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University of Cape Town

**Application of Advances in Automotive Technologies  
To  
Electrification in Rural Sub-Saharan Africa**

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Thesis submitted to the  
University of Cape Town  
in fulfillment of the requirement for the award of the degree of

**Doctor of Philosophy**  
In the  
Department of Electrical Engineering

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*To*  
*The Glory of God*  
*and*  
*Peace on Earth*

## **Declaration**

The thesis is submitted as a requirement for the award of the degree of Doctor of Philosophy in Electrical Engineering at the University of Cape Town. It has not been submitted before at this or any other university. The author hereby confirms that it is based on his own work. The total number of words is less than 80,000.

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## Abstract

Continued lack of electrification in rural sub-Saharan Africa poses a major challenge. The consequences are well documented. Major research is required to redress the situation but the meager financial and energy resources are major hurdles.

In the meantime elsewhere in the first world, investment in research and innovation continue to attract investors. For example a massive automotive energy conservation research drive was initiated in the mid 1990's by a Partnership for a New Generation of Vehicles (PNGV). The PNGV advanced three important public policy objectives: environmental protection, energy security, and U.S. economic competitiveness. To achieve this mammoth challenge they proceeded by re-examining automotive energy conservation right from first principles. Their centerpiece was a coordinated portfolio of hundreds of research projects by among others, 19 US Federal National Laboratories, United States Council for Automotive Research (USCAR), automotive parts suppliers, university research facilities and a range of stakeholders. These were subsequently augmented by similar efforts in Europe and Japan.

The thrust of this work draws parallels between an automobile and a remote village to consider the adaptation of the new automotive technologies to rural electrification. The author further augments this by additional contributions in load modelling, mini distribution network loss minimisation and energy economy by appropriate system configuration.

The main issues that are shared by an automobile and a remote rural village can be revealed as finite energy resources without a supporting grid infrastructure, which must cope with, poor energy resource-to-need conversion technologies, adverse human factors, poor load factors, inefficient appliances and poor storage technologies, among others. These must all interact to meet objectives on service quality and the environment. Furthermore, the

expected economies of scale in the automotive industry should subsequently make the adoption of these technologies affordable for rural applications.

A typical rural sub-Saharan scenario is depicted in chapter 1. Chapter 2 identifies human factors that constitute major obstacles to rural electrification. Chapter 3 deals with white light emitting diodes (LEDs) and numerical calculations show the tremendous energy savings that would accrue from the adoption of LEDs to rural lighting. Chapter 4 adapts new automotive drives and air-conditioning technologies to rural water pumping and refrigeration. Chapter 5 discusses load modelling of critical rural loads of lighting, refrigeration and water pumping. Chapters 6 and 7 introduce a new automotive generator technology to the African rural village, the fuel cell and show how it could function using biogas: a gas that could be inexpensively produced in the rural areas. Chapter 8 discusses common energy resources of wind, hydro and incident solar radiation (insolation) and how they could be cost-effectively harnessed in data-deficient locations in sub-Saharan Africa. In Chapter 9 a new automotive storage technology, the flywheel, is introduced in the rural context in the form of a possible design specification. Chapters 10 and 11 discuss additional non-automotive contributions, by the author, in system configuration and distribution network design, which together with the automotive technologies provide new possibilities for rural electrification. This includes the use of a new automotive power distribution system, the 42 V PowerNet, described in chapter 12 for rural electrification.

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# 1. Electrification in Rural sub-Saharan Africa:

## A Background and a Way Forward

### 1.1. Background

Electrification, a key ingredient in the delivery of modern life's basics like, health, education, communication and light, remains largely elusive for most African rural communities [1-5]. In fact there's no other region in the world with a lower per capita level of electrification than sub-Saharan Africa. In the East African Community states of Uganda, Kenya and Tanzania the average per capita grid electrification is less than 8% and mainly urban based [6].

Kenya [7, 8] has a population of just over 31 million (2003) and a land mass covering 582, 650 square kilometers (km) of which 13, 400 square km are rivers and lakes. The bulk of the population (75%) are rural people and are concentrated in the medium to high rainfall areas suitable for crop agriculture, which constitute only 20% of the total land mass. In these areas the population densities rise up to highs of 300 inhabitants per square kilometer. This is in apparent contradiction of a generally held view that lack of modern infrastructure in rural sub-Saharan Africa is largely a consequence of scattered and sparsely populated settlements. Despite the observation though, some 95% of the 4 million Kenyan rural households are still without electricity. In addition, Kenya's rural thermal energy needs are largely met by burning wood. The demand for wood outstrips the rate of forest replenishment and the deficit is expected to continue rising. There is therefore a major deforestation problem as well.

"We'll make electricity so cheap only the rich will burn candles," Thomas Edison once declared. He certainly could not have anticipated that one hundred years on, smoky kerosene candles [9], could still be the main sources of household lighting for any community!

Way back in 1973 the government of Kenya created the Rural Electrification Program (REP) [7, 8] with the aim to electrify the whole countryside especially those remote areas that would not automatically attract the power utility company. The aim was mainly to encourage agro-based and small-scale rural enterprises. Unfortunately, the overall

performance of this parastatal enterprise was dismal. After 17 years of its existence REP had electrified only 62,000 households or 2% but with a staggering expenditure of 600 million US dollars which translates to just under \$10,000 per household! In addition, government policy failed to evolve as alternative rural energy conversion technologies emerged over time. For example photovoltaic (PV) technology remained classified the same way as it was at the inception of REP and technically not a recognised means of electrification. It could therefore not qualify as an acceptable option in government sponsored programs. Amid all this the government remained unwilling to relinquish its legal monopoly on power generation and distribution. Consequently rural communities had to fend for themselves and a private sector rural energisation drive sprung up to fill the void. Notable among these was the improved *Jiko* (charcoal stove) for thermal energy needs and solar PV for lighting and infotainment. The latter saw remarkable growth especially during the decade leading up to the end of the millennium. Cumulative sales, particularly for PV solar home systems (SHS), were in excess of 150,000 units by the close of the decade with annual sales rising to approximately 20,000 modules by the year 2001, and anchoring Kenya as the clear world leader (ahead of India and China) in rural PV dissemination. Even then the cumulative household percentage coverage remains dismal and more work needs to be done.

Typically a family simply ties a PV module to their roof and directly wires it to a car battery that they previously owned and charged at petrol stations, which could be as far away as 50 km. From studies conducted in [10-13] the overwhelming majority of installations (over 87%) consisted of a single module. Only 11.6% of homes had two modules and the remaining 1.4% had three. Of these panels, approximately 85% were amorphous silicon type (a-Si) modules of 10 to 14 peak watt (Wp) capacities and the other 15% were crystalline panels ranging in size from 10 to 50 Wp. With regard to balance of system (BOS) components, data indicated that batteries were generally the main sources of consumer dissatisfaction. Moreover, batteries in all the PV installations visited had reportedly been over-sized in comparison to the panel capacities. Apart from the unnecessary surcharge to the consumers such batteries would most likely suffer from sulfation due to chronic under-charge. In addition, consumer loads often seemed to far outstrip power source capacities thus escalating the deep discharge problems. Reliability was low and increased the need for

frequent maintenance and component replacement. All these require manpower and capital, which are the scarcest commodities in rural areas.

On another front, but on a substantially smaller scale, the use of pico hydropower in Kenya sprang up right at the dawn of the new millennium [14-20]. This late development was in part due to the 1997 Kenya Power Act, which for the first time legalised independent power producers. Previously it was illegal to connect two neighbouring households from a privately owned generator, even on a non-commercial basis. The most notable developments in pico hydropower have occurred in the hilly regions of Mount Kenya and South Nyanza provinces. For example between 1999 and 2002 two projects [15, 16] were reportedly carried out through a collaborative effort between the Micro-hydro Center of the Nottingham Trent University of the United Kingdom and their Kenyan rural hosts. Kenya government's recently created Renewable Energy department and a Non-government Organisation (NGO) coordinated the projects. In the Kathamba village of Kirinyaga district, a capacity of 1.1 kW is generated by an induction generator from a tributary of the Mukengeria River and distributed to a neighbourhood of 65 households within a 550-meter radius at 230 V ac. In Thima village a 2.2 kW generator supplies power to 110 households and basically meets their lighting and small radio power requirements. Figure 1.1 illustrates a mini grid map of the pico power distribution network in Kathamba village.

Like elsewhere in Africa, the least exploited renewable resource in East Africa is wind. This has in part been blamed on lack of appropriate know-how and resource assessment data, especially at the micro level [13]. There are, in fact, instances where this problem has resulted in major losses. For example, an estimated 35% of some 150 wind pumps in Tanzania's Singida region are reportedly not operational due to inadequate wind potential; a fact that should have been established before the undertakings. There's however a new wind resource assessment project currently (2003) underway in Tanzania under the sponsorship of the Danish International Development Agency (DANIDA) [21]. In Kenya and Rwanda, grid connected wind pilot projects are in operation. Grid connected ventures however, do not generally benefit rural African communities [6].

On a similarly small scale some countries in West Africa (notably Mali, Ivory Coast and Ghana) as well as in the South (Zambia and Zimbabwe) are growing commercial crops like Jathropa and Sunflower for the extraction of bio-diesel to run internal combustion engines for rural energisation [22-24]. The purchase price and maintenance have however been decried as major setbacks. In addition, a separate Indian study [25] has cited the extensive use (or rather misuse) of agricultural resources (land and manpower) and discouraged the use of bio-diesel technologies in the third world altogether. Such observations are quite important for Africans to take note of as African food production is perennially far below consumption requirements.

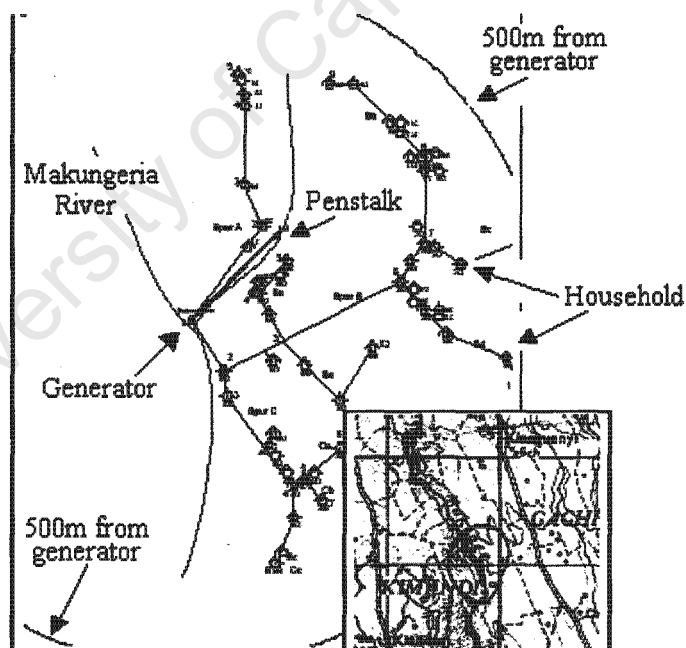


Figure 1.1. A pico-hydro mini-grid in Kathamba village in Kenya

## 1.2. A way forward

The foregoing background mainly characterises the energy situation in rural Kenya, but has very close parallels elsewhere on the continent. Technically it can be argued that free or

inexpensive renewable energy resources are available in most of these rural areas and should hence be harnessed to address the problem. However the means to harness them are capital intensive. Unfortunately these capital costs are pre-determined from abroad where the equipment is manufactured. Given the meager financial resources, attempts to minimise these costs often end up in undersized and/or substandard installations. For example, in a large majority of the cases cited above, the nominal average power supplied per household is of the order of 10 W. This meager effort had the immediate effect of providing clean light, boosting the social esteem of a household and the mitigation of possible respiratory and sight illnesses associated with the previous lighting means. It is however quite evident especially from the Kenyan PV case studies that consumer demands far outstripped their generator capacities. Proposing to solve capital issues with further external borrowing without anticipated growth in rural economic activity couldn't be a viable option, as it would only deepen an already grim African foreign debt burden [26].

A Ugandan proverb; *nyama ntono, okayana eri mu nkwawa*, does however provide the right cue. It is simply about that age-old engineering spirit that a bird-in-hand is always better than two in the bush. Assuming that all one had was the nominal 10 W per household, as depicted above, how could its efficacy be possibly stretched to run more functions? Or, could some innovative energy conversion technology, perhaps enable the harnessing of more power without any increase in generator size? This section examines some technological options in a search for a viable solution.

The 21<sup>st</sup> century has been ushered in by a renaissance of several technologies from past centuries. Among these are fuel cells (FC) and distributed power generation (DG). The reluctance machine built by Davidson as a traction drive for an electric locomotive in 1838, is currently a subject of immense interest [27-34]. In 1912 General Motors rolled out a Cadillac model that had an integral starter-generator (ISG). Today an ISG is "state-of-the-art". In the continuing quest for answers to African rural electrification, it would seem reasonable to take cue and probe back into these same periods for possible clues. The age-old "battle of the currents": a debate about alternating and direct current (ac and dc) is one such example.

In May 1893, the Board of Directors of Cataract Construction Company (in USA), which was charged with administration of the proposed Niagara Falls hydroelectric generating project, approved the adoption of alternating current (ac), in preference to direct current (dc) [35-41]. This decision was soon to have a profound and lasting impact on the rest of the world. For George Westinghouse, the winning contractor, "it was the triumphant end to a brilliant struggle". But was it a genuine technological triumph?

There's no doubt that the discovery of ac and invention of related technologies have had a tremendously positive impact on modern industry and society. However, the adoption of ac was to the near total exclusion of dc from mainstream power delivery. Could this have been an unfortunate historical mistake? If today's technology had been available then, would the same decision have been made? Historians have popularly referred to Thomas Edison as arrogant and stubborn for his alternative view that small dc generating plants, as many as are required, should be built according to local needs.

In fact these issues are being revisited for a number of applications including shipboard power systems. High voltage direct current (HVDC) is already widely used worldwide for bulk transmission over long distances or to interconnect ac systems of different frequencies. Thus dc has always had immense potential, with a wider range of applications emerging with the advances in power electronics. With the relegation of dc out of mainstream power delivery, energy storage technology was denied the massive consumer demand that could have given it the impetus to keep pace with other modern technologies. Consequently, the most popular electric energy storage in rural Africa today, the lead acid battery, is hardly different from Count Alessandro Volta's invention in the 18<sup>th</sup> century [42]!

Turning to more recent events, particularly in the decade leading to the end of the millennium, technological revolutions in automotive energy conservation have been unfolding [43-44]. In September of 1993, a summit between US President Bill Clinton and the CEOs (Chief Executive Officers) of Chrysler (now DaimlerChrysler), General Motors and Ford Motor Company, inaugurated a Partnership for a New Generation of Vehicles (PNGV). The partnership was a collaborative research and development programme between the US government and the United States Council for Automotive Research

(USCAR), represented by the president and the CEOs respectively. The mission statement was short but had far-reaching energy conservation implications: to produce an affordable medium sized family car capable of achieving a fuel economy of up to 80 miles per gallon (33.8 km/liter) but without infringement on safety and environmental regulations. The PNGV identified the systems that required radical re-innovation to obtain appropriately efficient power trains and reduced parasitic losses. Subsequently resources from 19 federal laboratories, universities, automotive parts suppliers, several US federal agencies and departments and USCAR were mobilised. In the meantime similar efforts had begun elsewhere in Europe and Japan and an international collaborative effort followed. In the process, the art of automotive energy conservation was practically reconstructed from first principles. These automotive industry stakeholders considered a worst case, electric loading, scenario in the time frame period 2005 – 2015, and the most suitable electrical architecture and adopted 42 volts as the distribution standard for the next automobile generation [45-53].

On yet another automotive energy conservation front, solid-state lighting (SSL) has been making great strides [54-57] especially since the early 1990's. In the 18 months, leading to the beginning of 2002, the market share of light emitting diodes (LEDs), in the traffic light and signal industry, in North America, increased from 8% to 20%. Energy savings of up to 80% were reported. These LEDs are fast evolving into the white LEDs for general lighting.

### **1.3. How relevant are automotive issues to rural electrification?**

Energisation problems in the rural areas of sub-Saharan Africa are characterised by remoteness of locality and scarcity of resources. Such a location and an automobile share a common sense of isolation: a sense of finite resources without a supporting grid infrastructure. These resources must be economised to meet a requirement while at the same time not compromising the quality of service delivered or degradation of the environment. Before achieving the objective, the limited resources must contend first, with inefficient resource-to-need conversion technologies. Secondly after conversion there are further inefficiencies due to, among others, adverse (consumer) human factors, poor load factors, inefficient appliances and poor storage technologies.

Development of an efficient automotive resource-to-need conversion technology was tackled by a selection of candidate technologies for primary power plants. They included various internal combustion engine types as well as the fuel cell. The latter was of particular interest to this author due to its fuel versatility, which reportedly includes biogas [58-61] a renewable fuel that could be inexpensively produced in African rural villages.

The automotive load factor problem was addressed by the creation of a hybrid electric vehicle (HEV) design. A smaller than usual primary power plant (PPP) is rated at about average load capacity and uses any excess energy to charge a battery. When accelerating or climbing a hill an electric motor, using the battery, assists the PPP, in a hybrid drive mode. The concept of the HEV utilises load levelling and has been used to improve the efficiency of other peripheral automotive applications like vapour compression cycles for air-conditioners [34].

Candidate technologies to tackle the automotive storage problem included flywheel batteries [62], ultra-capacitors, chemical batteries and fuel cells. This author was particularly attracted to the flywheel battery. Unlike other types of accumulators and energy sources like chemical batteries, flywheels reportedly, hold tremendous potential as they have virtually no theoretical limits as to how much energy they can store or how much power they can deliver or receive. They also do not have disposal problems associated with chemical batteries.

The impact of human behaviour has traditionally not been considered as a major issue in automotive energy conservation design. This oversight was clearly evident immediately before the initial launch by Toyota Motor Corporation [63] of their ultra-fuel economy model, the Prius, in North America. It had been realised during pre-launch tests that the original design, which had performed so well in Japan, performed very poorly with American drivers. It then became quite apparent that a correlation existed between the Japanese driving culture and the fuel performance of the car. Consequently the American version had to be redesigned and the launch postponed (for a year) to the summer of 2000. This landmark discovery by the automotive industry has parallels with, and far reaching implications for African rural energisation.

As mentioned, the PNGV committed itself to achieving its objectives within accepted environmental norms. On its part the UN Forum Convention for Climate Change has established ingenious mechanisms like CDM (clean development mechanism). Under Article 12 of its Kyoto Protocol [64-66] the CDM is meant to reward organised development programs in the third world that are designed to save energy and/or protect the environment, in a sustainable manner. Technology and finance can flow from Annex I countries (“the haves”) to qualifying non-Annex I countries (“the have-nots”) and in return these Annex I participants can earn green credits to meet their greenhouse gas emission targets. Thus, adoption of those automotive technologies for African rural electrification should be a win-win venture.

