at Gobabeb is monitored continuously, and vital system data including the energy, power, apparent power, voltage, current, maximum and minimum power per phase is logged in five-minute intervals. Data files are downloaded to a computer every couple of months, even though this has not always been done in the past.

The Centre's administrator collects data regarding the number of people visiting Gobabeb, and knows how many staff is present at any one time. This allows an assessment of the energy used per person, taking the varying occupancy levels into account. Figure 4 below shows the electricity consumption per person for some 79 days in 2006, and also shows that the daily consumption per person decreases as the number of people at Gobabeb increases. This is due to the base load being spread amongst more people, while the contribution of the variable load per person makes a smaller impact on the total consumption. The solid trend line in Figure 4 has only been drawn in for 60 residents and less, as the statistics for occupancies larger than 60 people do not allow meaningful conclusions to be drawn.

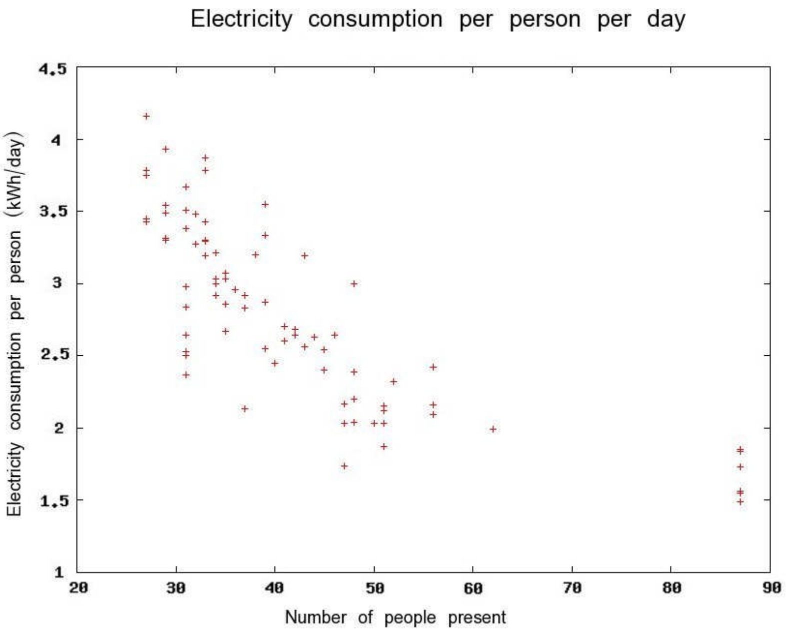

Figure 4: Electricity consumption per person per day as a function of the number of people using the system

3.4 Pre- and co-requisites for the operation of the Gobabeb hybrid system

The social, technical and economic skills and services needed to operate the Gobabeb hybrid system are summarized in
Table 5. It is noted that the demand and momentary needs for specific skills will change with time.

What?	Activities	Skills/items needed	Timescale
Daily Management	- Checks of system functioning - Reading electricity usage - Comparison to expected performance - Energy management: o Schedule deferrable and high power loads o Dispatch genset as required - Communicating overuse - Take measures to anticipate overuse	- Communication - Basic system knowledge - Manual for emergencies	Daily
Cleaning and Maintaining system	- Top up battery water - Clean solar panels - Check wiring - Perform small fixes	- General technical skills - Labour to clean - Diligence	Weekly-Monthly
Monitoring	- Check monitoring logs - Save data on server and backup - Analyse data	- Computer skills	Monthly
User feedback and revenue collection	- Check monthly consumption - Check use per person/group - Communicate usage to users - Charge users for consumption - Communicate system issues arisen - Advice users on energy reduction	- Bookkeeping skills - Communication - Financial skills - Basic system knowledge - Basic energy knowledge	Monthly (Weekly?)