#### **1.4. Contributions of this dissertation**

This work took an extensive examination of the methods, choices and experiences that emerged from the aforementioned PNGV technological search and selection processes. The information needed was obtained from among others, literature studies of, archives, research publications, documented case studies, projection models of future technological developments and participation in various international forums and workshops as well as the author’s anecdotal industrial and rural experiences of over some twenty odd years. The author also benefitted from numerous discussions and e-mail correspondences with a multidisciplinary range of experts from various departments at the University of Cape Town and overseas. Using the above and with the help of mathematical modelling, Matlab simulations and some laboratory experimentation, the author systematically correlated and extrapolated possible applicability of these technologies to a future rural sub-Sahara African environment. Because much of the work deals with technologies in transition, some issues like cost were mainly treated qualitatively, considering the multitude of dynamic factors that would continue to affect them. The author also considered the evidence of the massive resources committed by the stakeholders (especially in the automotive industry) and found reasonable grounds to assume a high likelihood for the success of these technologies in the near future. Additionally, while it may have been indicated, from above, that the most probable power distribution scenario in rural Kenya is from an off-grid source, the arguments raised in this work would be equally valid if the power were supplied from a central (or national) grid. These arguments and results have also been articulated in a

collection of international publications authored and/or co-authored by this author [27-29], [67-69]. The structure of this thesis is described in the following paragraphs.

Taking cue from the aforementioned Toyota Prius launch debacle, chapter 2 discusses at length and identifies a range of analogous human factors that determine how conducive a given rural environment is to development in general and electrification in particular. Among others, it looks at issues of policy, social equity and the environment as well as human relationships.

Chapters 3 and 4 discuss the possible impact of new appliance technologies on rural electrification. In chapter 3 new technologies are proposed for rural lighting. A background on lighting load modelling highlights the anomalies and omissions of traditional approaches to electrical light modelling and why non-electrical illumination technologies should be incorporated to obtain more accurate electrical lighting solutions. The emerging role of solid state lighting and its projected impact on energy conservation are discussed.

Chapter 4 proposes advances in automotive technologies in air conditioning and motor drives as solutions for the critical rural functions of refrigeration and water pumping. First, a background of the state-of-the-art refrigeration technology used in Kenya is given, as well as its shortcomings. Then the chapter goes on to give an overview of the Carnot Cycle, modelling of the vapour compression cycle and the advances made in automotive air-conditioning research. The subsequent sections briefly cover similar advances made in automotive motor drives. Finally examples are given of how rural applications could benefit from the adoption of these automotive developments.

In chapter 5 mathematical and graphical models of critically important rural electrical loads of lighting, water pumping, refrigeration as well as aggregate loads are derived in the transient and steady states. A new method for deriving a mathematical model of an average daily load profile using a Matlab tool is introduced.

Chapters 6 and 7 look at biogas as a viable renewable electrical and thermal energy source for rural energisation and propose its use in an ultra modern automotive PPP, the fuel cell.

Chapter 6 discusses the basics of biogas production by anaerobic decomposition. Then using case studies estimates of the materials required for the production of biogas are derived. Chapter 7 begins with fuel cell basics and relationships. Then in an example of a possible rural application the usefulness of these relationships is demonstrated by a derivation of a specification of a solid oxide fuel cell (SOFC) with a capacity to satisfy a daily load from a South African case study. A graph is finally derived to illustrate quantities of animal and/or crop resources that would be required for the production of adequate quantities of biogas for fuel cell applications to satisfy various sizes of villages.

Chapter 8 deals with the common renewable energy resources of insolation, wind and falling water. Apart from discussing the functional basics of current energy conversion technologies, the main concern of the chapter is the challenge of harnessing the resources in data-deficient remote locations of sub-Saharan Africa. This is especially true for wind and insolation. The availability and function of state-of-the-art weather models for generating synthetic data as well as the use of commercially available design software are illustrated as promising solutions to the challenge. In worked out examples the practical applicability of the methodologies and software are demonstrated.

Chapter 9 discusses the rural energy storage issue and proposes the automotive flywheel battery as a future solution. In the introduction, the shortcomings of the chemical battery technologies that are currently used in Kenya are highlighted. Basics of kinetic energy storage are covered. The two sections that follow cover the function and design equations of a motor/generator using the Halbach magnetic system as well as the role of power conditioning electronics. The usefulness of the electromagnetic design relationships is illustrated by a design specification for a flywheel battery suitable for a rural South African household load (though under near idealised conditions) is derived. The current status, some pending research issues and the projected future of the flywheel battery, are then discussed. Thereafter, conclusions as to the possible future role of the flywheel in rural electrification are drawn.

Chapter 10 analyses the energy efficiency of rural off-grid systems that are typically found in Kenya and using Matlab simulations derives new configuration variants that are more energy efficient.

Chapter 11 proposes a new method for minimising losses in rural mini power distribution networks using idealised network models and a novel thermodynamics concept that was originally meant for maximising heat dissipation into heat sinks.

In chapter 12 the new automotive power distribution standard, the 42-V PowerNet is proposed as the next rural electrification standard for sub-Saharan Africa. Using the traditional 230 V ac as the benchmark and the network analysis methodologies developed in chapters 10 and 11, it is shown that the attributes of the new standard make it a more suitable choice.

## 1.5. References I

1. "The Challenge of Rural Poverty In Developing Countries," World Energy Council and Food and Agricultural Organization, 1999. [http://www.worldenergy.org/wec-geis/publications/reports/rural/exec\\_summary/exec\\_summary.asp](http://www.worldenergy.org/wec-geis/publications/reports/rural/exec_summary/exec_summary.asp)
2. "Energy in Africa," United States Department of Energy. <http://www.eia.doe.gov/emeu/cabs/africa.html>.
3. Karekezi S., "Poverty and Energy in Africa-A brief review," Energy Policy, vol. 30, pp. 915-919, 2002.
4. Karekezi S., Kimani J., "Status of Power reform in Africa: Impact on the poor," Energy Policy, vol. 30, pp. 923-945, 2002.
5. Teferra M., "Power sector reforms in Ethiopia: options for promoting local investments in rural electrification," Energy Policy, vol. 30, pp. 967-975, 2002.
6. Karekezi S., Kimani J., Mutiga A., Amenya S., "Energy services for the poor in Eastern Africa- Sub-Regional "Energy Access" Study of East Africa. Global Network on Energy for Sustainable Development, April 2004.  
<http://www.gnesd.org/Downloadables/Technical%20report%20AFREPREN%20-corr%2014-4.pdf>

7. Agumba M., Osawa B., "Kenya's PV market," The ISES International Solar Energy Society, 2000. <http://roo.undp.org/gef/SolarPV/docs/bgmateral>.
8. Hankins M., "The Kenya Experience," November 2001. <http://roo.undp.org/gef/SolarPV/docs>.
9. Mumford, J. L., "Lung Cancer and indoor air pollution in Xuan Wei, China: Possibly Due to Smoky vs Smokeless Coal Use Indoors," *Science* Vol. 235 pp. 217-220, January 1987.
10. "Field Performance of Amorphous (a-Si) Photovoltaic Systems in Kenya: Methods and Measurements in Support of a Sustainable Commercial Solar Energy Industry," A project of, Energy Alternatives Africa (EAA), Renewable and Appropriate Energy Laboratory (RAEL) and the Energy and Resources Group (ERG), University of California, Berkeley.  
[http://ist-socrates.berkeley.edu/~kammen/ESMAP\\_kenya\\_asiPV.pdf](http://ist-socrates.berkeley.edu/~kammen/ESMAP_kenya_asiPV.pdf)
11. Duke R. D., Jacobson A., Kammen D. M., "Photovoltaic module quality in the Kenyan solar home systems market," *Energy Policy*, Vol., 30, Issue 6, May 2002, pp. 477-499.
12. Nieuwenhout F.D.J., van Dijk A., et al, "Monitoring and Evaluation of Solar Home Systems: Experiences with applications of solar PV for households in developing countries," ECN-C-00-089, September 2000.
13. Karekezi S., "Renewable energy technologies as an option for a low-carbon energy future for developing countries: case examples from Eastern and Southern Africa," AFREPREN/ Foundation for Woodstove Dissemination (FWD), Nairobi, Kenya. <http://www.uccee.org/CopenhagenConf/karekezi.htm>
14. Maher P, Smith NPA, "Pico hydro for village power — a manual for schemes up to 5 kW in hilly areas" Internet-published training document, 2001. <http://eee.ntu.ac.uk/research/microhydro/picosite>.
15. Smith NPA, Maher P, Williams AA. "Strategies for sustainable and cost effective village electrification using Pico hydro power". World Renewable Energy Congress VI. Elsevier Science Ltd.; 2000, pp. 1490–1496.
16. Maher P., "Kirinyaga case studies 1 and 2." January 2002. <http://www.eee.ntu.ac.uk/research/microhydro/picosite/>

17. Kahiga T. "Renewable energy policy in Kenya," Department of Renewable Energy, Ministry of Energy, P.O. Box 30582, Nairobi, Kenya, presented at NTU Coordinated Policy Workshop, Nairobi, September 2001.
18. Gitonga S, Balla P., "Poverty impacts of Pico hydro power schemes in Kenya." Post Installation Socioeconomic Report for European Commission, March 2002.
19. Maher P., Smith N.P.A., Williams A. A., "Assessment of Pico hydro as an option for off-grid electrification in Kenya," *Renewable Energy* 28 (2003) 1357–1369  
<http://www.eee.ntu.ac.uk/research/microhydro/picosite/>
20. "Affecting Electricity Policy through a Community Micro Hydro Project in Kenya," *Global Village Energy Partnership Newsletter*, Issue #59. January 23, 2004
21. "Wind Power Initiatives in Tanzania," Tanzania Traditional Energy Development and Environment Organization (TaTEDO).  
<http://www.gvep.org/content/general/detail/7249>
22. Bielenberg C., "Village Electrification Using Jatropha Curcas Oil," *The Better World Workshop*, RFD 1, Marshfield, Vermont 05658, USA. Published in the *BWW-newsletter* Nr. 5, Summer 1998.
23. Burn N., Coche L., "Multi-functional Platform for Village Power."  
<http://www.ptfm.net/Mali%20Final%20English%201.pdf>
24. "Fuel plant breakthrough," Bio-Diesel SA.  
<http://www.biodieselsa.co.za/fuel%20plant.htm>
25. Rosenblum, J. L., "Feasibility of Biodiesel for Rural Electrification in India," *Carnegie Mellon University*, June 2003. [http://www.thinkcycle.org/tc-filesystem/download/development\\_by\\_design\\_2001](http://www.thinkcycle.org/tc-filesystem/download/development_by_design_2001)
26. Talbot A., "World Bank Report catalogues a social catastrophe in Africa," *WSWS: News & Analysis: Africa*. <http://www.wsws.org/articles/2000/jun2000/afri-j16.shtml>
27. Sebitosi A. B., Pillay P., "Applications of Advances in Automotive Electronics to Rural Electrification: The 42V Power-net for Rural Electrification," *Proceedings of the IEEE PES General Meeting*, 13 – 17 July 2003, Toronto, Ontario, Canada.
28. Sebitosi A. B., Pillay P., "White LEDs for Rural Lighting," *Proceedings of the IEEE PES General Meeting*, 13 – 17 July 2003, Toronto, Ontario, Canada.

29. Sebitosi A. B., Pillay P., "New Technologies for Rural Lighting in Developing Countries: White LEDs" IEEE Transactions on Energy Conversion, (Accepted December 2003 & to be published in 2004).
30. Chiaki Umemura, "Development of Switched Reluctance Motor EV traction vehicle." Society of Automotive Engineers, 2001.
31. Rahman K. M., Fahimi B., Suresh G., Rajarathnam A. V., Ehsami M., "Advantages of switched reluctance motor applications to EV and HEV: design and control issues", IEEE Transactions on industrial applications, Vol. 36, Issue 1, pp. 111 – 121, Jan/Feb 2000.
32. Yasuki Ishikawa, "A Motor drive system that takes into account EV characteristics", Society of Automotive Engineers, 1999.
33. Lawrenson P. J., Stephenson J. M, Blenkinsop P. T., Corda J., Fulton N. N., "Variable speed switched reluctance motors", IEE Proceedings, Vol. 127, pt. B No. 4, July, 1980.
34. Nadamoto H., Kubota A., "Power saving with the use of variable displacement compressors", Society of automotive engineers, 1999.
35. Frank Lewis Dyer and Thomas C. Martin "Edison – his life and inventions" Harper Brothers, 1929. New York
36. Francis E. Leupp "George Westinghouse – his life and achievements." Boston. Little Brown and Company, 1918.
37. McMahon A.M., "The Making of a Profession: A Century of Electrical Engineering in America". New York: IEEE Press, 1984.
38. Derganc C.S., "Thomas Edison and his electric lighting system," IEEE Spectrum, vol. 16, pp. 50-59, Feb. 1979.
39. "Creating the electric age," EPRI Journal., vol. 4, no. 2, March 1979.
40. "The Electric century, 1874-1974," Electrical World, June 1974.
41. "Pearl Street, A Centennial Commemoration," IEEE Power Engineering Society, 1982.
42. "Fascinating facts about Alessandro Volta, inventor of the Electric Battery in 1800".  
<http://www.ideafinder.com/history/inventors/volta.htm>
43. SCIENCE COMMITTEE U.S. HOUSE OF REPRESENTATIVES, "Technology Administration -The Department of Commerce's Current and Planned Global Climate Change Initiatives," Remarks by Gary R. Bachula Acting Under Secretary for

- Technology U.S. Department of Commerce February 12, 1998.  
[http://www.technology.gov/Speeches/p\\_globclim.htm](http://www.technology.gov/Speeches/p_globclim.htm)
44. Review of the research program of the Partnership for a New Generation of Vehicles: Fifth Report (1999). <http://books.nap.edu/books/0309064430/html/R1.html>
  45. Kassakian J. G. et. al. "Automotive Electrical Systems, circa 2005", IEEE Spectrum, Aug. 1998, pp. 22
  46. Miller J. M., Goel D., Kaminski D., Schonert H.P., Jahns T.M., "Making a case for a next generation automotive electrical system." MIT Consortium.  
[http://www.infineon.com/cmc\\_upload/0/000/011/089/Making\\_the\\_Case.pdf](http://www.infineon.com/cmc_upload/0/000/011/089/Making_the_Case.pdf)
  47. Hans-Dieter Hartmann, "Standardization of the 42v PowerNet- history, Current Status, Future Action." SISCAN GmbH, Hanover. <http://www.sci-worx.com>,
  48. Hans-Dieter Hartmann, "Standardization of the 42 V Powernet – Intention, Values," sci-worx GmbH, Hannover, July 2000.  
[http://www.bordnetzforum-42v.de/bordnetz/bn42VpaperStand\\_Intente.pdf](http://www.bordnetzforum-42v.de/bordnetz/bn42VpaperStand_Intente.pdf)
  49. Desroches P., Evans J., Seubert T., "Electrical Architecture Spectrum of 42 V Power Nets", conference proceedings "42V PowerNet – The First Solutions", Villach, Austria, Sept. 1999
  50. Miller J. M., Emadi A., Fahimi B., Ehsai M., "On the suitability of low voltage (42 V) electrical power system for traction applications in the parallel hybrid electric vehicles." Society of automotive engineers, 2000.
  51. Heitner K. L. et al "Advanced Automotive Technologies Energy Storage R&D Programs at the US Department of Energy-Recent Achievements and Current Status." Society of Automotive Engineers, 2000.
  52. Guyonvarch G., Aloup C., Petitjean C., De Mont A., "42 V Air Conditioning Systems for Low Emission, Architecture." Society of automotive engineers, 2001.
  53. Joachim Langenwalter, "42 V Design Process" Society of Automotive Engineers, 2000.
  54. Narendran N. et al. 2000, "Characterizing white LEDs for general illumination applications." Proc. SPIE 3950.
  55. Narendran N et al. 2001a, "What is useful life for white light LEDs?" J. Illum. Eng. Soc. 30(1) 57.

56. Drennen T., Haitz R., Tsao J., "A market diffusion and energy impact model for solid-state lighting. SAND2001 – 2830." Sandia National Laboratories, Agilent Technologies, E20 Communications and Hobar & William Smith Colleges.
57. Arthur D. Little, Inc, "Energy saving potential of solid state lighting in general light applications". US Department of energy.  
[http://www.eere.energy.gov/buildings/documents/pdfs/ssl\\_final\\_report3.pdf](http://www.eere.energy.gov/buildings/documents/pdfs/ssl_final_report3.pdf)
58. Staniforth J., Kendall K., "Biogas Powering a Small Tubular Solid Oxide Fuel Cell," journal of Power Sources, Vol. 71, pp. 275-277, 1998.
59. Siegel R. J., Trocciola J. C., Preston J. L., "Test results for Fuel-Cell Operation on Landfill Gas," Energy, Vol. 22, No. 8, pp. 777-786, 1997.
60. Spiegel R. J., Preston J. L., Trocciola J. C., "Fuel Cell Operation on landfill gas at Penrose Power Station," Energy, Vol. 24, pp. 723-742, 1999.
61. Spiegel R. J., Preston J. L., "Test Results on Fuel Cell Operation on Anaerobic Digester Gas," Journal of Power Sources, Vol. 86, pp. 283-288, 2000.
62. Post R. F., Fowler T. K., Post S. F., "A high efficiency electromechanical battery." Proceedings of the IEEE, Volume 81, No. 3, March 1993.
63. "Behind The Scenes of Prius Launch - An Interview with Toyota's Mark Amstock," EV World, September 29, 1999.  
<http://evworld.com/view.cfm?section=article&storyid=115>
64. "A guide to the Climate Change Convention and its Kyoto Protocol," Climate Change Secretariat. Bonn, 2002. <http://unfccc.int/resource/guideconvkp-p.pdf>
65. Begg K.G., "Initial Evaluation of CDM type projects in Developing Countries," Annex 1 - Projects Selection and Data Collection Centre for Environmental Strategy, Project Coordinator University of Surrey, March 2000.  
<http://www.surrey.ac.uk/CES/ji/index.htm>
66. Begg K., Jepma C., " Procedures for Accounting and Baselines for Projects under Joint Implementation and the Clean Development Mechanism (PROBASE)," Reporting Period: 1<sup>st</sup> January 2001 – 31<sup>st</sup> December 2002.  
<http://www.surrey.ac.uk/CES/ji/probase.htm>
67. Sebitosi A. B., Pillay P., Ramakumar R., "Electrification in sub-Saharan Africa," Proceedings of IEEE PES General Meeting, Denver, Colorado 6 – 12 June 2004.

68. Sebitosi A. B., "How conducive to electrification is the African rural environment?"  
Journal of Energy in Southern Africa, vol. 14, No. 3 August 2003.
69. Sebitosi A. B., Pillay P., "Energy Services in sub-Saharan Africa: How Conducive is the Environment?" Journal of Energy Policy, Elsevier (Accepted March 2004 & to be published 2004, Reference, JEPO 1502 )

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## 2. How Conducive to Electrification is the African Rural Environment?

### 2.1. Introduction

Rural electrification has over the decades been the subject of numerous authors and the theme at countless forums. The grim reality [1, 2] of rural electrification or rather the lack thereof, in the third world and particularly in sub-Saharan Africa, implies that a lasting solution is still elusive. Berne [3] has suggested that the prevalence of chronic problems is largely because their root causes are either never identified or not effectively tackled when identified.

Problems affecting rural development can be characterised by a combination of diverse factors. Joan du Toit [4], for example, has summed up the primary factors influencing household energy conservation as being of a 'technological and behavioural nature'. Obviously this is just an aspect of a bigger picture. In fact each of a whole range of professionals, including economists, social scientists, engineers and religious groups has a perspective. It is reasonable to assume that everyone aims at a modernised healthy society as the ultimate goal. It could further be assumed that these groups of professionals do recognise each other's potential and often combine their inputs to optimise the product. But even then there could still be an omission. Given, for example, that the product is to be utilised by a third party, the consumer, would s/he possibly have had a suggestion to make? Could such a suggestion have made any difference? Is this product the consumer's priority? In the words of Waingart [5], "If renewable energy is the answer, what is the question?"

In fact leading edge corporate management are now pondering these questions. None other than Steve Jones, the chief marketing officer for the world's number one commercial brand, Coca-Cola, has conceded that the 'one-size-fits-all' model, used in the past, in global promotions, has had to finally to give way. "But we are changing to the world of the consumer. Our job is to fit the brand into people's lives." Datson [6] of the Sunday Business Report quoted him.

This chapter will discuss a range of social, economic and political issues that constitute major obstacles to the realisation of sustainable rural development in sub-Saharan Africa. Examples are given of models that were used in history to tackle similar problems elsewhere. It will be shown that many similarities exist between diverse cultures and across generations and many lessons and experiences can be shared.

## **2.2. Policy and partnerships**

In many developing world rural communities, poverty is largely due to failure by society to productively deploy human resources. It is reasonable to assign the major part of people's welfare to their own responsibility. Berne [3] refers to a prevalent discounting mechanism by which people tend to minimise their positive attributes (or those of others). "They maintain a dysfunctional frame of reference that distorts reality." And as Archbishop Tutu has once observed, one is never aware of it. As communities, however, people also look up to leadership for competent guidance and an enabling environment. A rarely recognised fact, by leadership, is that apart from working to survive, most humans derive a purpose to live from meaningful and satisfying activity. In practice, though, rural people are apparently not often regarded as active contributors to development but just liabilities to national budgets. A spirit of partnership or teamwork with expected mutual benefits is not very evident in white papers and forums on poverty alleviation (or eradication) [7-12]. Instead many a government seems to express an intention, willingness or commitment to underwrite this as a "responsibility". In an editorial *The Sunday Independent* [13] once observed, "The African National Congress (ANC) government's short term solution (to poverty) has been to throw money at the problem through a welfare system, which is unsustainable."

Economists generally classify human resources as simply, management, skilled and unskilled [14]. Rural folks are naturally lumped into the latter category. It seems to be accepted that they know nothing: meaning that it is neither possible nor desirable for them to make any contribution. Theologians, Moser et al [15] call this "a 'conservative' aim to integrate the marginalised masses into existing society so that they would come to 'know their place' in it." They propose a contrasting approach with a 'liberative' aim that invites (and encourages) society to participate in a common national challenge.

Consumer participation for sustainable development has been articulated at international forums and in publications [16-18] as being advantageous. In practice however, the concept appears to be generally shunned and even when, occasionally tried, the needs of the consumers are presumed and their roles prescribed. The ambitious African recovery program, the New Partnership for African Development (NEPAD) has been criticised for this very mentality. Among others, a Ugandan academic, Nabudere [19] wrote, "The argument is that NEPAD needs to be grounded in the African people if the process of empowerment is ever to take place." He added, "The leaders have no confidence in the creative and innovative powers of their own people."

The story of the solar PV industry in Kenya [20-22& anecdotal] that has thrived particularly since the beginning of the decade leading up to the end of the millennium, with a few shortcomings notwithstanding, provides a good example of consumer participation.

The Kenyan case makes particularly interesting reading especially when contrasted with Zimbabwe. The two countries had each a modest solar PV industry by the beginning of the 1990's. Just about that time Zimbabwe qualified for a Global Environment Fund (GEF)/World Bank [23] sponsored rural solar PV electrification program. The program was to realise the electrification of 9000 households by the end of a 5-year period and all necessary mechanisms were put in motion.

Meanwhile in Kenya this marked the beginning of more than a decade of World Bank imposed economic sanctions. Financially, the Kenya government was literally on its knees and rural electrification wasn't a likely priority. As a result the rural people had to fend for themselves. By the end of the 5-year period (1997) the Zimbabwe target had been reached and in fact exceeded by 1000 households. However, the majority of the installations and therefore the essence of the GEF project had collapsed [24] along with the reputation of the solar PV industry in Zimbabwe. In contrast the Kenyan solar PV industry had grown to a world record setting pace reaching a figure of 20,000 installations per annum by the year 2001; sustainably and growing! At the risk of sounding cynical one might be tempted to wonder whether the absence of both the World Bank and Kenya government interventions were the enabling conditions that the Kenyans needed to achieve the feat.

'Lessons learnt' is a commonly used slogan at the conclusion of most UN reports. These conclusions often influence replication, modification or total abandonment of a previously used model. In the case of Zimbabwe, however, the World Bank [23] report did not exactly depict the project as the failure it in fact was, despite overwhelming evidence [24, 25]. Consequently, a model along very close lines has been recommended for Uganda. Using the model, Uganda anticipates achieving a mammoth rural electrification coverage target of 10% by the close of the first decade [8]. This is in total disregard of facts from its next door neighbour, Kenya [22], which even after achieving such a high market penetration rate in the sector and with a somewhat more affluent rural population only managed a mere 4% of rural consumer coverage over a similar period.

### **2.3. Social equity and the environment**

In its 1997 report, "Energy After Rio," [26] the United Nations Development Programme (UNDP) laments that, "poverty has received scant attention from an energy perspective". Economics models have perennially cited social equity and environmental issues as beneficial to society but continued to term them as 'intangibles' and resisted assigning them any quantifiable values. It would appear, though, that the denial of basic services to people results in real economic losses. It has in fact been argued that rather than being the consequence of poverty, wide spread deficit of energy services in sub-Saharan Africa may be the cause [27]. Thus the most expensive unit of energy is actually the missed one.

In his contribution to a 1935 US Congress debate on rural electrification, former U S Senator George W. Norris of Nebraska [28], gave an insight into the kind of value one could attach to social equity.

I had seen first-hand the grim drudgery and grind which had been the common lot of eight generations of American farm women. I had seen the tallow candle in my own home, followed by the coal-oil lamp...(See appendix II at the end of this chapter).

Why shouldn't I have been interested in the emancipation of hundreds of thousands of farm-women?

There is however some ray of hope, as the World Bank group [29] has been working and collaborating with countries, academics, researchers, aid agencies and NGOs to build and test various techniques and tools that evaluate these so-called intangible factors. An

additional window of hope is one mentioned in chapter 1 where the United Nations Forum Convention for Climatic Change (UNFCCC) has devised some financial mechanisms to reward countries with well-defined programs that are sensitive to the environment and lead to sustainable growth [30]. Unfortunately the ratification of the Kyoto Protocol is currently (2003) in limbo, mainly, as a result of policy indecision by the United States, the single largest carbon dioxide emitter. Without some kind of concerted effort such words as 'equity' and 'sustainability' along with UN proclamations like, the 'Declaration of the Rights of the Child' and 'Agenda 21' [31-33] will remain consigned to the catalogue of slogans.

#### **2.4. Rural administration and politics**

The quality of local administration has an obvious direct impact on rural development. The current (2003) Kenyan model of rural administration is one case under review. It is a practice, left over from colonial statutes, that seemingly ensures that government appointed local administrators do not originate from their host communities. Consequently their failure could be as a result of their inability to identify with the host community priorities (due the absence of representative forums). Or, as is often politically construed, simply act as central government agents with an agenda to ensure that little or no development goes on in districts considered to be politically hostile to the incumbent regime. In fact, Nabudere [19] has observed that, "many African leaders do everything possible to undermine entrepreneurs!" Impoverishment seems to have been used as a political tool in post-colonial Africa. Thabo Mbeki [34] has lamented this, "abuse of state power to impoverish the people and deny our continent the possibility to achieve sustainable economic development."

It has been suggested that a new Kenyan constitutional draft should seek to create more administrative transparency in the rural areas by proposing elected as opposed to appointed local administrators. But there is evidence already that this may not necessarily provide a panacea. At the root of the problem seems to be a culture of deceptive political rhetoric that often gives the impression of an impending delivery of a "national cake" by the prospective victors. In Kenya the slogan is *matunda ya uhuru* (the fruits of independence). The apparent impression given is that these (fruits) are to be anticipated when 'one of our own' ascends to power. One only needs to look at the numbers and origins of presidential candidates for the 2002 Kenya election [35, 36]. A similar observation was made by BBC's Winter [37] after the

2003 Nigerian election results were announced. "... One explanation for the swing (in voting) from the AD to the PDP in the south-west is that the region felt excluded from national influence - and money - when it was seen as an opposition stronghold."

Consequently, at community level infrastructure and services like electrification are often, erroneously, treated as commodities. In this regard electrification becomes an end rather than a means. In African politics it doubles as the proverbial 'carrot and stick': rewarding politically friendly communities and denied to communities that are perceived to be politically hostile. A delegate at the Science Forum of the 2002 Johannesburg, World Summit for Sustainable Development (WSSD) shared an experience from his native Malaysia. During polling campaigns, politicians reportedly, went as far as delivering electric power poles to villages, apparently as proof of a *fait accompli* but would subsequently recover them after the polling! In apparent retaliation for a previous experience, the villagers would, collect the poles, whenever such a ploy would be repeated, and use them as firewood and building material. Sadly this would include occasions when the intentions to electrify were genuine.

There is also evidence that electrification may not be the only arena vulnerable to political opportunism. In the South African 2004 election campaigns the magic promise of the anti-retroviral drug has been invoked. Apparently implying what would be corrected if his party were elected to power an opposition candidate gave a testimony [38], "the doctors themselves, in an act of heroic desperation, are paying for anti-retroviral drugs from their own pockets". Like African oral literatures, more testimonies are often from oral sources and any inferences may easily be dismissed as conjecture. Quite often these could be the only link to subtle but very destructive reality on the ground since such political actors may not be likely to include their motives in the campaign manifestos.

Such scenarios sharply contrast with the infancy days of rural electrification in the USA, for example, where a cooperative movement for rural electrification sprang up across the country in the 1930's with full Federal Government support and funding through the Rural Electrification Authority, (REA) [39]. Initially established by President Franklin D. Roosevelt's executive order, REA was subsequently enacted by congress through the Rural Electrification Act in 1936. The bill authorised the REA to avail loans to the cooperatives

and encouraged them to actively participate in their own rural network operations. In addition to making funds available, REA provided massive logistical support to rural communities by routinely dispatching personnel to educate consumers about electricity and its uses. They also published (and still do) magazines, like *Rural Lines* and *Rural Electrification News* as well as documentary films. Other consumer services included technical, managerial, legal and accounting matters. They even used to liaise with manufacturers to design equipment that they deemed more suited for rural applications [40].

## **2.5. Researchers, planners and rural communities**

A gap in communication between service implementers and researchers is an issue of concern for a range of fields from software to health [41-44]. Likewise in sub-Saharan rural areas, this issue has been cited as a development barrier due to a perceived sense of aloofness by the largely urban-based researchers about rural issues. For example, one often reads from technical publications such lamentations as [45], “rural communities have failed to fully realise the advantages of electrification!” In a cynical way, this may be likened to seed cast into a field, without regard to the latter’s condition, by a sower who expresses shock when on inspecting the field six months later hardly finds any sign of life. If surely, a good standard of living were to be universally recognised as the purpose for all humankind’s endeavours then focus would be on those developments that have names like health, education, shelter, environment, infotainment and civil order. These would require to be sustained by viable commerce and agriculture, which would in turn require functioning infrastructure that would include electrification among others.

At the project level the choice of an appropriate energy conversion technology is also critical. The most inefficient way to use electricity is by applying it for a purpose that could more efficiently be performed by a different form of energy or fuel. In fact economists [14] refer to opportunity cost, which is defined as ‘the benefit foregone by using a resource for a purpose instead of its best possible alternative. Says Ramakumar, [46]“What is needed is energisation in contrast to conventional electrification.” Therefore the design criteria must be to adopt prudent resource to need conversion technologies that take into account all constraints.

To begin with, the social requirements must be identified. In addition a true energy efficient system should ensure, first and foremost, optimum performance of the process or ultimate function for which the energy is delivered as a unit lost in the final process results in several units wasted from the generator. For example, if it's true that drip irrigation requires only 60% of the water used by regular methods, then the electrical engineer can ill afford to brush this fact aside without due consideration. In general the ultimate function is a social human requirement. Hence the knowledge, character and goodwill of the consumer community are critical to the efficient and sustainable operation of any system.

Apart from a general national policy like the aforementioned REA, there are cases in history where successful rural community development has been preceded by specifically targeted legislation. The Tennessee Valley Authority Act of 1933 [47] (in the USA) is one such example. In this case one would assume that if such a program of action were drafted, specific energy sources and requirements would be assessed and the rest would fall in place. But then, one could ask why, Kenya having enacted no less than five parliamentary bills and actually set up provincial development authorities (DA), which include, Kerio Valley DA, Tana and Athi rivers DA and Lake Basin DA did not replicate the American results.

Apart from the standard factors that included suspected corruption, mismanagement and government interference, the Kenyan DAs were apparently never conceived to develop the communities in their locations. Instead they seem to have simply been mandated to look at ways to exploit the natural resources potential for use only at national level. For example, the Tana and Athi Rivers DA Act [48] says in part, "...for the integral development of several river basins in the Tana River including their hydroelectric potential."

Lamentations by communities displaced by flooding hydroelectric dams but continue to stay in darkness long after the projects are commissioned are fairly common, even worldwide. Barbara Adair [49], a travel journalist, aptly illustrates this when she describes a Malian fisherman on the Niger, as he casts his fish net. "He is doing the work he has done all his life; the work that has been done unchanged for centuries. The hydroelectric plant being built somewhere upstream, to light up three West African states, means nothing to him." Inevitably this approach has historically been a potential source of agony and frustration for

rural communities. It is billed as responsible for Africa's inaugural post-colonial civil war, the Biafran war [50], in Nigeria.

The enlisting of local communities as stakeholders of economic ventures in their neighbourhoods has, in fact, been shown to be not just politically moral but very cost effective. The Kenya Wild Life Services [51], for example, found that the prevalence of game poaching was far less in areas where local councils had a share in the tourism revenue.

## **2.6. Human inertia to change**

The Department of Energy and Mineral Affairs of South Africa funded a social research project, in East London, to investigate reports that after electrification poor households still continued to use previous fuels such as kerosene. In his report, Leslie Bank [52] cites culture as a major determinant in the choices of fuels and consequent lifestyles of the people. The discussion in [52], however, does not suggest much as a way forward. Culture seems to be depicted as an abstract, rigid and unchangeable given state. It is not evident that there was any participatory dialogue with the people or an attempt to compare relative fuel prices. The conclusions derived, for example, that the kerosene was specifically preferred by the wife to 'enhance her power in the household,' sound a little far fetched.

In fact available evidence seems to point elsewhere. For example, while opening the International Domestic Use of Energy Conference 1998, the Vice Chancellor of the Cape Technikon, Dr. Balintulo, remarked, "We all know electricity, but we all know, experience and appreciate it differently. People in the townships have told our Energy Technology Unit, during a country-wide survey, that they perceive electricity to be an unreliable source of energy." Another plausible reason is provided by Courter [52] who, when writing about Aladdin, the kerosene lamp from his native America, laments society's tendency to hold on to its past. "For many it has been the only light of their entire life. Even when the electricity comes, there are a loyal few who profess to use the electric light only 'to find the match' to light their Aladdin!"

Kebede [54] in his analysis of the Ethiopian energy consumption habits points to the anomalies of the so-called energy ladder. While there may be evidence of tendencies towards

use of electric energy for cooking, as family incomes improved, they did not abandon previous fuels like charcoal and kerosene. In fact their affluence seemed to enable them to consume even more charcoal as their overall household energy consumption increased. Adds Kebede, "Firewood/electricity are substitutes, but kerosene/charcoal and charcoal/electricity are complementary pairs," with the prevailing commodity prices determining the ratio of use.

Additionally, certain traditional meals (like *injera*) are preferable when prepared with a traditional stove and this will transcend economic class barriers. This author can also testify to this fact from a personal anecdote in the preparation of a traditional Ugandan banana meal. In South Africa, when one refers to the *braai* (barbecue), charcoal (or firewood) as a fuel is implied, regardless of social status or race of the host. Numerous other examples across continents can be quoted [55, 56]. Lebot [57] in his French experience has lamented that, "considerable energy savings have been identified in the cooking sector but these often involve changes in common cooking practices that may breach current cultural and behavioural norms and hence could encounter consumer resistance." Ironically, many of these households actually acquire the ultra-modern appliances but often end up with higher energy bills. For example, the microwave oven, that was originally meant to replace the traditional electric cooker, is more popular as a defroster for precooked food: food that has already had its energy allotment! This is before one considers the energy required freezing it. So, evidently, these cultural tendencies have no specific ethnic tag and are much more universal than one ordinarily imagines. Clark et al [57], in a paper entitled, "South Africa's Efficient Lighting Initiative (ELI)", have shown that through a well-orchestrated campaign and participatory consumer engagement, consumer culture can indeed be re-moulded.

Finally, from the author's anecdotal experiences, there is an apparent linkage between a community's recent history, their outlook to life and how they subsequently interact with a new technology as illustrated by some brief examples. In Uganda a demoralizing legacy of HIV/AIDS, seemed to have eroded away people's desire for long term outlook and planning. The trend has been apparently reversing lately. Tanzania with a past legacy of *ujama* (socialism) the incentive for individual excellence may have been tampered by a past system that seemed to reward more for political correctness. In Ethiopia there is an uncommon

level of gender balance in technical fields and a strong sense of self-reliance even under a very challenging economic environment, that could be linked to their former Soviet ties.

## **2.7. Concluding remarks**

The benefits of rural development to society cannot be overstated. There are however, detractors who still insist that services like electricity should follow rather than lead economic development. True, it is, that energy is a derived demand of economic activity but this may be precisely what obscures the fact that its absence could actually perpetuate the lack for its demand. Consequently, lack of energy services cannot easily be identified as the cause of poverty that it, most likely, is. Current annual national economic reports in sub-Saharan Africa do not seem to depict the true extent of rural poverty [59]. Unquestionably, energy facilitates all human endeavour. There is therefore urgent need for economics models by which African governments can tangibly quantify, in terms of losses, the continued lack of energy services to rural communities, if this cannot be figured out otherwise.

The solution however cannot be simply, the massive undertaking of rural development programs by governments, while the recipient communities are relegated to observer status or a waiting queue. With all their good intentions, such approaches have repeatedly been shown to maximise on government expenditure with unsustainable results [23, 24] on the ground.

As seen from historical examples of successful rural electrification [39-40], the communities were the primary driving agents. They did not achieve this totally on their own either. Instead, their governments empowered them with the necessary logistical and material support that included finance as well technical, managerial, legal and commercial skills. This approach has an additional sustainability factor since communities' priorities remain the same while those of governments can change over time. Moreover, the entrenchment of democracy and good governance that are so needed for rural development would be enhanced, as the more empowered communities would inevitably be less prone to political manipulation. In the case of investment in rural neighbourhoods the enlisting of local community members (individually or collectively) as partners (stakeholders), even if with a minority stake, has been shown to be both morally right and cost effective.

Drawing from the above however, it is quite apparent that a dilemma may exist between the necessity to productively engage rural human resources as the primary agents of rural modernisation and inherent human nature that seems to resist change. This can be manifested in either the disseminator or the recipient. In the case of the disseminator legislation and guidelines can be put in place. As for the recipient however, a different approach may be more appropriate. In fact well-meaning intentions may on occasion raise ethical questions. Moser et al [15] tackled this issue by coining the term 'conscientization' of society. They however, pointed out that even this would not be without a challenge for, "How does one conscientize society without appearing to impose an ideology?" they posed. This could be in the form of introducing a more efficient agricultural technique to a village. Genetically modified maize is a common example.