Analyse costs and payments	- Check yearly consumption - Check revenues raised - Check yearly expenditure (unforeseen and writing off) - Adjust tariff as necessary - Communicate decision	- System logs - Finance logs - Economical skills - Communication	Annually
Analyse possible investments	- Check consumption trends - Check system performance - Check financial situation - Analyse current system sizing - Decide to expand or reduce the system	- System logs - Finance logs - Advanced technical skills - Advanced economical skills	Two yearly
Analyse system type	- Analyse energy needs developments - Analyse system technical performance - Analyse social adaptation - Analyse economical changes - Decide on continuation of system or change to different technology	- System logs - Finance logs - Social analysis - Advanced technical skills - Advanced economical skills	10-15 yearly

Table 5: Pre- and co-requisites of the operations of the Gobabeb hybrid electricity system

It is essential to note that some of the activities require ongoing capacity building/refreshers throughout the service life of a hybrid system (e.g. due to staff changes). In most cases, this need has to be met through outside service providers, such as the technology provider or an Energy Services Company.

4. COST/BENEFIT ANALYSIS OF THE GOBABEB HYBRID SYSTEM

4.1 Introduction

This section quantifies the costs and benefits of the Gobabeb hybrid electricity system as of May 2007. The approach followed in this section entails a verification of historical costs, the forecasting of future system costs, and the calculation of present values. The total present value system costs are then divided by the total expected electricity output supplied by the system over its entire lifespan, so as to compute the cost per kWh supplied. A sensitivity analysis shows the effect of different discount rates.

In the interest of readability, this section is deliberately kept brief, and a more detailed exposition of the underlying data is presented in Appendix A. However, unless the reader is interested in detailed costing details and the various rates used in this section, the section aims to present an overview of the multitude of system costs and the underlying assumptions on which this cost-benefit analysis is based.

4.2 Capital expenditure

The 2004 capital costs of the hybrid system are summarized in Table 6 [1]:

[1] As per Solar Age Namibia Contract Agreement of 8 Apr 2004. It is to be noted that the costs of the PV array D_2 (30 x Shell Solar SM55 in combination with Arco M55 panels, 1.65kWp) could not be traced to original contracts or invoices, and had to be estimated using the most likely historical prices. Likewise, the construction

ITEM	**2004 COSTS [N$]**	**ESTIMATE**
PV array A	195,150	
PV array B	195,560	
PV array C	176,429	
PV array D_1	70,571	
PV array D_2	42,000	Y
PV array A structure, incl. labour	152,517	
PV array B-D, incl labour	180,000	Y
Batteries	195,807	
Power converter	388,638	
Hybrid control	10,000	
Electronics, misc	40,750	
Matching & commissioning	117,070	
Cooling of battery room	32,000	
Grounding and lightning protection	40,000	
Pole fence array protection	20,000	
TOTAL excl VAT	1,856,492	
15% VAT	278,474	
TOTAL in 2004	**2,134,966**	

Table 6: Capex of PV system components in 2004

Using the annual Namibian inflation rates between 2004 and 2007 [2], the capital expenditure in 2007 dollars associated with the hybrid system's PV components is:

TOTAL capex for PV component of hybrid in 2007	**N$ 2,417,031**

The cost (in 2004) of the two diesel-powered generators in operation since 1972, consisting of two identical 50 kVA three phase generators powered by six-cylinder Deutz diesel engines, are summarized in Table 7:

ITEM	**2004 COSTS [N$]**	**ESTIMATE**
2 x 50 kVA diesel genset	200,000	**Y**
diesel meter	30,000	
monitoring system	82,000	
cables and upgrades to match PV genset	60,000	
TOTAL excl VAT	372,000	
15% VAT	55,800	
TOTAL	**427,800**	

Table 7: Capex of diesel-powered gensets in 2004

costs and associated labour for the PV array stands for arrays B – D could not be ascertained, and had to be estimated.

[2] The following inflation rates were used: 2004/5: 3.91% pa; 2005/6: 4.50% pa; and 2006/7: 4.26% pa

The approach taken in this paper is to cost all existing assets, even if such equipment would not necessarily have been part of a Greenfield installation[3]. Using the annual Namibian inflation rates between 2004 and 2006, the capex in 2007 Namibian dollars associated with the hybrid electricity system's diesel-powered gensets and system is:

TOTAL capex for diesel gensets, in 2007	**N$ 484,320**

In total, the capital expenditure – in 2007 dollars – of the Gobabeb hybrid electricity system is:

TOTAL capex for hybrid system, in 2007	**N$ 2,901,351**

4.3 Operational expenditure

Although ongoing operational expenditures associated with diesel-solar hybrid electricity systems are generally lower than for stand-alone diesel-powered systems, these expenses are still important to take into account in terms of their contribution to the total cost of having electricity supplied by such a system.