It could be argued that in modern society legitimate sovereign governments have mandates as well as responsibility to make some choices for and on behalf of their own people by way of legislation and regulations. But should this justify the common approach that presumes what a community's needs are? In fact Moser et al [15] have advocated for a process of a 'dialogical nature'. It's argued that true education starts from the premise, that peoples and nations are the true agents of their own education. The initiator or proposer must learn to balance his act of influencing while open to learning from the influenced. "This is the consciousness of solidarity that offers an opportunity of providing sustainable political, economic and social changes," they conclude.

## **2.8. Appendix II**

In his contribution to a 1935 US Congress debate on rural electrification, former U S Senator George W. Norris of Nebraska, gave an insight into the kind of value one could attach to social equity.

I had seen first-hand the grim drudgery and grind which had been the common lot of eight generations of American farm women. I had seen the tallow candle in my own home, followed by the coal-oil lamp. I knew what it was to take care of the farm chores by the flickering, undependable light of the lantern in the mud and cold rains of the fall, and the snow and icy winds of winter.

I had seen the cities gradually acquire a night as light as day.

I could close my eyes and recall the innumerable scenes of the harvest and the unending punishing tasks performed by hundreds of thousands of women, growing old prematurely; dying before their time; conscious of the great gap between their lives and the lives of those whom the accident of birth or choice placed in the towns and cities.

Why shouldn't I have been interested in the emancipation of hundreds of thousands of farm-women?

## 2.9. References II

1. "Energy in Africa," United States Department of Energy. <http://www.eia.doe.gov/emeu/cabs/africa.html>
2. Talbot Ann, "World Bank Report catalogues a social catastrophe in Africa," WWSW: News & Analysis: Africa. <http://www.wsws.org/articles/2000/jun2000/afri-j16.shtml>
3. Berne E., "Games People Play - The Psychology of Human Relations," Grove Press, Inc., New York, 1964.
4. Du Toit J., "Energy conservation in the home: some international trends and the situation in South Africa." International Conference on Domestic Use of Electrical Energy, 1998, Cape Town, South Africa.
5. Weingart J., "Enterprise models for rural services: Building a momentum for large-scale use of small scale new and renewable energy systems," Alternative Energy Development, Inc (AED). 2000 –2001 APEC Energy R&D and technology transfer seminar.
6. Datson T., "Coke keeps on getting it right," Business Report, South Africa p6, 10<sup>th</sup> November 2002.
7. ANC (African National Congress). "The Reconstruction and Development Programme: A policy framework". Johannesburg: Umanyano, 1994.
8. The Government of Uganda: "Rural electrification Strategy and Plan covering the period 2001 to 2010". Ministry of Energy and Mineral Development, Feb 2001.
9. DME (Department of Minerals and Energy). White Paper on Energy Policy for South Africa. Pretoria: DME, 1998.
10. "White Paper on Water Policy," Republic of South Africa, 30 April 1997.

11. Habtetsion S., Tsighe Z., (eds), "Energy for Rural Development in Eritrea – Proceedings of a National Policy Seminar." Afrepren Occasional Paper No. 9, 2001
12. Teferra M. (ed), "Energy for Rural Development in Ethiopia – Proceedings of a National Policy Seminar." Afrepren Occasional Paper No. 11, Nairobi, 2001.
13. "There can be no more excuses for failure to deliver," *The Sunday Independent*, pp. 8, 8<sup>th</sup> February 2004.
14. Davis M., Horvei T., "Handbook for the economic analysis of energy projects." Development Bank of Southern Africa, 1995.
15. Moser A., Leers B., "Moral Theology: Dead Ends and Ways Forward," Burns & Oats/Search Press, 1990.
16. Hadi A., "A Participatory Approach to Sanitation: Experience of Bangladesh NGOs," Health Policy Plan, Sep 2000.
17. O'Toole K., Macgarvey A., "Rural women and local economic development in south-west Victoria" *Journal of Rural Studies* vol.19 pp.173–186, 2003.
18. Anderson J. R., "Risk in rural development: challenges for managers and policy makers," *Agricultural Systems* 75 (2003) 161–197.
19. Nabudere D. W., "NEPAD needs a more introspective approach," *The Sunday Independent*, South Africa, pp. 6, October 27, 2002.
20. Karekezi S., "Renewable energy technologies as an option for a low-carbon energy future for developing countries: case examples from Eastern and Southern Africa," AFREPREN/ Foundation for Woodstove Dissemination (FWD), Nairobi, Kenya, Jan 2000. <http://www.uccee.org/CopenhagenConf/karekezi.htm>
21. Duke R. D., Jacobson A., Kammen D. M., "Photovoltaic module quality in the Kenyan solar home systems market," *Energy Policy* 30 (2002) 477–499.
22. Agumba M., Osawa B., "Kenya's PV Market," Solar Energy Network (SOLARNET) - Rose Av., Off Ngong Rd. - P.O Box 76406 Nairobi – Kenya
23. "Zimbabwe Rural Electrification Study," March 2000 Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP).
24. Ndlovu A., "The GEF PV Solar project in Zimbabwe - an appropriate yet ineffective RET dissemination approach?" *Renewable Energy for Development*, April 1998, Vol. 11, No. 1, pp. 4.

25. Mulugetta Y., Nhete T., Jackson T., "Photovoltaics in Zimbabwe: lessons from the GEF Solar project," *Energy Policy* 28 (2000) 1069-1080.
26. "Energy After Rio: Prospects and Challenges," UNDP in collaboration with International Energy Initiative and Energy 21 Stockholm Environment Institute, 1997. <http://www.undp.org/seed/energy/contents.html>
27. Diallo, S., "An African perspective in donor energy policy," *Renewable Energy for Development*, SEI Stockholm, September 1996.
28. "George Norris--champion in the fight for the common man." <http://www.nebraskahistory.org/sites/norris/>
29. "Toolkit for Evaluating the Poverty and Distributional Impact of Economic Policies." World Bank. <http://www.worldbank.org/poverty/psia/tools.htm>
30. "A guide to the Climate Change convention and its Kyoto Protocol," Climate Change Secretariat. Bonn, 2002.
31. "Our Common Future (the Brundtland Report)," World Commission on Environment and Development, Oxford: Oxford University Press, 1987.
32. "Declaration of the Rights of the Child. Proclaimed by General Assembly resolution 1386(XIV) of 20 November 1959." Office of the High Commissioner for Human Rights. <http://www.unhchr.ch/html/menu3/b/25.htm>
33. Report of the United Nations Conference on Environment and Development. Rio de Janeiro, 3-14 June 1992. **A/CONF.151/26 (Vol. I)**
34. "The Renaissance of Africa," Keynote address by Deputy President Thabo Mbeki, 13 August 1998 Gallagher Estate, Johannesburg, South Africa.
35. Mutahi Ngunyi, "Succession and the 'Kikuyu Question'." *Transition Watch*, Sunday Nation, February 10, 2002.  
<http://www.nationaudio.com/elections/opinion/story3.htm>
36. Kenyan Elections: Only the faces change (or do they?)  
<http://www.khilafah.com/home/lographics/category.php?DocumentID=5957&TagID=1>
37. Winter J., "Nigeria's powerful new governors," *BBC News Online*, Abuja 22 April, 2003. <http://news.bbc.co.uk/2/hi/africa/2967881.stm>

38. "The cause of change," Statement issued by Tony Leon, Leader of the Official Opposition. Wednesday, March 24, 2004.  
<http://www.da.org.za/DA/Site/Eng/Speeches/Speech.asp?ID=642>
39. Cooke M. L., "Electrifying the countryside," Survey Graphic, 1935. Survey Associates Inc.
40. [http://www.nreca.org/news/news\\_rel0311\\_10.html](http://www.nreca.org/news/news_rel0311_10.html)
41. Ralph A. O., Lambert III S. H., "Bridging the Communication Gap Between Research Scientist and Facilities Planner" Planning, Design, and Construction [Critical Issues in Facilities Management #7], 1990
42. Silverman D., "Doing Qualitative Research", Sage Publications. London, 2000.
43. Silverman D., "Qualitative research: meanings or practices?" Information Systems Journal 8, pp. 3-20, 1998.
44. King, S., "Case tools and organizational action," Information Systems Journal, 6, 173-194 (1996).
45. Cecil Thom, "Rural Electrification Policy in South Africa, Some Recommendations," International Conference on Domestic Use of Electrical Energy, 1999, Cape Town, South Africa.
46. Ramakumar R., Abouzahr I., Ashenayi K., "A Knowledge-based approach to the Design of Integrated Renewable Energy Systems," IEEE Transactions on Energy Conversion, Vol. 7, No. 4 pp. 648-659, December 1992.
47. The Tennessee Valley Authority. <http://newdeal.feri.org/tva>
48. Kariuki K. K., "Developing a regulatory Framework in a Reforming Power Sub-Sector: The Case Study of Kenya," Africa Power 2000 Conference on 18 April, 2000 in Sandton, South Africa
49. Barbara A., "Magical Mali" Sunday Life pp. 6-8, The Sunday Independent, South Africa, 20 Oct 2002.
50. "The Biafra Civil War, 1967-1970" Vanguard Daily (Lagos), 1 March 2001
51. "Crocodile / Human Conflicts Workshop," Kenya Wildlife Services Training Institute, Naivasha, Kenya, 28-29 June 2001. Crocodile Specialist Group Newsletter vol. 20, no. 3, Jul-Sept 2001, pp. 52-54
52. Bank L., "Basic energy needs and multiple fuel use: Some reflections on energy policy and social theory," Domestic use of energy conference 1999, South Africa.

53. Courter J. W. "Aladdin: The magic name in lamps," Wallace-Homestead Book Co., Des Moines, IA, 1978.
54. Kebede B., "Modern Energy Use and urban Poor in Ethiopia," Africa Energy Research Network, Newsletter No. 34, May 2002.
55. Akinbami J. F.K., Ilori M.O., Oyebisi T.O., Akinwumi I.O., Adeoti O., "Biogas energy use in Nigeria: current status, future prospects and policy implications," *Renewable and Sustainable Energy Reviews* 5 (2001) 97–112.
56. Gaurav Srivastava, "Psychological Resistance to biogas generated from human excreta," Final Paper - 11.479 May 13, 2002.
57. Lebot B., "Energy efficiency for electrical appliances in the building sector: opportunities and benefits," International Conference on Domestic Use of electric Energy 1998, Cape Town South Africa.
58. Clark A., Bredenkamp B., "The efficient lighting initiative: Bringing about a light revolution in South Africa," Domestic use of energy conference 1999, South Africa.
59. Collier P., "The Challenge of Ugandan Reconstruction, 1986-98," World Bank, November 2, 1999.  
<http://www.worldbank.org/research/conflict/papers/uganda.pdf>

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### **3. New Automotive Technologies for Rural Lighting in Sub-Saharan Africa: White LEDs**

#### **3.1 Introduction**

A new trend across Africa that began in the last decade of the millennium led to the systematic unbundling and privatisation of national utilities and parastatal institutions that had, at least in principle, social components to their mandates [1-2]. The new, solely profit-driven, entrepreneurs have moved swiftly to consolidate their operations in the mainly urban enclaves, and put paid to any remote hope for further rural activity. Consequently, it's slowly being realised that off-grid is the way forward for the abandoned rural areas. As these communities transition towards electrification, lighting is often the priority load. For these emerging electric consumers the alternatives are burning reeds and smoky kerosene candles. Apart from the aforementioned respiratory and sight illnesses, these rudimentary means provide poor lumen levels and have environmental implications as well.

Limited generation and storage capacities characterise these upcoming small rural power installations. The resource constraints call for effective demand side management that conserves energy but with minimal compromise on service delivery quality. Globally, electric lighting accounts for some one fifth of all the electric energy consumed, and a similar percentage of electric energy related green house gas (GHG) emissions. Therefore, any efficient electric lighting initiative is a subject of interest for all humankind.

Lighting loads are often inaccurately modelled due to the omission of a number of relevant non-electrical parameters. Illumination as a technology, has made its own advances, independently, that must be included in the ultimate electrical lighting solution [3-7]. High benefit lighting in the work place, for example, optimises sight dependent tasks while minimising the energy used. Illumination experts point out [8, 9] that over-lighting a space or task area degrades the lighting quality in addition to wasting energy.

As already mentioned, solutions for electrification or energy development in the developing world need not follow the same path as for the developed world. Instead relevant technical

solutions for advanced applications in the developed world can be used to leapfrog intermediate technologies and applied directly, with benefit to the developing countries. The Internet for example, has over the past decade been making quite some impressive inroads and changing lives in sub-Saharan Africa. In the field of lighting, recent developments in automotive electronics may yet launch another cutting edge technology into the rural communities. The red light emitting diode (LED) that recently made remarkable gains in the traffic and car tail light markets is fast evolving into the white LED for general lighting and may be applied directly to rural electrification problems.

This chapter examines the lighting issue at depth. Section 3.2 will describe how radiometric power output of a light source (in watts) relates to photometric or light power (in lumens) by incorporating the human eye frequency response. Section 3.3 will discuss lighting load modelling. A range of attributes of a light source will be described. How they contribute to the lighting quality and thus finally impacting on the electric power source will be explained. Using the South African lighting standard, section 3.4 will discuss the requirements of a rural household and compare the performance of a state-of-the-art rural lighting system to the white LED. Section 3.5 will briefly discuss the present and the projected future of technological and commercial issues of the LED. Section 3.6 will give empirical graphical comparisons of transient loading for the white LED, the incandescent and fluorescent lamps. Conclusions will then be drawn on the possible impact of LEDs on rural electrification.

### **3.2 Background: Lighting Load modelling**

When connected across a voltage source, an incandescent light bulb draws a current with a waveform that is a near replica of (and in phase with) the voltage and therefore at a near unity power factor. This is the classic criterion for an ideal electric load yet this, apparently, ideal load is labelled as inefficient: in fact, very inefficient. How is this possible?

Modelling lighting loads is unique as it involves the human eye as the ultimate load determining the required electric power input. Any losses prior to the eye constitute power delivery losses and failure by light to reflect off an intended target and then to the reception of a normal eye constitutes system inefficiency. In figure 3.1, the curve represents the

radiometric output power, in watts, of a tungsten incandescent light source as a function of wavelength. The shaded area represents the visible output of the source, defined as the range from 360 nanometers (nm) to 830nm. This fraction determines the efficacy of the light source. However, the human eye responds differently to different wavelengths (within the visible range) and the light source efficacy is not (literally) the shaded area divided by the total area.

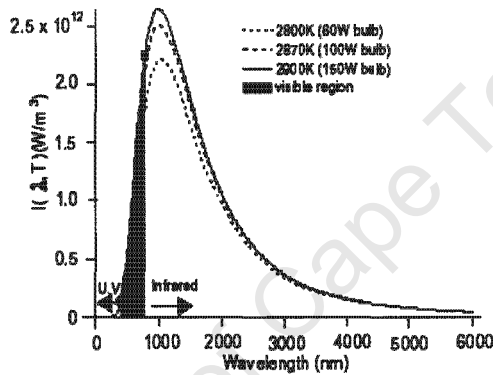


Figure 3.1. Output energy as a function of wavelength for an incandescent tungsten bulb

Figure 3.2 is an empirical curve, drawn by the International Commission on Illumination (CIE), of an average human eye response as a function of wavelength. This is the photopic curve. (The scotopic curve is the response during very low light levels and is not part of this illustration.). As seen on the photopic function, the human eye responds best at 555nm. This point defines the full coefficient, 1, of the eye's response. The unit of light power is the lumen (lm). The eye receives radiometric watts and interprets them in lumens using the response function. For example, 1 watt of (monochromatic) radiometric power at 500nm will be interpreted, in lumens, as 0.3 in value compared to 1 watt at 555nm.

The following is an elementary illustration of a general monochromatic case. The symbols used are not the authentic illumination symbols but merely serve to illustrate a point.

Let  $y_1 = f_1(\lambda)$  watts, represent the radiometric function (due to the light source) in figure 3.1 (where  $\lambda$  is the wavelength)

And  $y_2 = f_2(\lambda)$ , represent the photopic function (of the human eye) in figure 3.2.

Then the light power,  $L_r$ , in lumens, of a monochromatic radiation of wavelength  $\lambda_r$  is given by

$$L_r = K f_1(\lambda_r) f_2(\lambda_r) \text{ lm} \quad (3.1)$$

The constant  $K = 683$  is the watt-lumen conversion constant. A lumen can then be defined as the (visual) power of monochromatic radiation of frequency  $540 \times 10^{12}$  hertz (which is 555nm in air or vacuum) equal to  $683^{-1}$  watt.

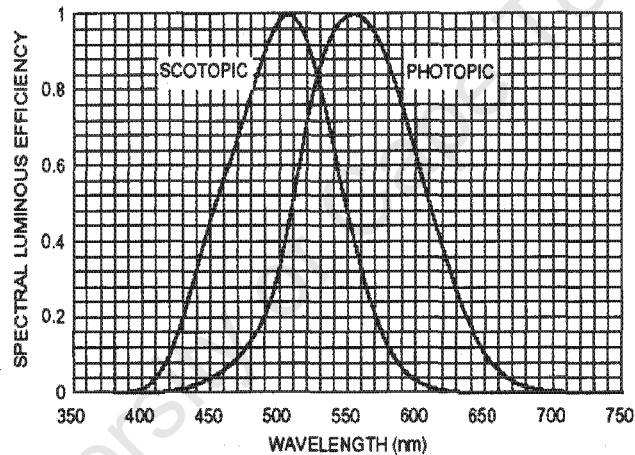


Figure 3.2. The human eye response plotted against wavelength

The conversion of radiometric power of a general non-monochromatic light source to luminous quantity, however, involves many other illumination functions that are beyond the scope of this illustration. Fortunately, light source manufacturers normally indicate the efficacies (in lumen per watt) of their products.

### 3.3 Light source modelling

As mentioned, efficacy is given as the number of lumens of light output of a light source per input watt of electrical power (lm/w). This is, however, just one of the indices of lighting quality. For a more comprehensive light source design one requires more data. Initially, the task for which light is required must be defined and the required amount of light quantified.

As an example one may consider an incandescent light source and a light emitting diode (LED), which currently (2003) have practically the same lumens per watt (efficacy) rating. It would therefore be reasonable to assume that the two light sources would consume the same amount of electric energy to perform the same task. How then could the traffic and signal lights industry report such massive energy savings of up to 80% by just replacing the incandescent lights with LEDs?

In the case of a 'stop' traffic light for example; the required task is the production of red light and only to the view of the car driver. The key words are colour and directivity. True efficiency must therefore be the amount of power successfully converted for the task per unit watt of input of electric power. In order to perform this task the incandescent light must use a reflector and a red filter. A 140 watt incandescent lamp with an efficacy of 15 lumens per watt will produce 2100 lumens. However, after the red filtering and reflecting the amount of red light that is finally available to the driver may be only 200 lumens, which happens to be adequate. A red LED, on the other hand, is a monochromatic device and has directivity with an appropriate angle. It is task specific: requiring neither filter nor reflector. Therefore, a replacement LED assembly for the same traffic light function only requires 200 lumens. Having the same efficacy as the incandescent, the LED ends up consuming only 10% of the power. Moreover the LED has other superior attributes like shock resistance; a problem that causes premature failure in incandescent traffic lights and vehicle taillights.

Light sources have a variety of other attributes in varying degrees as illustrated in appendix III at the end of this chapter. These determine the suitability and therefore efficiency of a light source for a given task. In addition, the colours of the surroundings having unique reflective properties will affect the amount of light required and ultimately impact on the required generation and/or storage capacity in an electrification design. "In some cases enhancement of these influencing factors can improve performance without the need to raise illuminance" [4]

As seen earlier in the case of traffic lights, confining light to a specific purpose does improve on energy efficiency. Philips engineers have also demonstrated the effectiveness of this technique, called 'tasking'. A set of specially constructed LED streetlights performed at par

with sodium lamps despite the overwhelmingly superior efficacy of the sodium (130 lm/W). If the purpose for a light source is reading, it would appear reasonable to infer that energy would be most conserved if the light were confined to a target area, namely the book. Illumination experts, however, caution that this may cause discomfort due to glare [4], if the background is pitch dark. Other symptoms include annoyance and reduced productivity. Some mild ambient lighting, of the order of at least 10%, which would otherwise be inadequate on its own is recommended [8].

Finally there are special circumstances that call for higher lamp lumen levels than would be required ordinarily. These include provision for visually impaired persons, or special age groups of occupants.

### 3.4 Rural lighting requirements

In South Africa, a code of practice [8] gives the minimum lux for a whole range of locations and activities. For example, kitchens are allocated 200 lux, 100 lux for bathrooms and 500 for study and reading. Like other standards, there may be variations from country to country. In the following illustration the specification of the South African Bureau of Standards will be assumed. An incandescent lamp and a white LED for reading are compared below.

If the reading area is  $0.25\text{m}^2$  and the required light density is 500 lumens per square meter, then the lamp should produce  $(500 \times 0.25) = 125$  lumens.

As of 14th April 2002 Lumileds [10] produced LUXEON-5W, a 120 lumen white LED light source with a power consumption of 5 watts. As mentioned earlier, LEDs have directivity and it is reasonable to assume that all the light can be confined to the required area. (More sophisticated issues like glare will be ignored here)

The incandescent lamp will use a reflector (luminaire) to attain the directivity. A good quality luminaire has a coefficient of utilization (CU) of 0.55 [6]. CU is the indication of the proportion of useful light emitted by a luminaire. Therefore in order to create the same effect as the Luxeon-5, the incandescent light must produce  $120/0.55 = 218$  lumens. The efficacy of a typical incandescent lamp is 15 lumens per watt. The wattage of this lamp will

be  $218/15 = 14.5$  watt. Incandescent lamp efficacies rise with filament temperature, which in turn rises with lamp wattage. So in reality a lamp of such low wattage will have an efficacy closer to 10 lumens per watt. This will make its wattage closer to 20 watts and hence will require 4 times the amount of power as the Luxeon-5.

### **3.5 Solid state lighting (SSL): current status and the future**

SSL has taken a foothold and is certain to revolutionise lighting energy consumption. Cynics refer to traditional electrical lighting, as a process of heating of a medium by the application of electricity until it's hot enough to give out some light. A grossly energy-squandering scenario!

In contrast LED technology involves a quantum process to convert dc current to light. Conversion efficiencies nearing 100% have reportedly been achieved in laboratory results with certain materials. Having said that, it should be pointed out that the LED has the same common p-n junction heat dissipating characteristics. In order to realise more brightness the dc forward current must be increased, which in turn increases the p-n junction temperature. Over-rating the temperature can compromise the lifespan of a device. So in order to realise sustainable brighter output, manufacturers are using higher thermally conductive lead frames and higher temperature epoxies in addition to higher efficiency semiconductor materials. The mounting of components on heat sinks further augments these with low thermal resistance. Then there is the issue of light extractability that is still another stumbling block. In fact, it would appear that the materials with the most efficient quantum conversions have the poorer extractability efficiencies. These are part of what research will address and should be awaited for with much anticipation by the African rural communities.

Lifespans of incandescent lamps average about 800 hours. LEDs have superior lifespans to incandescent light sources. However, like other light source types LEDs suffer from lumen depreciation and one ought to exercise caution with hyped brochure figures like 100,000 hours [11-13]. Independent researchers have pegged the 50% lumen depreciation lifespan of a white LED to a more realistic figure of 6000 hours. The 100,000 hours is probably when the LED finally shuts down. This gradual deterioration, once understood, could be factored into scheduled maintenance. Unlike the abrupt failures by incandescent and fluorescent

lamps it would be an added advantage.

White light from an LED is obtainable in several ways. The resulting “whiteness” will vary depending on the method, and material combination used (among other factors). In illumination terminology these various tints are referred to as chromaticity points defined by pairs of x-y coordinates on the CIE 1931 diagram [14]. One method of generating white light is by the convergence of beams (of primary colours) from three monochromatic chips of red, green and blue. This is theoretically the most accurate method (especially with colour rendering) but in practice is still riddled with calibration problems.

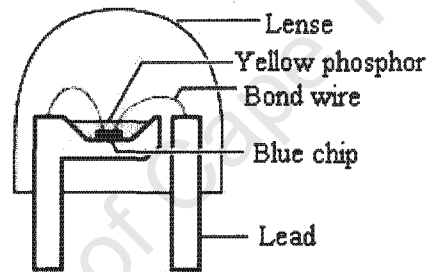


Figure 3.3. The anatomy of a phosphor-based white LED

A second method involves the use of monochromatic ultra violet (UV) light generated by a single chip to excite three phosphors of red, green and blue. The method is particularly discouraged due to a possibility of leaking UV light to the user. The colour (or whiteness) is also said to be angle dependent.

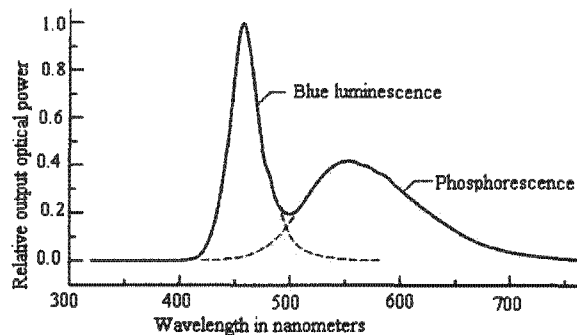


Figure 3.4. A typical emission spectrum for a phosphor based white LED

The third and currently most preferred method, (and credited to [15]) is illustrated in figure 3.3. It involves a monochromatic blue light emitting gallium nitride chip, (GaN), (typically at 265 nm) that is coated with yttrium aluminium garnet (YAG), a yellow fluorescent phosphor. The yellow phosphor is excited by the blue light to produce a broad emission spectrum, in a process somewhat analogous to the fluorescent tube light. Figure 3.4 illustrates a typical emission spectrum of a phosphor based white LED. Conversion efficiencies are dependent on the quality of the phosphor and the composition of YAG can be varied to generate a variety of chromaticity points. The phosphorescence typically peaks at about 555 nm with a CRI of 85 and is hence a reasonable mimic of white light. Additionally, the chromatic performance of a phosphor based white LED will be affected by the drive current and component age.

However in apparent acknowledgement of the transitional nature of the technology, many applications (like automotive lights) have specs that permit some flexibility on chromaticity. A possibility that future colour mixing may be managed externally by waveguiding, optical luminaires using light from several monochromatic chips has been raised in [16].

Historically the LED efficacy has been doubling every 18 to 24 months since the beginning of the 1970's. Such evolution is highly dependent on funding. In July 2001 the US Senate launched, 'the Next Generation lighting Initiative' with an ambitious goal to achieve 25% market penetration by the year 2012.

As of 2003, the commercial white LED had reached an efficacy mark of 25 lm/w. According to Sandia National Laboratories the projected efficacy for the white LED before the end of this decade is 50 lumens per watt, with a possibility of nearing 100 lm/w with accelerated effort [17, 18]. According to the projection model in [17] the accelerated track option is conditional upon adequate funding. Figure 3.5 is a graphical illustration of the model.

On the 25<sup>th</sup> of April 2002 the US Senate passed bill S.517, and committed over 1 billion US dollars per annum for research and development (R&D), for "such areas as next generation lighting technologies." This is cause for optimism. The same forecast projects that at 50

lm/w the per kilo lumen price will still be US \$ 8.30 against the incandescent lamp's current US \$ 0.56. Cost is still a major shortcoming for the LED. If the accelerated track should be followed a price breakthrough of US \$ 0.50 is projected at 120 lm/w of component efficacy.

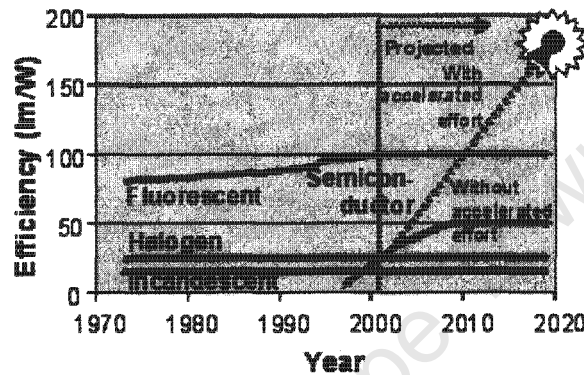


Figure 3.5. A Sandia National Laboratories projection model of the future of general lighting

The aforementioned 6000 hours lifespan however gives an 8:1 advantage of cost over the lifespan of the white LED against the incandescent lamp. It means that for every time one buys an LED lamp one requires to buy at least 8 incandescent lamps to last as long, giving a much better cost effectiveness scenario in favour of the LED. It also means that even at the projected lower end value of 50 lm/w the LED will be far more cost effective to use than the incandescent lamp, while LED power consumption will be less than a third.

It should also be noted that the Sandia model focused on efficacy as the major index for market response. There are other possibilities. The market could, for example, be impressed by other improving attributes like the lifespan or colour rendering index CRI and realise a price breakthrough much earlier.

The time it takes to start a light source can in certain instances be important. Currently, compact fluorescent lights (CFL) are very popular in off-grid systems. There is a time delay to get to full brightness. So the incandescent lamp still ends up standing in for that odd function like closet lighting. The LEDs are not only as fast as the incandescent lights to start but even faster when going off. CFLs have additional shortcomings like disposal.

The directivity attribute has been hitherto highlighted as a major efficiency factor for tasking and signals applications. However, for uniform and homogeneous lighting applications the nature of LEDs being point sources presents a challenge. Moreover manufacturers continually caution against the dangers posed by the high intensity of these sources. Therefore waveguide optics are required. In [16] it is suggested, though, that the very nature of the point sources should in fact make them even easier to convert as compared to traditional intermediate size sources. This should be more so especially with the emergence of inexpensive plastic waveguides.

At the current levels of technology the white LED's advantage over the incandescent lamp would appear to be mainly in task applications, like reading and perhaps the kitchen. But when considering lumen depreciation (also called light loss factor, LLF), the LED scores yet another point. Because the reflectance of the reflector deteriorates as well, the incandescent lamp has two depreciation factors to contend with against the LED's one.

Consider a rural African household comprised of two bedrooms, a kitchen, a bathroom with a toilet and a lounge/dinning at the far end. One may assume over 80% of the full lighting load for the four hours per evening and only incandescent lamps in use. Assuming also, that the room sizes and surrounding wall reflectances are such that the required lux levels can be achieved using the following wattages. A 60W in the kitchen, 40W in each of the bedrooms 25W in the bathroom, 60 W for ambience in the lounge/dinning room and an additional 20 W for the table reading lamp. The total peak load would be 225 W. If compact fluorescent lights (CFL) with average efficacy of 50 l/W were used then the total consumption would be 67.5 W. An incandescent light and a CFL radiate light in all directions.

If white LEDs were used they would have a directivity advantage. Assuming a collective projected LED beam angle from the sealing of  $120^\circ$  then its approximate solid beam angle would be  $2\pi(1 - \cos\frac{\theta}{2}) = 2\pi(1 - \cos 60) = \pi$  steradians [16, 17]. But a sphere is  $4\pi$  steradians. Therefore the white LEDs are only required to supply one quarter of the lighting power. If the efficacy of the WLEDs were 15lm/W their peak power consumption would be  $(225 \div 4) = 56\text{W}$ . But the WLED efficacy is currently (2003) of the order of

25lm/W. Therefore the consumption drops to  $\left[\frac{56}{25} \times 15\right] = 33.6\text{ W}$

If one should consider the same WLED having evolved to efficacy levels of 120 l/W then the peak load would become  $(56 \times \text{incandescent efficacy})/(\text{LED efficacy})$ .

Peak load demand per household =  $(56 \times 15)/120 = 7\text{ W}$ . For a village of 40 similar households the maximum non-coincident electricity demand due to lighting would be 280 W.

### 3.6 Transient Loading

A series of tests were carried out on various lighting loads to establish their transient responses to step input voltages. The response (on and off) of a series string of LEDs (with a current limiting resistor) is illustrated figure 3.6. The load current was 20 mA and measurements were taken using a 100 MHz scope. It would appear from these results that the response of an LED load to a step input voltage is a near replica of the response of an ideal resistor with no traceable transient overshoot. This exerts minimal stress on the power source. This can be contrasted with figures 3.7 and 3.8 for an incandescent and a fluorescent tube light respectively, which have high magnitudes of starting currents.

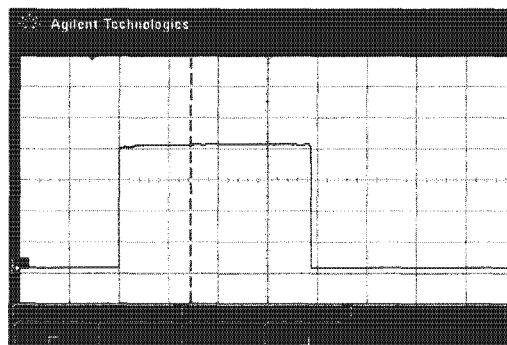


Figure 3.6. A plot of a transient loading of a string of LEDs at 20 mA

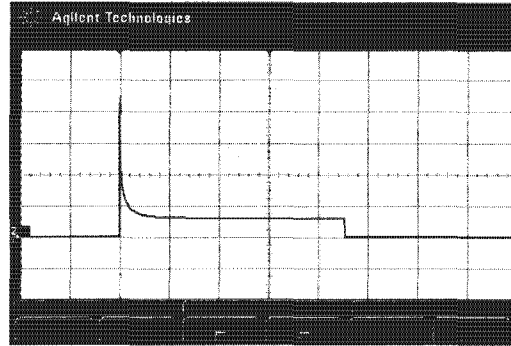


Figure 3.7. The response of an incandescent lamp to a step input voltage

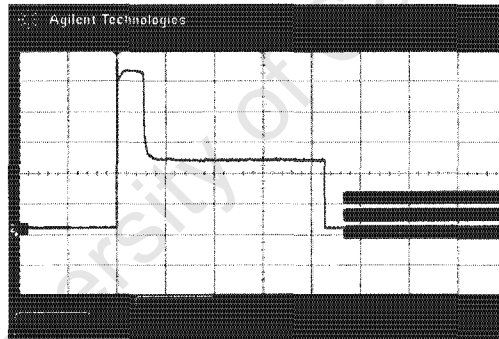


Figure 3.8. The response of a fluorescent tube light to a step input voltage

### 3.7 Concluding Remarks

This chapter has discussed the advantages of advanced illumination technologies in maximising lighting quality while minimising electric power consumption. Using the South African lighting standard, the lumen requirements of a rural household have been enumerated. In addition the performance of a state-of-the-art rural lighting system has been compared to the white LED. Thus the superior energy saving attributes of LEDs have been demonstrated. These would augment the illumination technologies and further cut down on electric power consumption. A discussion of the current and projected status of the white

LED points to ultra high performance with long lifespans at low prices in the near future. Empirical graphical comparisons of transient loading for the white LED, the incandescent and fluorescent lamps have shown further loading advantages of the LED.

The above facts strongly suggest that the white LED has technical and cost advantages over traditional lighting systems even in its present state and should be the light for now and future rural applications. They also vindicate the use of pico power as the viable way forward to the future of power generation.

### 3.8 Appendix III

*Color rendering index* (CRI) is a relative scale from 0 – 100 and determines how colors of an object are perceived under an artificial light as compared to a reference light. The low-pressure sodium lamp, for example, while reputed to have the highest efficacy figures of the order of 130 to 150 lumens/watt, has a CRI of nearly zero. So it can only be said to be efficient for the outdoors and certainly very inefficient indoors, as most colors appear black under this light. The incandescent lamp, on the other hand, has a very high CRI of nearly 100. Or put simply, colors appear most agreeable under light from an incandescent bulb. This could partly explain why even people who are clearly aware of relative lamp performances, and energy benefits and can afford the 'better' types (like CFLs) still keep choosing incandescent lamps. The current white LEDs perform very well with a CRI of 85, which matches the compact fluorescents (CFLs), and they will get better. Besides, CFLs use toxic mercury to function and their disposal is a problem.

*Lumen depreciation* is the reduction in output lumens of a light source with age. The depreciation rate is dependent on lamp type, environment and rate of usage. The life span of a light source is deemed to have ended if the amount of lumens falls below 50% of the initial figure. "In lighting design we must take into account this fall by use of a maintenance factor"[3]. This is one piece of data that is frequently a subject of distortion by manufacturers. The fact that lumens per watt values on the labels are only valid for new lamps is hardly ever mentioned. However, considering this omission as a constant across the board, LEDs have relatively far longer lifespans than any other type.

### 3.9 References III

1. Turkscn, J., "The Electric Utility Industry: Path to Restructuring in Sub-Saharan Africa," UNEP Collaborating Centre on Energy & Environment. Risø National Laboratory, Roskilde, Denmark.
2. Karekezi S., Kimani J., "Status of Power Sector Reform in Africa: Impact on the Poor" African Energy Policy Research Network (AFREPREN), P.O. Box 30979, 00100 Nairobi GPO, Kenya. Energy Policy
3. Lighting Education (1983 – 1989), Publication CIE 99 – 1992. ISBN 3 900 734 36 4
4. Lighting of indoor work places, Publication CIE Standard: S008/E – 2001
5. Maintenance of indoor electric lighting systems, Publication CIE 97 – 1992 ISBN 3 900 734 34 8
6. Discomfort glare in interior lighting, Publication CIE 117 – 1995 ISBN 3 900 734 70 4
7. Proceedings of the first CIE symposium on lighting quality, CIE x015-1998 ISBN 3 900 734 91 7
8. SABS 0114-1:1996. Interior Lighting. (Part 1: Artificial lighting of interiors). South African Bureau of Standards
9. SABS 0114-2:2002. Interior Lighting. (Part 2: Emergency lighting), South African Bureau of Standards.
10. <http://www.lumileds.com/newsandevents/event.cfm>
11. Narendran N. et al., "Characterizing white LEDs for general illumination applications." Proceedings of the International Society of Optical Engineers. SPIE 3950, 2000.
12. Narendran N. et al., "What is useful life for white light LEDs?" Journal of Illumination Engineering Society. Vol.30, No.1 pp.57, 2001
13. Operational considerations for LED lamps and display devices. Application note 1005, Agilent Technologies.
14. Commission Internationale de L'Eclairage. <http://vi12n153.members.eunet.at/cie/>
15. Makia, T., Nakamura S., "White and UV LEDs." Oyo Buturi vol. 68, pt.2, pp.152-155, 1999.
16. Tsao J., "Light Emitting Diodes (LEDs) for General Illumination" (An OIDA Technology Road Map Update) Sandia National Laboratories, 2002.