Using the assumptions provided in Appendix A, monthly operational expenditures associated with the Gobabeb hybrid system – in 2007 values – include:

ITEM	2007 COSTS [N$]	ESTIMATE	ASSUMPTION
energy manager	2,600	Y	13% of billable time per month
diesel service minor	551	Y	i.e. one service per year
diesel service major	338	Y	i.e. one service every 2 years
diesel service rebuilt	489	Y	i.e. one service every 20 years
diesel, 20 litres	126		i.e. some 66 kWh/mo from genset
de-ionised water	20		
miscellaneous articles	250	Y	
ongoing training	167	Y	16hrs pa
once off start-up training	506	Y	every 5 years
battery system replacement	8,155	Y	replaced every 10 years
TOTAL per month	**13,202**		

Table 8: Monthly operational costs of Gobabeb diesel-PV hybrid electricity system, in 2007

All operational and maintenance costs summarized in Table 8 are expressed as costs per month. This allows the system owner-operator to readily identify the primary cost drivers associated with the operation of the system, and focuses attention on those aspects that have significant monetary implications. It is noteworthy that, for the purpose of the analysis, some costs that are traditionally considered capital costs are expressed as monthly operational costs, such as the expenses related to the exchange of the battery system in 10-yearly intervals[4]. This real-cost approach used

[3] A Greenfield installation would in all likelihood not have included two diesel generators, would not have included Gobabeb's elaborate monitoring system, as well as the expensive diesel consumption meters.

[4] Gobabeb's 200 kWh battery system has a depth-of-discharge of approx. 40% at a daily consumption of 140kWh.

here allows the manager to justify why the recovery of regular expenses is essential – if it is feasible to recover and save ongoing operational costs – which poses a well-known managerial problem when capital and operational costs have to be budgeted for and justified separately.

The replacement of the battery system is often considered a capital expenditure item, considering that it has to take place only once every 7 to 12 years (in this case, it is assumed that the battery system will have to be replaced every ten years, i.e. in 2014, and in 2024 [5]). However, in the interest of focusing the owner-operator on the necessity to make provision for such expenditures from day one of the operations of the system, this primer takes the view that such costs are part of the ongoing operational expenditure for which provision has to be made, and for which savings are required to allow the uninterrupted operations. Similarly, the annual minor diesel service, bi-annual major diesel service and the rebuilding of the diesel engines every 15,000 hours (considering the current operations of the Gobabeb system this will only happen once in its remaining lifecycle) are considered as ongoing operational expenses for which monthly provisions have to be made.

Figure 4 depicts the various monthly operational cost components listed in Table 8, and thus allows the owner-operator to identify the three main recurrent necessities, namely

a) to make provision, for example in annual operating budgets, for the replacement of the hybrid system's battery system,
b) to ensure that an experienced energy manger is available and takes care of the requirements of the system for the duration of the system's operation, and
c) to plan and cost the required diesel system maintenance costs.

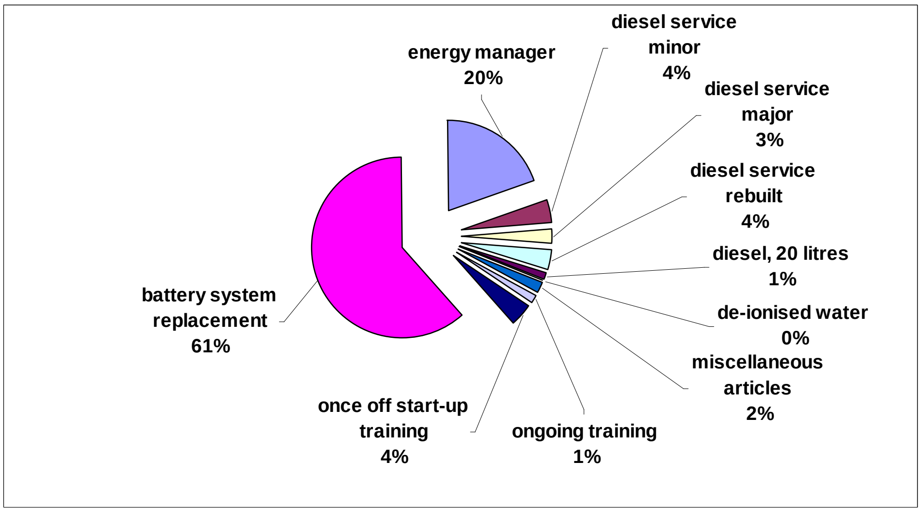

Figure 4: Breakdown of the monthly operational expenditures, in 2007

Operational expenditures have to be budgeted for, and have to be available from day one of the operation of a hybrid electricity system. The total operational costs incurred between 2004 and 2007, expressed in 2007 currency, are:

[5] Given the present day maintenance routine, and assuming that the system will not be significantly overused in future.

TOTAL system opex since 2004 - until 2007 - in 2007 currency N$	**595,713**

Based on the operational expenditure in 2007, such costs are used to project future running costs, using a low (110 kWh/d), medium (135 kWh/d) and high (160 kWh/d) future electricity consumption scenarios for the period 2008 to 2028, under the assumption that the PV panels, inverter system and other electronics have a total life of 25 years [6].

The present value in 2007, of all past and future operational expenditures, amounts to:

Low usage scenario at 110 kWh/d from 2008	Medium usage scenario at 135 kWh/d from 2008	High usage scenario at 160 kWh/d from 2008
N$ 2,459,409	N$ 2,742,735	N$ 2,996,001

Table 9: Present value of total operational expenses, in 2007 currency

4.4 Cost-benefit

The hybrid electricity system's sole purpose is to provide electrical energy on demand, an output most conveniently measured in kWh. Rather than postulate consumption scenarios, this section calculates the actual cost per kWh, as kWh's are the commodity and benefit that the consumer has from having electricity supplied by the hybrid system. In this way, the owner-operator of the system can calculate which future system extension opportunities are most cost-effective, and can also compare the system's energy costs to what other contemporary supply options, such as grid electricity, diesel-only, or solar-only would cost.

As discussed in section 4.3, the system's total capex in 2007 amounted to N$ 2,901,351, while the system's total operational expenditure over the system's lifetime is summarised in Table 9 above, and depends on whether a low, medium or high electricity consumption future is envisaged between 2008 and 2028[7].

Gobabeb's recent average daily electricity consumption is depicted in
Figure 5, and shows an average daily consumption of 112.3 ± 22.8 kWh [8] over a period of 629 days, with the lowest daily consumption of 72.8 kWh, and a maximum of 228.4 kWh. For the purposes of calculating a per kWh price of electricity, the daily consumption was assumed to lie in an envelope of 110kWh/day, 135 kWh/day and 160kWh/day respectively, which implies an annual electricity consumption of 40 MWh, 49 MWh and 58 MWh respectively, or a total system output of 1.0 GWh over 25 years, or 1.2 GWh or 1.39 GWh respectively[9].

[6] Given the present day maintenance routine & assuming that the system will not be significantly overused in future.
[7] It is assumed that some 110 kWh / day were consumed in the years 2004 to 2007.
[8] From weekly consumption data records at Gobabeb.
[9] Assumed consumption is 110kWh/day between 2004 and 2007, and 110, 135 or 165 kWh/d between 2008 and 2028.