[http://www.netl.doe.gov/ssl/workshop/Report%20led%20November%202002a\\_1.pdf](http://www.netl.doe.gov/ssl/workshop/Report%20led%20November%202002a_1.pdf)

17. Drennen T., Haitz R., Tsao J., "A market diffusion and energy impact model for solid-state lighting. SAND2001 – 2830." Sandia National Laboratories, Agilent Technologies, E20 Communications and Hobar & William Smith Colleges.
18. Arthur D. Little, Inc, "Energy saving potential of solid state lighting in general light applications". US Department of energy.  
[http://www.eere.energy.gov/buildings/documents/pdfs/ssl\\_final\\_report3.pdf](http://www.eere.energy.gov/buildings/documents/pdfs/ssl_final_report3.pdf)
19. Gibson D., "Candlepower." CREG Journal 26, pp. 27, December 1996.
20. Light emitting diode (IRED) power output specifications. Honeywell application note, pp. 348-349.  
<http://content.honeywell.com/sensing/prodinfo/infrared/application/In1eng.pdf>

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## **4. Other Critical Appliance Technologies**

### **4.1 Introduction**

Apart from lighting, refrigerators and water pumps are also critically important in rural areas. This chapter will highlight how advances in automotive air-conditioning and motor drive technologies could be adapted for rural electrification. Section 4.2 will describe a state-of-the-art refrigerator in Kenya and its shortcomings. Then an overview of the Carnot and vapour compression cycles will be given. It will then be shown how research in automotive air-conditioning has systematically worked on each of the sections of the vapour compression cycle to achieve high efficiency results. The section is concluded by an example of a state-of-the-art rural vaccine storage technology and how it could greatly benefit by adapting the new automotive air-conditioning technologies.

Section 4.3 will provide a background of recent developments in automotive motors and drives. These include the concept of designing motor/drive systems that match the expected load characteristics. Then, in an example of a water delivery system in rural South Africa, the advantages of applying these automotive advances will be demonstrated. Conclusions will then be drawn as to the possible impact of adapting these automotive technologies to rural loads.

### **4.2 Refrigeration**

#### **4.2.1 Background to Refrigeration**

Refrigeration is critical to the delivery of health services as well as for food storage in rural communities [1-2]. This service is required round the clock and hence has quite a significant impact on energy generation and/or storage. The most common refrigerator found in Kenya, has a reciprocating hermetically sealed compressor together with a single-phase induction motor [3]. The motor capacity is typically in the range of 75 to 250 watts. This design is a proven age-old technology and has attributes such as low cost and robustness associated with an induction motor but is riddled with drawbacks.

Firstly, the fixed displacement compressor runs at a single speed and is optimised for maximum loading under the expected worst ambient conditions. It is therefore over-

specified. If the compressor discharge pressure is lower than the desired condenser pressure, the condenser will not be able to condense the gas at higher coolant temperatures. Therefore, exit pressure is set to err on the higher side resulting in energy loss. In order for the refrigeration system to operate at the required capacity the compressor is cyclically switched on and off. During each start-up phase the oil pressure is low and bearing lubrication is not optimal. Repetitions result in frictional losses as well as a reduction of compressor life [4]. Additionally, at start-up more oil leaks into the refrigeration fluid system than during continuous operation, further depriving the bearings of oil as well as compromising refrigeration efficiency [5]. The fluid turbulence that characterises these abrupt full speed starts and stops, is also a major contributor to inefficiency.

This type of compressor cycle is characterised by a widely varying torque during its mechanical cycle. The average versus peak torque ratio can be 1:4 at its worst, and a starting torque of (often) 2 times the rated [2]. Without considering the compressor inefficiencies the induction motor efficiency would only range between 55 – 70%. The refrigeration system uses the traditional ozone depleting CFC refrigerants, which renders the operation of this type of refrigeration system practically obsolete.

In the 1970's the percentage consumption of energy by refrigerators in the USA was estimated at 25%. This prompted high profile efforts to improve refrigeration efficiencies and research has been on-going over the years [6-11]. In France, for example, studies [12] have shown that energy savings of factors up to 3.2 using energy saving refrigeration technology can be achieved. Unfortunately these activities seem to have largely focused on large commercial systems and domestic capacities commonly used in the more affluent households of the developed world. Additionally, being designed to operate exclusively from mains excludes their application for off-grid rural applications.

A turn of events in the 1990's however focussed research on automotive air-conditioning with technologies that could more easily be adapted to African off grid and rural refrigeration requirements. These events included, the 1992 Montreal Protocol [13] (banning ozone depleting substances), the 1993 Partnership for a New Generation Vehicle's (PNGV) [14] and the Kyoto Protocol [15] (on green house gas emissions). In addition, there are other

regional automotive regulations such as the US Federal Test Procedure (FTP) [16] for vehicle emission control. The provisions of the FTP require that tests be done while the air conditioner is running. Each of these standards imposes stringent demands on the automobile air conditioning system. Consequently automotive air-conditioning became one of the most scrutinised technologies. Despite the apparent encumbrances, air conditioning has emerged as a *de facto* standard automotive accessory in the world's largest automobile market, the USA. This development has offered ample opportunity for further development.

In the next generation automobile, the internal combustion engine will be required to shut down at traffic stops or slow traffic instead of idling, as an emission control measure. At this stage the air conditioning load will be at maximum as there will be no supporting air draught and the only energy source will be the battery. H. Nadamoto et al emphasize, "It's important to keep the A/C power as low as possible and at the same time secure its minimum required capacity" [16]. This, unlike any other situation, is a virtual replica of an off-grid refrigeration scenario.

#### 4.2.2 Overview of the Carnot Cycle

The Carnot cycle is perceived as a heat pump with an ideal working fluid [17-21]. The fluid undergoes no phase change and all processes are reversible.

Heat energy is drawn from a high temperature reservoir to a low temperature reservoir using the working fluid as the transport medium. The cycle ends at the low temperature reservoir where the heat is converted to work. It is comprised of four stages in which the following happen.

- First there is an *isothermal* process (without change in temperature) where heat is transferred from a high temperature reservoir (at temperature  $T_a$ ) to the working fluid.
- Secondly the working fluid undergoes an *Isentropic* process (without heat exchange with the surroundings) and its temperature drops to  $T_b$ .
- Thirdly, heat is transferred from the low temperature working fluid to a low temperature reservoir *isothermally*.
- Finally the working fluid undergoes an *Isentropic* process and its temperature rises to  $T_a$ .

Then the cycle resumes.

An ideal refrigeration cycle is based on the reverse of the Carnot engine cycle. Instead, work is put into the system via the compressor's mechanical shaft. An isentropic compression converts this mechanical work into an equivalent amount of heat using the refrigerant as the working fluid. The refrigeration cycle performance is therefore judged against this input work. This is the coefficient of performance (COP), which is the amount of heat removed from a low temperature reservoir divided by the net mechanical input work to the compressor shaft.

#### 4.2.3 Modelling a real refrigeration cycle

The overview in section 4.2.2 enables one to comprehend what would happen under ideal conditions at each stage. In practice, refrigeration systems use the standard vapour compression cycle which at best will perform less efficiently than the aforementioned ideal cycle. The refrigerant at the condenser stage is at high pressure, in saturated liquid form and at temperature  $T_c$ , which varies somewhat from  $T_a$  above. It is then throttled through an expansion valve, into the evaporator, does work as it expands and drops in temperature. At the evaporator it absorbs heat from the load. At this stage it is in saturated vapour form. The saturated vapour then undergoes compression. It gets super heated and condenses into a saturated liquid in the condenser as it rejects heat to the surroundings (air, water or fan draught). The condenser is in the form of a heat radiator. (See figure 4.1).

Looking at each of the cycle stages, the indices of performance for the various components can be tabulated as follows:

- Compressor isentropic efficiency,  $\eta_i$ , considers what percentage of the mechanical work input to the compressor shaft is transferred to the working fluid and what factors are responsible for any losses [22, 23].

$$\eta_i = \frac{\text{IsentropicWorkInput}(w_i)}{\text{ActualWorkInput}(w)}$$

It is shown in [22] that a higher  $\eta_i$  implies a higher COP.

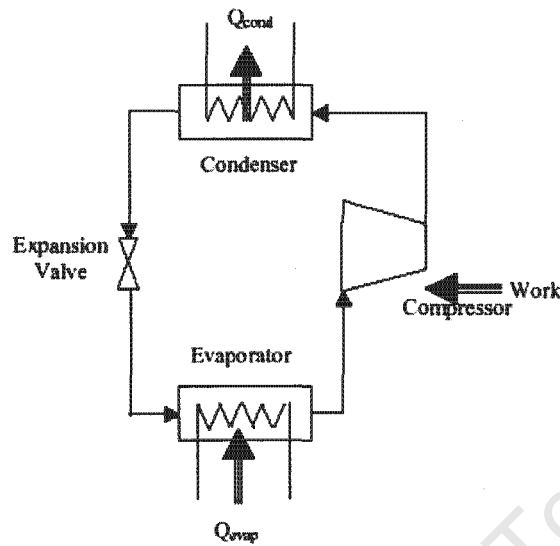


Figure 4.1. A typical vapour compression cycle

- Condenser efficiency considers how efficiently heat is transferred to the surroundings from the condenser: how close the condenser temperature is, to the ambient. This can be enhanced by the use of a blower fan but then its power consumption must also be taken into account [24].
- The effectiveness,  $\epsilon$ , of a heat exchanger is defined as the ratio of the actual heat transfer rate to thermodynamically possible maximum heat transfer rate that can occur in a counter flow heat exchanger of infinite size [22]. It is also dependent on the heat capacity,  $C$ , of the fluids involved in the exchange (which is the product of the fluid mass flow rate and its specific heat capacity).

It can be shown [22] that

$$\epsilon = \frac{C_h(T_{h,i} - T_{h,o})}{C_{\min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{\min}(T_{h,i} - T_{c,i})} \quad (4.1)$$

Where the subscripts  $c$ ,  $h$ ,  $i$ , and  $o$  respectively stand for cold, hot, in and out.  $T$  is temperature and  $C_{\min}$  is the capacity rate of the smaller of the rates of the hot and cold fluids. In this case the hot fluid is the refrigerant and the cold is air.

- Throttle (or expansion device) isentropic efficiency considers how well the throttling process maintains the energy integrity of the fluid. It examines the factors that contribute

to losses like heat radiation to the surroundings and frictional resistance as the fluid moves through the throttle [25] and expands into the evaporator. The device also serves to establish proper temperatures and pressures in both the condenser and evaporator for optimal performance.

- Evaporator efficiency considers how efficiently heat is transferred from the load to the evaporator working fluid [25]. This function is the identical inverse of the condenser stage.
- Load management considers other measures that could be taken to reduce the load to minimal levels [22, 26]. The ambient temperature at the condenser stage, for example, is important [16]. African thatch roofing, for example, is known to create cooler interiors than corrugated iron roofing. A refrigeration system under such an environment would therefore perform more efficiently than under iron roofing.
- Refrigerant efficiency considers efficacies of different refrigerants [28].

The choice of refrigerants, however, has environmental implications as well [5, 29-32]. The automotive industry pioneered the transition from R12, which has been classified as an ozone depleting substance (ODS), to R134a.

As mentioned earlier the refrigeration parameter to be optimised is the coefficient of performance (COP). Since the purpose of the exercise is cooling a load, COP can be defined as the amount of heat removed from the load (in joules) for each input mechanical joule to the compressor shaft in one cycle.

$$\text{COP} = (Q_{\text{Evap}} / W_{\text{in}}) \quad (4.2)$$

(where  $Q_{\text{Evap}}$  is the heat removed from the load and  $W_{\text{in}}$  is total mechanical work input to the compressor)

Looking from the electrical power source, the overall efficiency is the coefficient of system performance (COSP). It is the ratio of heat removed from the load at the evaporator stage ( $Q_{\text{Evap}}$ ) to the total amount of electrical energy consumed by the whole system including extras like fans.

$$\text{COSP} = \frac{Q_{\text{Evap}}}{\text{Total Apparent Power From Electric Source}} \quad (4.3)$$

#### 4.2.4 Advances in automotive air-conditioning systems

Nadamoto et al in [16] have proposed the improvement of the compressor and condenser efficiencies by the use of an externally controlled variable displacement compressor. The compressor would be optimally controlled by the use of software. The driver enabling this approach would be pulse width modulation (PWM) control. A standard car condenser uses a fan and they proposed to optimise its speed by synchronising it with the power requirement of the compressor motor. Given that the load torque for a fan increases as the square of the speed, this technique can realise an appreciable amount of energy saving.

Variable displacement compressors, unlike the common fixed displacement compressors, are designed to run continuously, by varying speeds according to load demand. A number of advantages of this mode have been listed [16, 23]. It is also argued that moderately controlled speed (and hence pressure impact) minimises back leakage and frictional losses, thereby transferring more of the energy to the working fluid and reducing the demand on the compressor. These are factors affecting compressor isentropic efficiency. In his treatment of, '*effect of compressor isentropic effectiveness*,' Bhatti [22] concludes that, "...an increase in compressor isentropic efficiency has a strong influence on the COP. For example, a 10% increase results in a 26% increase in COP."

The authors in [16] reported laboratory trial results showing up to 30% efficiency improvement by variable displacement, software-controlled compressors over standard fixed displacement ones.

Ambient temperatures (or the climate in general) affect the performance of a refrigeration system. Kampf et al [27] proposed a technique of using computer simulations to evaluate the power consumption of an automotive air conditioner under a range of different ambient conditions. They then used load map data from government weather authorities to predict the yearly consumption of a system at certain locations. (Load maps show the relative ambient temperature throughout the year). Then these results are used to predict system performance in other locations with similar climatic conditions. Currently, synthetic global climatic generating software exists [33, 34] that could be used for various sub-Saharan locations that may not normally have databases.

In a comprehensive analytical treatment Delphi Harrison's Bhatti [22] developed a consolidated computer code to predict the automotive air conditioning system performance comprised of the following. At the compressor stage were the volumetric and isentropic efficiencies, displacement rate and rotational speed. At the evaporator stage were, the airflow rate, pressure drop and device effectiveness. At the condenser stage were airflow rate, device effectiveness, pressure drop and lubricant mass fraction at outlet. Finally he included outside temperature and relative humidity and conditioned air temperature. Then using a simulation, he compared standard commercial system performance against a system with functional enhancements that were deemed realistic (or achievable). It included; lubricant containment in the compressor, 17% increase in compressor isentropic efficiency, 10% decrease in compressor pressure drop and a 30% reduction in air pressure drop in the evaporator. The refrigerant in both cases was R-134a. The projected COP increased by 53% under static conditions and by 38% under road conditions (at 50-mph/80 km/h).

#### 4.2.5 Rural refrigeration.

In rural refrigeration the most critical application is vaccine storage. Stringent restrictions are set by the World Health Organisation [35, 36] such that the specifications of ordinary domestic refrigerators are unsuitable. Furthermore the units are almost invariably operated in remote off-grid locations, which eliminates any possibility of using the mains operated commercial units. Consequently, vaccine refrigerators are manufactured in certain quantities by certain manufacturers and using traditional design technologies as the economies of scale do not warrant venturing into modern design options. One of these models uses a solar PV/battery power source and the aforementioned cyclically controlled fixed displacement compressor [36]. The alternative options that will not be considered here, use fuels like kerosene and are much more inefficient as well as being more environmentally unfriendly.

Efficiency advantages of variable against fixed displacement compression refrigeration technologies were highlighted earlier. However the following facts about a commercially available brand of a vaccine refrigerator will help to underscore the point [38].

Among other factors the manufacturer's data sheet points out that the unit only runs for 27% percent of the time at 43°C ambient temperature. This is apparently meant to be a

marketing attraction but is in fact a disadvantage. It implies, among other things, that the actual battery and compressor capacities are  $\frac{1}{27\%} = 3.7$  times what they should have been in a continuously operated system. It would also result in a much more costly unit. This is before one considers all the aforementioned related efficiency encumbrances.

With the emergence of automotive systems and parts, these refrigerators can be modernised as the former are off grid and solar PV compatible while the automotive market will take care of economies of scale. Much smaller and hence less costly batteries and compressors will be required to perform the same function.

Major players in the automotive air conditioning industry include Delphi-Harrison of USA and Denso of Japan. Reference [39] confirms “a new US \$500-million contract to provide a new energy-efficient compressor for auto air conditioners” by Delphi-Harrison. The new-design compressor is expected to be used in two Renault "world cars" sold in 15 countries worldwide. Such reports are characteristically scanty on technical specifics but are very encouraging developments.

### **4.3 Motorised Loads**

#### **4.3.1 Advances in automotive motor drives [40-64]**

Electric motors are required for a variety of domestic and community loads in the rural areas. It is often stated that motors are responsible for 60% of the electric power consumed worldwide. However, this could be misinterpreted to mean that motors are energy end-users. Motors are in fact energy delivery conduits. Consequently disproportionate attention may sometimes be paid to improving motor efficiencies at the expense of the processes they are in fact supposed to deliver this energy to. For example, the US Department of energy (DOE) [40] has verified that pump motors are a much smaller efficiency factor in the whole system than often thought to be. They only affect an order of 10% of overall efficiency in many industrial operations. However for every watt saved at the load, the order of 6 watt are saved at the source.

For the next generation of vehicles the functionality of motors is expected to increase as more functions including traction, steering, braking and air conditioning will be 'by wire' (electrically driven) [41]. In order to produce the appropriate motor sizes and designs the following candidate technologies, the permanent magnet (PM) motor, the induction motor (IM) and the switched reluctance motor (SRM), each with varying attributes, were selected [42-65].

However it is ultimately argued that each driven process is performed optimally under unique conditions. Given that no motor can viably be designed to operate optimally over an entire torque/speed characteristic range, each motor/drive system can be developed to suit unique load conditions. In [61], an ingenious automotive procedure for electric vehicle (EV) design that first investigates consumer driving habits then optimises with a matching motor torque/speed characteristics is illustrated. This way, the motor selected or designed will perform optimally for a given purpose.

The next sub-section will demonstrate how this automotive technique can be deployed to achieve optimum efficiency for water pumping loads in rural applications.

#### 4.3.2 Rural Water delivery

The Department of Water Affairs, in South Africa, has specified 6000 liters of water per month as the basic requirement for a household of 8 people. This means that the necessary and sufficient efficiency criterion is the delivery of  $(6000/30) = 200$  liters per day. If it should be assumed that this water is pumped from an underground well into an overhead storage tank, then the ideal energy required is the product of the weight of the water and the height through which it is lifted.

Using Bernoulli's principle the energy in a frictionless stream is a constant and the head at any point is given by

$$\frac{V_1^2}{2g} + \frac{P_1}{\rho} + Z_1 = \frac{V_2^2}{2g} + \frac{P_2}{\rho} + Z_2 \quad (4.4)$$

Where,

V is the velocity

P is the pressure

Z is the elevation

$\rho$  is the viscosity of the fluid

g is the gravitational acceleration.

In reality the flow is not frictionless and results in a head loss given by

$$\text{Loss} = f \cdot \frac{L}{d} \cdot \frac{V^2}{2g} = K \frac{V^2}{2g} \quad (4.5)$$

Where L is the pipe length, d is the pipe diameter and f is the *Darcy* friction factor. Collectively, these constitute K, the loss coefficient of the plumbing system and are dependent on various impedances. They include (in addition to the pipe dimensions), the friction within the fluid itself, the roughness of the pipe walls, bends, tee junctions, valves, reducers, expanders and joints, among others. But these are all fixed.