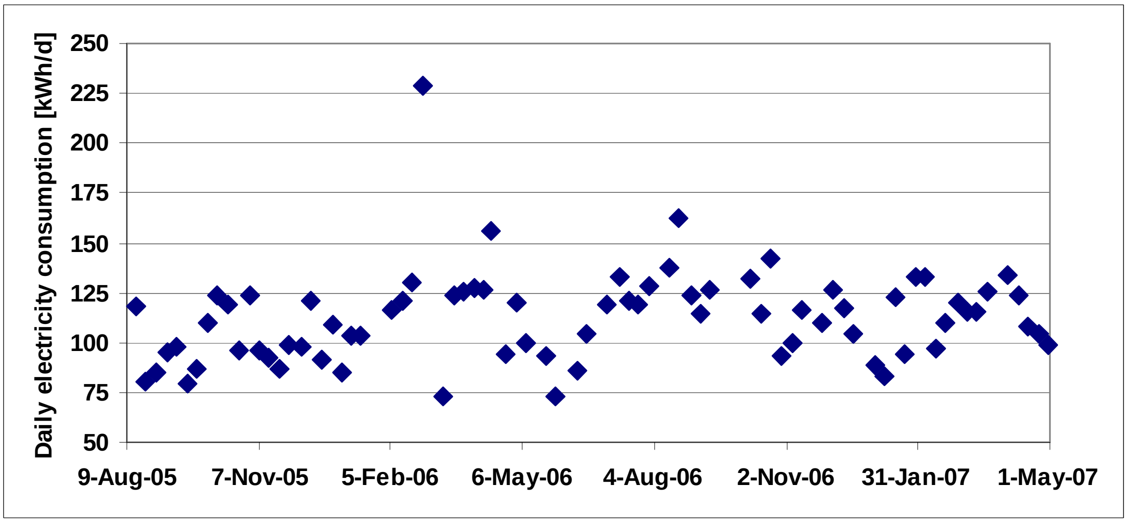

Figure 5: Gobabeb daily electricity consumption figures, since August 2005

Taking the total costs and total lifecycle electricity production figures into account, the above figures imply a 2007 price per kWh – in a low electricity usage future – of N$ 5.34/kWh, while the 2007 price per kWh in a medium electricity usage future amounts to N$ 4.72/kWh, while the 2007 price per kWh with a high electricity usage future amounts to N$ 4.25/kWh.

4.5 Sensitivity analysis

Figure 6 shows the results of a sensitivity analysis with respect to the discount rate (DR) as a function of the daily electrical output of the hybrid system in kWh/day. It is seen that high discount rates ensure that income from more immediate future payment periods are more significant than those of the more distant payments, but that the influence on per kWh rates remains small.

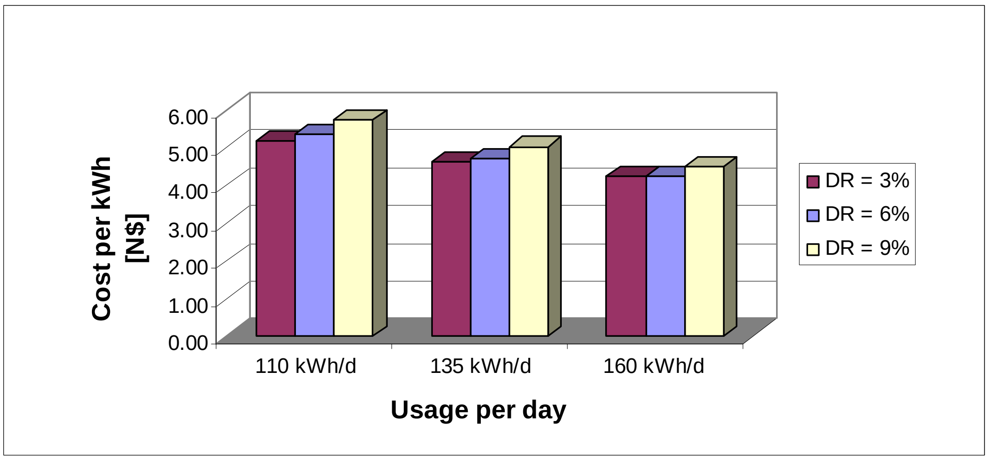

Figure 6: Sensitivity analysis of discount rates (DR) as a function of the daily electricity consumption in kWh/d

5. CONCLUSIONS

5.1 Operational issues and challenges

The following long-term operational issues and challenges have become evident in the Gobabeb diesel-hybrid system.

User pays principle:

- The user pays principle is difficult to implement, yet is a cornerstone of the systems long-term viability.
- The change-over from the previous 'consume-as-much-as-you-like' to an energy conscious environment has been difficult and requires the ongoing attention of the energy manager.
- Introducing metered electricity to users that were accustomed to free electricity services is a challenge that requires careful ongoing management.
- The amortisation of system components with an expected lifetime less than the overall system, such as the battery system, and associated assessment of user charges, determines to a large degree how viable the system can remain over the longer term.
- In order to spread the ongoing costs of operating and maintaining the system amongst users, users should pay for what they have or will be consuming, necessitating metering technologies such as pre-payment or cumulative usage meters. Flat rate user tariffs, as are used at Gobabeb (N$4/person/day used), do not provide an adequate signal to users to limit their consumption, and may in the long run lead to non-optimal system use.

User behaviour:

- Behaviour monitoring, and the associated ongoing education of users, including those that benefit from system for a short period only, is and remains essential.
- The relationship between the energy manager and system users determines, amongst others, how well users adhere to user guidelines. Systems operating for large non-cohesive users will require different engagement and interaction strategies as well as technical solutions.

System monitoring and maintenance:

- The ongoing monitoring of usage and key system variables remains essential, especially to capture changing user preferences and consumption patterns, and ensure the continued balance of the phases of the system.
- Ongoing system maintenance, including trivial activities such as battery water control, array monitoring and battery state-of-charge monitoring is essential.

Technology:

- Introducing energy efficiency measures to users accustomed to 'consume-as-much-as-you-like' requires a phased implementation, funding and communication plan.
- The technical design needs to allow to the greatest possible extent that consumption patterns may change either per phase, or for the entire system. Here, the balancing of loads per phase is a particularly challenging task as many of the loads are dynamic, and depend on non-technical user preferences

and managerial decisions. As the performance envelope per phase is frozen by the initial system design, it is important that sufficient flexibility and over-capacity is designed into the system so as to allow future load changes and growth.

- Heavy in-frequent loads, such as air-conditioner systems or kilns/ovens need to be three phase loads.

The technological part of an energy solution is only one aspect of several important aspects in hybrid system installations: the day-to-day management aspects, including maintenance, revenue collection and ongoing optimal system operations are other critical issues which will ultimately ensure the long-term sustainability of the energy solution.

5.2 Summary of risks and possible mitigation measures

Table 10 summarises some risks and associated mitigation measures that system managers of hybrid electricity systems similar to the Gobabeb system need to be aware of.

Risk	**Possible mitigation measure**
Ineffective or non-regular maintenance routine and first-line service, especially for system components requiring regular monitoring and maintenance, such as the battery system	• Procedural guidance of energy manager to include suitable maintenance and monitoring regime • Regular cross-check by superior
Insufficient long-term system monitoring, e.g. over annual and longer intervals, making management decisions (e.g. investment decisions) difficult	• Maintenance regime to include short-, medium and long-term activities, including data capture and regular data analysis • Regular reporting on medium- and long-term monitoring results • Energy system to be discussed regularly at managerial level
Availability of capacitated energy manager with sufficient technical background and hands-on experience	• Management recognises the energy system as an essential asset that requires the ongoing attention of a qualified and experienced energy manager
Insufficient ongoing cost recovery makes replacement of system components difficult without outside subsidization – use separate account for system revenues	• Management establishes a separate financial account for energy system income • Ongoing recovery of costs – through adequate and annually reviewed electricity tariffs – is ensured
Availability of spare parts and required person available to undertake repairs	• Energy manager to be sufficiently qualified to undertake first-line maintenance • Essential spare parts available on site
Service agreement does not cover contingencies	• Management to ensure that service agreements specify contingencies to a level that allows the energy system to operate at more than 99% availability
User compliance with system requirements (who use large loads and/or change circuit breakers without proper consultation with energy manager)	• User compliance to be ensured by way of technical (e.g. circuit breaker limitations) and awareness (e.g. users understand the system limitations and consequences of their system usage) measures • Regular check of user demand and usage

	patterns by energy manager
Consumption per phase unbalanced	• System design to ensure that phases are optimally balanced • Regular monitoring of usage per phase • Corrective action to be taken by energy manager if non-transient imbalance of usage of one or several phases is evident
Non-permanent availability of energy manager	• Clear system operating and maintenance procedures available • Codified hand-over process in place, even if energy manager is only absent for short periods • system operating and maintenance procedures
Catastrophic system failure necessitates specialist – who may be unavailable immediately	• Service agreements with principal suppliers to specify level and availability of specialised service personnel in case of serious system failure • Remote monitoring of key system data by expert – to forewarn of potential system failure • Clear instructions for emergency operation on diesel generators
Theft and/or vandalism of solar modules	• Solar modules to be permanently marked • Module fixtures to make dismantling difficult (e.g. pop-rivets instead of nuts and bolts) • Positioning of PV arrays within sight of key users
Component lifetime shortened due to extreme conditions	• Service agreements to spell out warranty periods, which are used in life-cycle and tariff calculations • Preventative maintenance regime in place • System maintenance fund established and regularly replenished by way of cost reflective usage charges
Distance to designer, manufacturer, supplier and service agents	• Service agreements with principal suppliers to specify level and availability of specialised service personnel