Therefore for a given plumbing system, K is a constant and the only independent variable is the velocity. So the lowest pumping velocity will result in minimal losses. In the above example 200 liters must be delivered in 24 hours. The lowest pumping rate is (200/24) liters per hour or  $2.31 \times 10^{-3}$  liters per second, continuously.

This strategy will be desirable for a power source (generator, or battery storage), as it will draw a level load round the clock and the necessary power and hence delivery losses will be minimal. Moreover, a continuous pumping operation mode avoids a multitude of other operational problems associated with intermittent on/off modes of flow control like, water hammer that causes untold damage to system components. (If the generator should be a photovoltaic (PV) source however, then it may be preferable to spread out the load during daytime only.)

In order to optimise the fluid flow process the choice of the pump must be one whose optimum operating point matches the above flow rate. A general choice exists between displacement and centrifugal pumps. In the case of a centrifugal pump, several design

variations can be made to the impeller geometry, impeller wall, suction (single or double), collector (volute or diffuser) among others.

A typical pump nameplate will specify, flow rate, head (meters), rotating speed and power (brake horsepower, BHP). These, however, only refer to a single operating point. A more accurate picture is depicted by the manufacturer's curves (see figure 4.2), which specify the head capacity, brake horsepower and pump efficiency as functions of speed. These parameters vary from design to design.

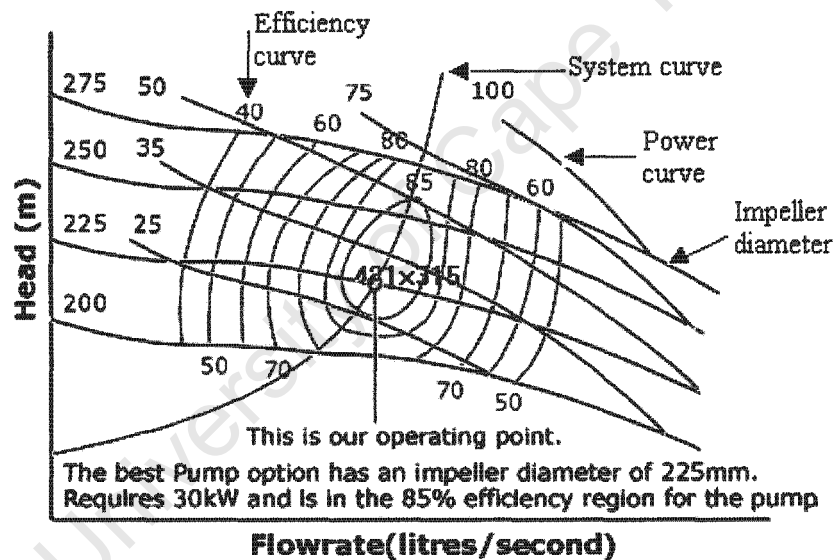


Figure 4.2. An illustration of a typical pump optimisation scenario

From the above, the required pumping rate per household is  $2.31 \times 10^{-3}$  liters per second. If a village were using a common pump and water storage then the total village demand would be worked out from the number of households. From figure 4.2, given that the flow rate and the head are known, the pump size and efficiency can be worked out.

Finally the motor must be chosen or designed to match the already optimised system.

As mentioned earlier traditionally mechanical automotive functions will, in the new generation of vehicles, be driven by wire and hence motorised. The range of motor drive sizes will be from watts

to the order of 50 kW, depending on magnitude of function and capacity of vehicles. The upper end includes military vehicles, some of which are reportedly on trials in the US Army. This therefore promises an ample choice of parts in rural applications.

#### 4.4 Concluding Remarks

Advances in automotive air-conditioning and motorised technologies to conserve energy have been highlighted. Parallels have been drawn between automotive air-conditioning and motor technologies on one hand and the critically important rural functions of refrigeration and water pumping, on the other.

A typical refrigerator in a rural Kenyan community clinic consumes between 300 and 700 watt-hours a day [1]. If the results in [16-23] alone could be translated into the Kenyan rural context, energy savings of at least 30% would be realised. The refrigeration designer in a rural scenario has an added advantage, in that, whereas the automotive designer may desire a larger condenser but lack the space, such a constraint would not exist in the rural context. This would give the rural designer more room for improvement.

From a point of view of an ailing off-grid dc bus (or deeply discharged battery) the variable displacement compressor system would have an added bonus. Most chemical batteries yield more energy when discharged at slower rates. By simply reducing the compressor speed, the power supply stands a better chance of bridging to the next charging opportunity. A fixed displacement compressor on the other hand would have had to be shut down at a much higher battery threshold. The same argument is valid for water pumping and other motorised rural loads.

#### 4.5 References IV

1. Jiminez T., "Stand Alone Power Systems in Rural Healthcare Facilities," National Renewable Energy Laboratories/National Wind Technology Center, November 1999.
2. Pryor P., "Vaccine refrigeration" Murdoch Energy Research Institute, Australia.  
<http://www.acre.murdoch.edu.au/unep/papers/Pryor%20Vacc.pdf>
3. Dincer I., "Refrigeration Systems and Applications," John Wiley & Sons; May, 2003

4. "Modulating Capacity control in the Refrigeration Cycle," Siemens HVAC Products, Landis Staefa Division. <http://www.landistaefa.com>
5. Petitjean C., Guyonvarch G., Benyahia M., Beauvis R., "TEWI analysis for different automotive air conditioning systems." Society of automotive engineers. 2000.
6. 21 – CR Ongoing research. <Http://www.art-21cr.org/research/ongoing/>
7. Arthur D. Little, "Opportunities for savings in the residential and commercial sectors with high efficiency electric motors" DOE contract No. DE-AC01-90CE23821. December 1, 1999.
8. Rice C. K., Fischer S. K., "A comparative analysis of single- and continuous variable-capacity heat pump concepts." Oak Ridge National Laboratory. Proceedings of the DOE/ORNL, Heat pump conference, Dec 11-13, 1984.
9. "Increased efficiency of air conditioners and heat pumps using advanced power electronics" Consultant Report of the California Energy Commission, P600-01-013, November 2001.
10. European Council for an Energy Efficient Economy "Sustainable Energy Opportunities for a Greater Europe." - Proceedings of the 1997 Summer Study
11. Positioning for the future: Strategic planning for the HVACR. Report I – Industry opportunities. Report II – Research recommendations. Dec 18, 2001.
12. Lebot B., "Energy efficiency for electrical appliances in the building sector." International Energy Agency – Organization for Economic Co-operation and Development. <http://www.ctech.ac.za/conf/du/SOURCE/Web/Lebot/Lebot.html>
13. United Nations Environment Programme: Ozone Secretariat [http://www.unep.org/ozone/Treaties and Ratification/2B\\_montreal%20protocol.asp](http://www.unep.org/ozone/Treaties_and_Ratification/2B_montreal%20protocol.asp)
14. "Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report." Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles Washington, D.C. 1999. National Academy of Sciences, 2003. <http://books.nap.edu/catalog/6485.html>
15. "A guide to the Climate Change convention and its Kyoto Protocol," Climate Change Secretariat. Bonn, 2002. <http://unfccc.int/resource/guideconvkp-p.pdf>
16. Nadamoto H., Kubota A., "Power saving with the use of variable displacement compressors", Society of automotive engineers, 1999.

17. Slaby, J.G., "Overview of NASA Lewis Research Center free-piston Stirling engine activities," Proc., Intersoc. Energy Convers. Eng. Conf. ; Vol/Issue: 3; Intersociety energy conversion engineering conference; 19 Aug 1984; San Francisco, CA, USA
18. Beck D, "The Carnot Cycle,"  
<http://wug.physics.uiuc.edu/courses/phys113/summer02/LECTURES/lect09/>
19. Russell L. D., Adebisi G. A., "Classical Thermodynamics," Saunders College Publishing/Harcourt Brace, 1993.
20. Çengel Y. A., Boles M. A., "Thermodynamics – An Engineering Approach – 4<sup>th</sup> Edition," McGraw-Hill Higher Education, 2002.
21. Incropera F. P., DeWitt D. P., "Fundamentals of Heat and Mass Transfer, 5th Edition" John Wiley and Sons (WIE) – 2001
22. Bhatti M. S., "Enhancement of R-134a Automotive air conditioning system" Society of automotive engineers, 1999.
23. Kishibuchi A., Nosaka M., Fukanuma T., "Development of continuous running, externally controllable displacement compressor", Society of automotive engineers, 1999.
24. Pomme V., "Improved automotive a/c using new forced sub-cooling technique," Society of Automotive Engineers, 1999-01-1192.
25. Singh G., Rodarte E., Miller N. R., Hrnjak P., "Noise generation from expansion devices in refrigerant," SAE, 1999-01-0866.
26. Kyu H. Lee, Jong Pil Won, "Thermal design study of high performance evaporator for automotive air conditioning system." Society of Automotive Engineers, 1999-01-1191.
27. Kampf H., Dienhart B., Taxis-Reischl B., "Optimization of Automotive Refrigeration Systems Using Load Maps." SAE 971801.
28. Mahmoud Gohdbane, "An investigation of R152a and hydrocarbon refrigerants in automobile air conditioning," SAE, 1999-01-0874.
29. Global warming impact of automotive air conditioning systems. SAE, 982929.
30. Kelemen K., Singh T., Mayne R., "Modeling of an automotive air conditioning system." Society of automotive engineers, 2000.
31. "Report of the Refrigeration, Air conditioning and Heat pump Technical options," UNEP 1998.

32. "2002 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC)," UNEP 2002, ISBN: 9280722883
33. Worldwide Hourly Climate Generator. Maui Solar Energy Software Corporation: Haiku USA 2000.
34. METEONORM, Global Meteorological Database for Solar Energy and Applied Climatology, Ver. 5.0, Edition 2003. <http://www.meteotest.ch/en/firma>.
35. World Health Organization, "Equipment performance specifications and test procedures." WHO/EPI/LHIS/97.03-14, (1997).
36. World Health Organization, "Product Information Sheets 2000 edition," WHO/V&B/00.13, (2000).
37. ITDG, "Solar Photovoltaic refrigeration of Vaccines" [http://www.itdg.org/html/technical\\_enquiries/docs/solar\\_refrigeration\\_vaccines.pdf](http://www.itdg.org/html/technical_enquiries/docs/solar_refrigeration_vaccines.pdf)
38. Sun Frost Vaccine refrigerators, "RFVB-134a Solar Powered Vaccine Storage Refrigerator Freezer" <http://www.sunfrost.com/vaccine.htm>
39. "Lockport-designed compressor will be manufactured elsewhere" <http://www.lockport-ny.com/Harrison.htm>
40. "Best Industrial Practices" DOE's Office of Industrial technologies. February 2001. <http://www.oit.doe.gov/pdfs/bestpractices.pdf>
41. David Hamilton, "Fiscal Year 2001- Progress Report for Vehicle Power Electronics and Electric machines Program." Office of Advanced Automotive Technologies, U S Department of Energy, December 2001.
42. Hsu J. S., "Electric Machinery Research and Development," ORNL, National Transport Research Center.
43. McKeever J. W., "Hybrid Electric Vehicle Switched Reluctance Machines," ORNL, National Transport Research Center.
44. Gallegos-Lopez G., Walters J., Rajashekara K., "Switched Reluctance machine Control Strategies for Automotive Applications." Society of Automotive Engineers, 2001-01-0955.
45. Vittorelli B., Keil M., Reinmuth K., "High End Automotive Servo Drives." Society of Automotive Engineers, 2000-01-0135.

46. McKeever J. W., "Field Weakening and Magnetic Retention for PM Machines." ORNL, National Transport research Center.
47. Moore S. W., Rahman K. M., Ehsani M., "Effect on Vehicle Performance of Extending the Constant Power Region of Electric Drive Motors." Society of Automotive Engineers, 1999-01-1152.
48. Zhao Z. M., Meng S., Chan C. C., Lo E. W. C., "A Novel Induction Machine Design Suitable for Inverter-Driven variable Speed Systems," IEEE Transactions on Energy Conversion, Vol. 15, No. 4, December 2000.
49. McKeever J. W., "HEV Motor Inverter Modeling," ORNL, National Transport Research Center.
50. Hsu J. S., "A Machine Approach for Field Weakening of Permanent-Magnet Motors," Society of Automotive Engineers, 2000-01-1549.
51. Hsu J. S., "Direct Control of air-Gap Flux in Permanent-Magnet machines," IEEE Transactions on Energy Conversion, Vol.15, No.4, December 2000.
52. Chang-Chou Hwang, Wu S. S., Jiang Y. H., "Novel Approach to the Solution of Temperature Distribution in the Stator of an Induction Motor," IEEE Transactions on Energy Conversion, Vol. 15, No. 4, December 2000.
53. Otaduy P. J., McKeever J. W., "Model-based Generation of Scaling Laws for Radial-Gap Permanent Magnet Motors.
54. Potgieter C., Hope W., Gregory E., "Magnetic Bearing Controls for a High speed, High Power Switched Reluctance Machine (SRM) Starter/Generator," Society of Automotive Engineers, 2000-01-3665.
55. Daugherty R. H., Wennerstrom C. U., "Need for industry standards for AC induction motors intended for use with adjustable-frequency controllers," IEEE Transactions on Industry Applications, vol. 27, pp. 1175 – 1185, Nov/Dec. 1991.
56. Nee N. P., Sadarangani C., "The influence load and rotor slot on harmonic losses of inverter fed induction motors," Proceedings of IEE Electrical Machines and Drives Conference, Sept. 1993, pp. 173 – 178.
57. Akiyama Y. et al., "A study of the most suitable design of inverter-driven induction motors," PCIM, pp. 38 – 44, June 1994.

58. Chen S., Yen S. N., "Optimal efficiency analysis of induction motors fed by variable-voltage and variable frequency source," IEEE Transaction on Energy Conversion, vol. 7, pp. 537 – 543, Sept. 1992.
59. Pillay P., Cai W., "An investigation into the vibration of switched reluctance motors," IAS Conference, St. Louis, 1998.
60. Dawson G. E., Eastham A. R., Mizia J., "Switched reluctance Motor torque Characteristics: Finite Element Analysis and Test Results," IEEE transactions on Industry applications, vol. IA-23, No. 3, May/June 1987.
61. Rahman Z., Ehsani M., Butler K. L., "An Investigation of Electric motor Drive Characteristics for EV and HEV Propulsion Systems" Society for Automotive Engineers, 2000-01-3062.
62. Emadi A., Fahimi B., Ehsani M., Miller J., "On Suitability of Low-Voltage (42V) Electrical Power System for Traction Appliances in the Parallel Hybrid Electric Vehicles," Society of Automotive Engineers, 2000-01-1558.
63. Rahman K. M., Fahimi B., Suresh G et al, "Advantages of Switched Reluctance Motor Applications to EV and HEV: design and control Issues," IEEE Transactions on Industry Applications, Vol. 36, No.1, January/February 2000.
64. Miller T. J. E., "Switched reluctance motors and their control", Magna Physics Publishing Division, Jan. 1993
65. Lawrenson P. J., Stephenson J. M., Blenkinsop P. T., Corda J., Fulton N. N., "Variable speed switched reluctance motors", IEE Proceedings, Vol. 127, pt. B No. 4, July, 1980.

## 5. Modelling of Critical Loads in Rural Electrification

### 5.1 Introduction

The primary objective of an energy delivery design is to obtain optimum sizes and ratings of generation and storage devices to meet the required loads in a reliable cost-effective manner. One of the conditions necessary to achieve this is to accurately characterise the system load. Apart from defining the acceptable voltage range for the powered equipment, it is important to determine the actual load demand (amps or watts) of each appliance in steady and transient states. For converter driven loads, the effect of the converter on source current characteristic and efficiency must be considered. In the case of mini-grid connected loads, the aggregate load effect of the collective loading must then be considered. Secondly, one must determine the daily load profile. (For example, a refrigerator may require a constant power for a full 24-hour period while a lighting system may only require a constant load for 5 hours at night.) Thirdly, there may be load variations from day to day as well as from season to season.

In order to achieve the above, load models are used [1-21]. In this chapter the loading characteristics of selected appliances for the critical rural loads of lighting, refrigeration and water pumping, as well as a 24-hour residential aggregate rural electric load profile will be modelled. Initially, empirical data will be used to plot graphs of the real load characteristics in the transient and steady states. Matching algebraic expressions for these profiles will then be derived to represent the typical load models and then matched against the real data in graphic form. Finally, a new method for modelling a load profile by joining partial model algebraic functions created in Matlab will be devised and illustrated. Conclusions will then be drawn as to the usefulness of the load models.

### 5.2 Load Models of Critical Loads

#### 5.2.1 Modelling of an incandescent light load

When measured, both the load currents for an incandescent light bulb and a water pump exhibited high starting currents that decay exponentially to their steady state values. Figure 5.1 is a typical characteristic of such a curve. The points marked  $Y_1$  and  $Y_2$  represent the

starting and operating appliance load currents respectively. The curve can be described by the following general expression.

$$I(t) = (Y_1 - Y_2) \text{Exp}\left(\frac{-t}{\tau}\right) + Y_2 \quad (5.1)$$

where  $\tau$  is the decay time constant of the curve.

From equation (5.1) when  $t = \tau$ ,

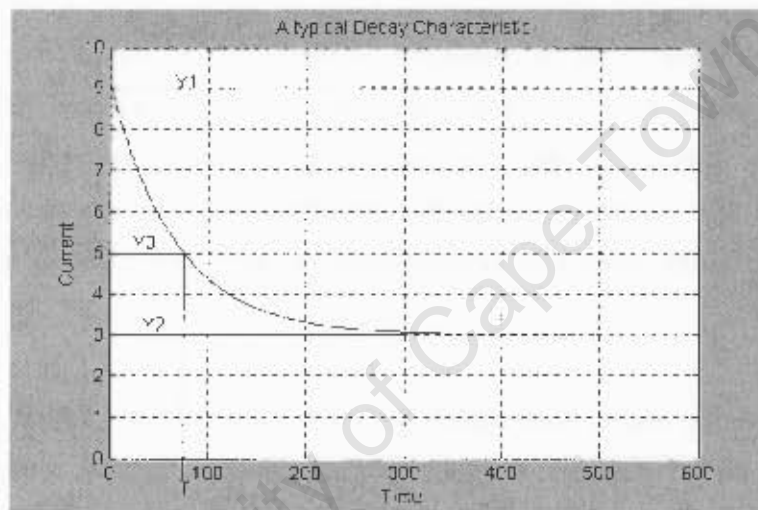


Figure 5.1. A typical decay curve

then

$$I(t) = I(\tau) = e^{-1}(Y_1 - Y_2) + Y_2 = 0.37(Y_1 - Y_2) + Y_2 \quad (5.2)$$

In practice it is often convenient to approximate  $\exp(-1)$  to  $1/3$ . By establishing the point where  $I(t) = I(\tau)$ , a horizontal line can be produced from this point until it intercepts the characteristic curve. When a vertical line drawn from the point of intersection crosses the x-axis it marks the time constant,  $\tau$ . In figure 5.1,  $I(\tau)$  and  $\tau$  are marked as  $Y_3$  and  $T$  respectively.

In physical electrical terms equation (5.1) can be modelled using a resistive/capacitive network as shown in figure 5.2.