Table 10: Risks and mitigation measures

5.3 Skills and knowledge required to operate a hybrid system

The following skills and knowledge are necessary to ensure the continued operation of a hybrid system similar to the Gobabeb electricity system:

- an energy manager – responsible for the day-to-day operational and technical system supervision – with mechanical and electrical aptitude and experience is a pre-requisite to operate a hybrid electricity system of the Gobabeb type, and thorough understanding of the concepts of power, energy and energy efficiency are essential.
- the energy manager, or a designated person having the required skills and experiences has to be responsible to communicate the usage patterns and energy efficiency measures to all end-users, and provide an introduction of the system limitations and behavioural guidelines to new users

- the energy manager's interest in and ongoing commitment to the system is essential
- data acquisition and regular analysis of key system in- and outputs underpin all future decisions regarding the system, which therefore requires the ongoing attention of the energy manager. Here it is observed that a high degree of data capturing automation is beneficial in the medium to long term.
- the energy manager is to have sufficient skills to independently undertake first-line mechanical, electrical and electronic maintenance and fault-finding activities
- step-by-step instruction manuals on how to operate and maintain the system are to be available, preferably with pictures illustrating key system features

5.4 Gobabeb's key success factors

Gobabeb is one of a handful of larger southern African hybrid electricity systems that works well. The key reasons for the successful operation of the electricity system are seen to be:

1. **Demand side issues:** these were explicitly taken into account in the design phase, for example, energy efficiency solutions have been incorporated wherever possible. In addition, user training is ongoing, and is reinforced through posted awareness materials, and is also enforced by way of behavioural guidelines promoted and controlled by the energy manager.
2. **Supply side issues:** these range from the required engineering, contracting and technology supply capacity, which in turn positively influenced the design, technology selection and hardware implementation. In addition, professional back-up services for all system components are available when required.
3. **Organisational capacity:** the presence of a technically skilled energy manager who is able to undertake all first-line maintenance and system monitoring tasks, and is responsible for strict user guidelines and the continuous awareness creation on both user and manager level, is essential.
4. **Revenue collection:** continuous revenue collection reminds users of the importance to use system energy sparingly, and encourages energy efficient consumption behaviours. In addition, continuous revenue collection using near cost-reflective tariffs creates the financial capacity to pay for the ongoing upkeep and any capital intensive replacements that may be needed in future.

The above illustrates that solid planning and implementation, focusing on demand and supply side issues, and the ongoing attention to the electricity system, through sufficient organizational capacity and continuous revenue collection constitute the foundation on which the long-term sustainability of the Gobabeb hybrid electricity system rests.

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APPENDIX A: CAPITAL AND OPERATIONAL COSTS

A.1 Solar and electronic components of the Gobabeb hybrid system

From a Solar Age Namibia Contract Agreement, dated 8 Apr 2004:

- PV array structure for Array A, inclusive of labour N$152,517
- Batteries: flooded lead-acid 200kWh (1,400 Ah at C5 rating) N$ 195,807
- Electronics: power converter including 30KW solar charge controller (30 kVA, 120 VDC) N$ 388,638
- Electronics: hybrid systems control N$ 10,000
- Electronics: other equipment N$ 9,547 + N$ 31,203
- Services: commissioning, incl matching of diesel gensets, training, transport, documentation, N$ 80,320 + N$ 36,750

Prices exclude 10% contingencies and 15% VAT; all inclusive N$1,115,739.23.

From an offer by Solar Age Namibia, dated 5 May 2004:

- Array A: PV modules 100 x 70 W CIS, 7 kWp, poly thin film Würth Solar WS11007, N$ 195,150 excl VAT

From a quote by Siemens Namibia, dated 5 May 2004:

- PV Array B (northern array): 100 x Siemens and Shell Solar SP70 monocrystalline, 7 kWp, N$195,560 excluding stand & VAT
- PV Array C (centre array): 100 x Shell Solar RSM75, 7.5kWp, N$176,429[10]
- PV Array D_1 (southern array): 40 x Shell Solar RSM75 multicrystalline, 3kWp, N$70,571

An estimate had to be made for PV array D_2, i.e. 30 x Shell Solar SM55 / Arco M55 monocrystalline, 1.65 kWp, for N$42,000.

A.2: Staff costs for systems maintenance and energy management

The following estimates are based on an interview with the Gobabeb energy manager on 9 March and 2 May 2007, and are understood to be approximations of the time spent by an experienced energy manager once the system is working satisfactorily, is stable, and that the broader system characteristics and daily, monthly and annual systems requirements are understood and carried out.

Operating and maintaining the system: total of ~**23 hr/mo, i.e. ~ 13% of the total monthly time available to a full-time energy manager**

- **day-to-day:** total of ~10 min/d, or 1hr/w
    - monitor state of charge of battery system: 4 min/d
    - monitor individual phase consumption: 4 min/d
    - monitor battery and battery room temperature: 2 min/d
- **weekly:** over and above the daily walk-past control and routine described above, total of ~60 min/w = 1hr/w
    - monitor acid levels in battery system: 10 min/w
    - visual inspection of panels: 10 min/w
    - filter cleaning of inverter: 15 min/w
    - visual inspection of diesel system: 5 min/w
    - record-keeping & analysis: 20 min/w, depending on monitoring system
- **monthly**, over and above the daily and weekly routine: total of ~14.3 hrs/mo
    - cleaning of filter of evaporative cooler: 1 hr/m

[10] Estimate from DEGREEE budget, March 2005

- cleaning of panels: 2 hrs/m
- diesel system maintenance (minor service & control, such as refuelling, oil change, routine checks): 3 hrs/mo
- genset service every four months, depending on use, ~4 hrs / 4 months, or 1 hr/mo
- load test on phases of inverter, every six months, 2 hrs per six months, or 20 min/mo
- ongoing education of existing users to ensure awareness of system requirements and user compliance, and to inform energy manager in case large loads are to be used, 2 hrs/mo
- educating new users, e.g. system limitations, circuit breaker limits, user-pay principle, 2 hrs/mo, but critically depending on number of new users and level of their interest and commitment to system integrity
- introduction of system to guests and interested parties, 3 hrs/mo

A.3 Costs of materials

The following materials are expected to be used as part of the daily, weekly, monthly and annual maintenance routines:

- de-ionised water for batteries: N$20/mo
- diesel: 20 litres/mo, i.e. N$128/mo
- diesel engine service: the diesel engines require a minor service after 250 hours[11], a major service every 500 hours[12], and a major overhaul after 15,000 hours[13]
- spare parts for diesel system, i.e. N$250/mo

A.4 Initial staff training costs

Staff start-up costs: total of **~ 224 hrs at the installation of the system, then ~16 hrs per year as an ongoing training and skills upgrading requirement**

- training, and participation in final installation to get to know critical system and component requirements and rationale for design: one month once off
- introduction to basic monitoring processes and first-line maintenance steps: one week once off
- introduction to the instrumentation and interpretation of monitoring system: one day once off
- trouble shooting, and first-line maintenance, fault finding and repair of system and components, 3 days once off
- ongoing access to technical advice, on an as-needed basis, 2 days / yr

[11] In 2000, oil and filters cost N$ 600, 4 hours of labour N$ 800 and transport N$ 1,600, bringing the overall cost for a minor service to N$ 3,000 per diesel engine or N$ 4,400 for both.

[12] Requiring a change of filters and oil, tuning of valve clearance at a cost of N$ 700, 6 hours labour at N$ 1,200 and transport at N$ 1,600, bringing the overall cost for a major service to N$ 3,500 per engine or N$ 5,400 for both.

[13] In 2000, the complete rebuilding of the engine costs N$ 43,000 per unit, including all transport, labour and diesel generator hiring costs, and the actual overhaul costs are approximately N$ 35,000 per generator.