The current  $I(t)$  flowing in figure 5.2 is given by the following expression.

$$I(t) = \left( \frac{V}{R_1} - \frac{V}{R_1 + R_2} \right) \exp\left(\frac{-t}{\tau}\right) + \frac{V}{R_1 + R_2} \quad (5.3)$$

where  $\tau$  is equal to the product of the capacitance and the parallel combination of both resistors.

$$\tau = \frac{R_1 R_2 C}{R_1 + R_2} \quad (5.4)$$

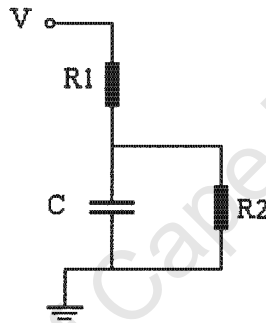


Figure 5.2. An RC model for equation (5.1)

The values of the resistors can be worked out using an empirical curve of the appliance load current.

When  $t=0$

$$I(t) = \frac{V}{R_1} \quad (5.5)$$

And as  $t$  tends to infinite

$$I(t) = \frac{V}{R_1 + R_2} \quad (5.6)$$

which is the rated current.

From equations (5.4), (5.5) and (5.6) the value of  $C$  (the capacitor) can also be calculated.

Alternatively, one can use Simulink functions as illustrated in figure 5.3. The result of the Simulink model in figure 5.3 is shown in figure 5.4.

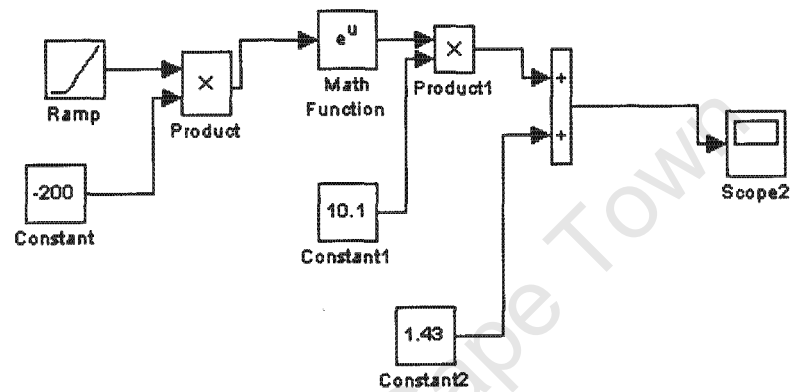


Figure 5.3. A Simulink model to simulate a load current with an exponential transient

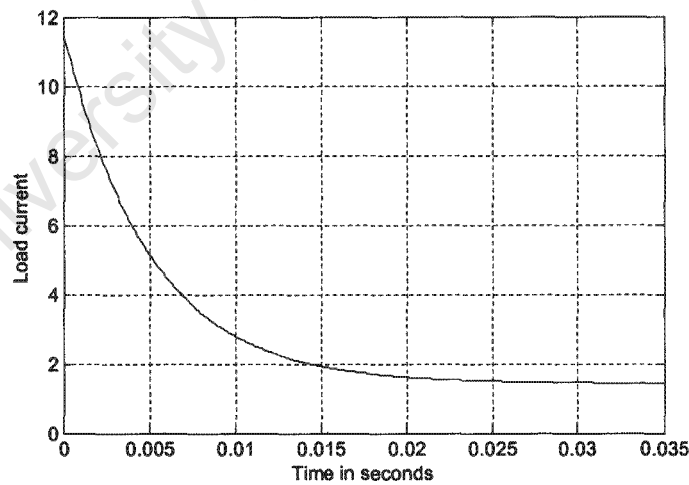


Figure 5.4. Plot from the Simulink model in figure 5.3

The measured time constant  $\tau$ , for the incandescent light source was 5ms, while the ratio of starting to the steady state load currents was 8 (figure 5.5). If the rating of the bulb was 60W at a supply voltage of 42V, the rated current  $I_2$  would be  $(60 \div 42) = 1.43\text{A}$  and the peak starting current = 11.44A. Therefore the light bulb current as a function of time is given by

$I(t)$  such that  $I(t) = 10.1\exp(-200t) + 1.43$ . Figures 5.5 and 5.6 represent the empirical and simulated results, respectively.

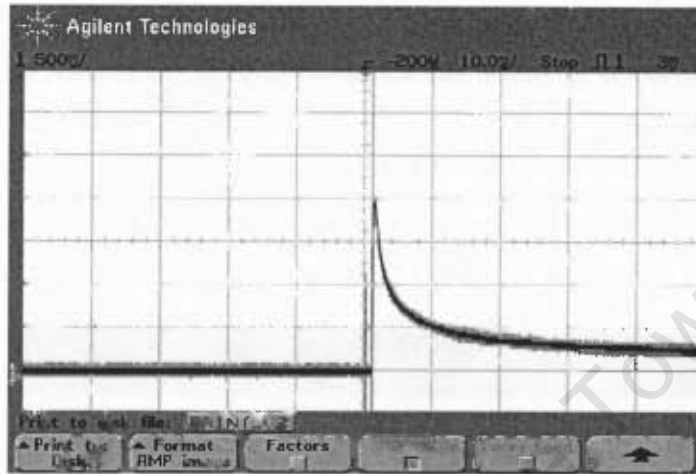


Figure 5.5. The empirical current characteristic for an incandescent light bulb

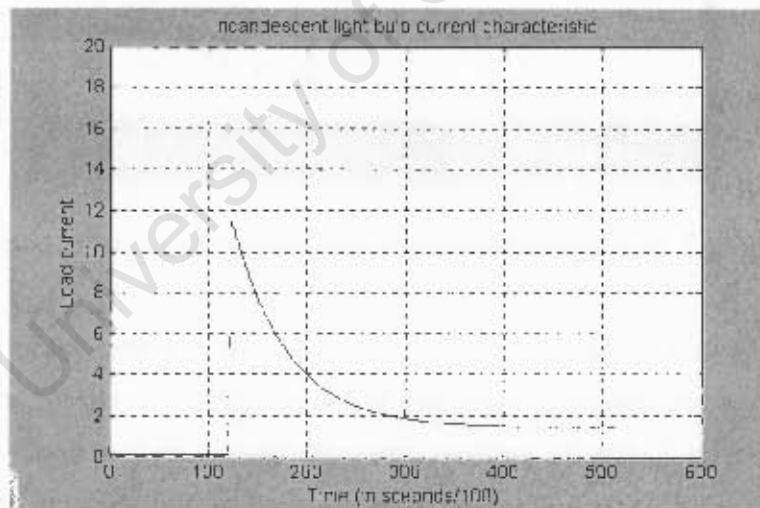


Figure 5.6. A Simulink/Matlab plot of the incandescent light bulb current

### 5.2.2 Water pump load model

The measured time constant,  $\tau$  for the water pump was 600 milli-seconds and the ratio of starting to the steady state current  $\frac{I_1}{I_2} = \frac{2.8}{1.8} = 1.56$ . If the pump power rating is 250W and

operating at 42V, then the rated current  $I_2 = 5.95\text{A}$ . The starting current is therefore  $(1.56 \times 5.95 = 9.26\text{A})$ .

Therefore the current,  $I(t)$ , drawn by this pump from a 42V supply is given by

$$I(t) = 3.31 \exp(-1.67t) + 5.95$$

Figures 5.7 and 5.8 show the empirical and simulated plots of the current characteristics of the water pump respectively.

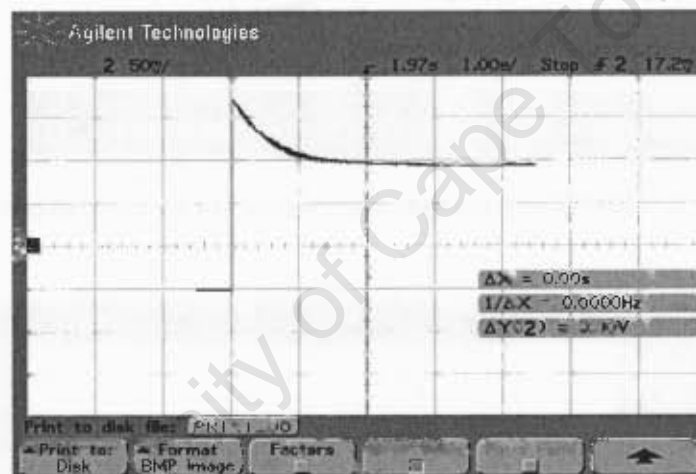


Figure 5.7. An empirical plot of a current drawn by a dc water pump.

Other lighting appliances tested were a series string of light emitting diodes (LEDs) and a camping dc fluorescent light tube. Their load current characteristics are shown in figures 5.9 and 5.10, respectively. Unlike the previous exponential decays, these are step functions. The size of the step for the LEDs is equal to their set running current, which in this case was set to 20mA. Electrically they can be modelled out of pure resistive components. The fluorescent current is comprised of a high starting step and a lower steady state step. The empirical ratio of the peak to operating current is 2.2. The starting current lasts for 250ms and then suddenly drops to the normal running current.

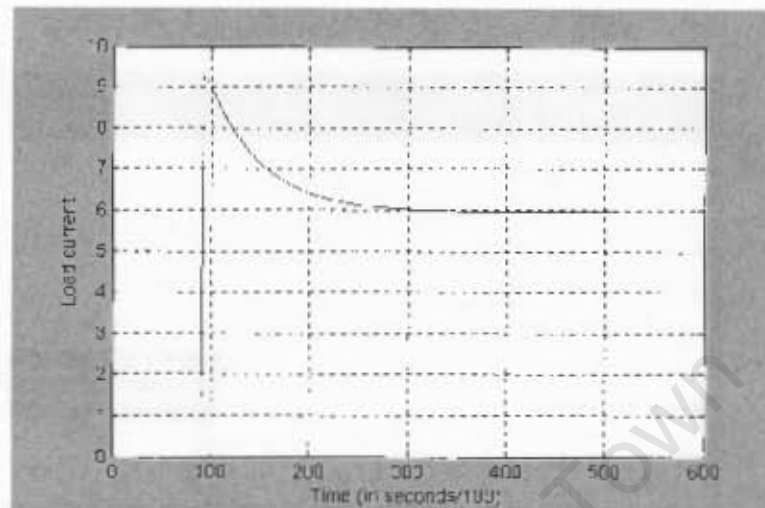


Figure 5.8. A Simulink/Matlab plot of the pump current using the function  $I(t)$

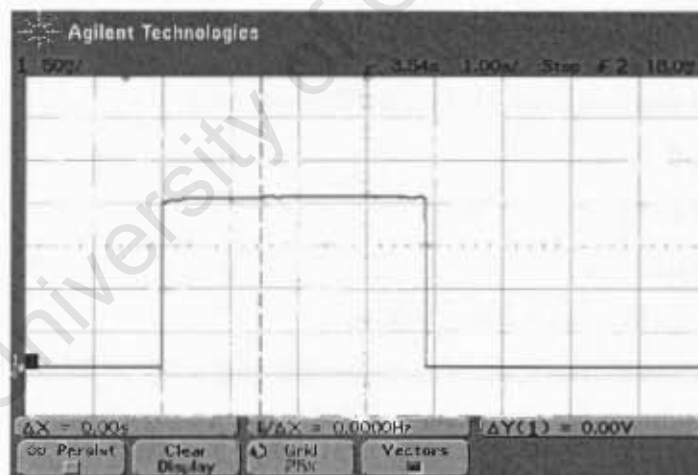


Figure 5.9. A characteristic plot of a 20mA load driven through a string of light emitting diodes when switched on and then off

If the rated power of the tube is 20W and operating at a voltage of 12V, then the rated current  $I_2 = (20 \div 12) = 0.476A$ . Therefore, the peak starting current is  $2.2 \times 0.476 = 1.05A$ .

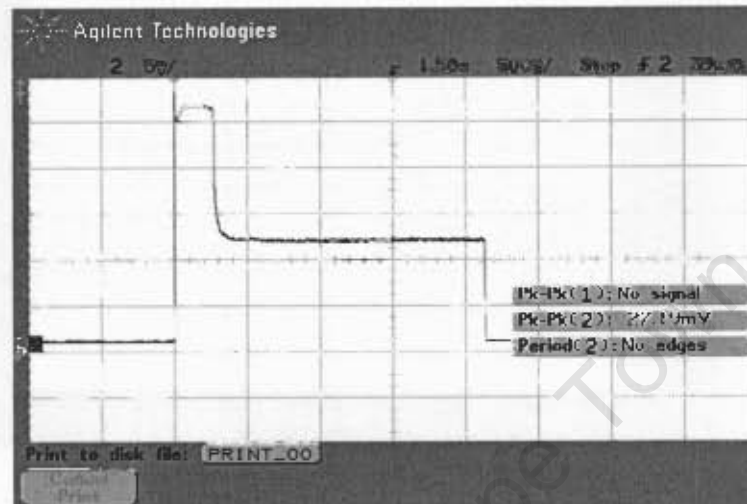


Figure 5.10. The characteristic current of a dc fluorescent light tube.

In order to model the current in figure 5.10, one must recognize the characteristic as a summation of two step functions  $AU(t)$  and  $BU(t)$  such that

$$AU(t) = \begin{cases} 0 & \text{for } t \leq 0 \\ 1.05 & \text{for } t > 0 \end{cases}$$

$$BU(t) = \begin{cases} 0 & \text{for } t \leq 0.25 \\ -(1.05 - 0.476) = -0.574 & \text{for } t > 0.25 \end{cases}$$

The complete current characteristic is therefore the sum  $AU(t) + BU(t)$ . Figure 5.11 is the simulink result of this model.

### 5.2.3 Compressor pump model

Figure 5.12 is the dc current drawn by an inverter when driving an induction motor driven compressor. The dark lines mark the effective dc current supplied by the dc source. As can be seen, the characteristic plot is of the same type as for the fluorescent light. It can therefore be modelled using two step functions as explained for the fluorescent light.

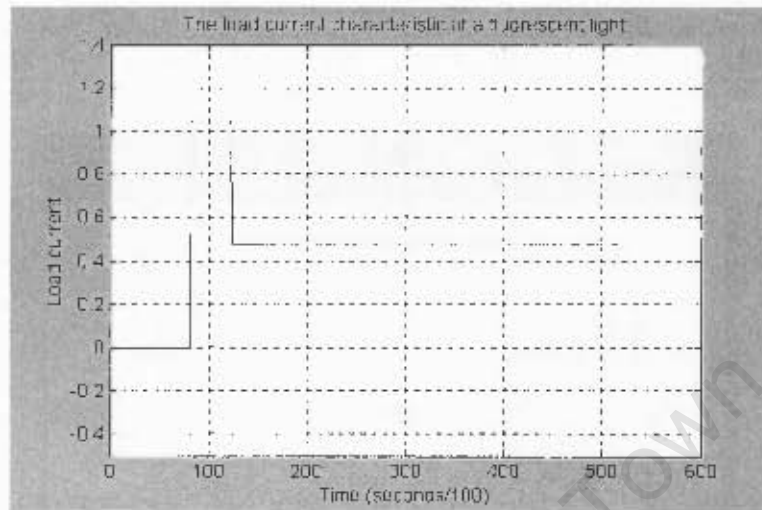


Figure 5.11. A simulink plot of a fluorescent light load current

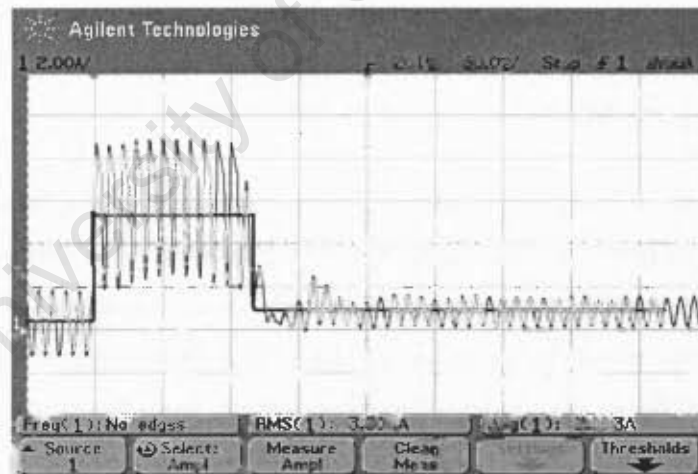


Figure 5.12. The dc current drawn by an inverter when driving an induction motor compressor

Induction motor driven compressors are the most common type used in refrigerators in Kenya. From the dark lines drawn, the ratio of the starting current to the running current is 17 : 2. The starting current lasts for 120 milliseconds. Figure 5.13, which was the actual ac

current drawn by the induction motor from the inverter, confirms the time measurement from the initial 6 cycles of the 50Hz ac current.

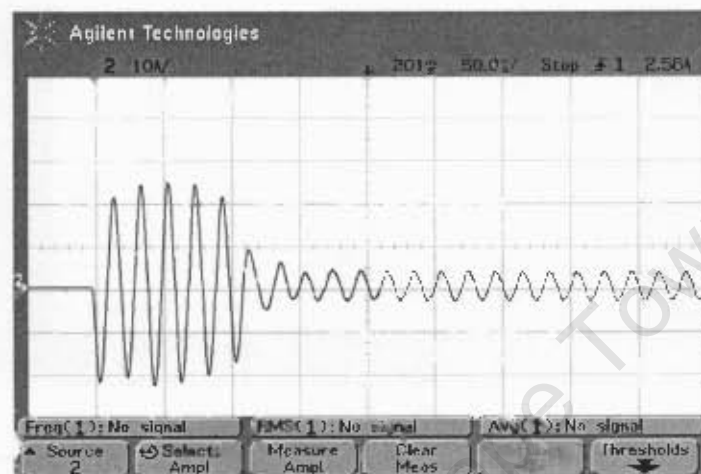


Figure 5.13. AC current drawn from an inverter by an induction motor driving a compressor

### 5.3 Aggregate Models

Figures 5.14 and 5.15 represent samples from a database of the South African National Rationalised Specifications (NRS) Load Research Project of a one-month study. The electric consumption by a rural community of 41 households in Garagapola was monitored round the clock for one month, between the 30<sup>th</sup> June 2002 and 1<sup>st</sup> August 2002. Figure 5.14 is a 24-hour load profile of a random individual household (from among these households) on a random day and figure 5.15 is the aggregate 24 hour load profile for the 41 household community on the same day.

The peak load for the individual household for the day was 7.85A, with an average of 0.66A and hence a load factor of 8.4%. The total energy consumed by the household was therefore  $(24 \times 0.66) = 15.84$  Ah. During the same day the community's peak load demand was 70.76A, with an average of 29.09A and a load factor of 41%. Their collective electric energy demand was therefore 698.16Ah.

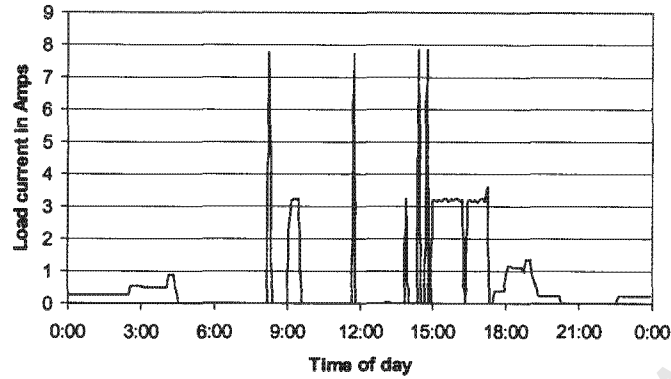


Figure 5.14. A 24-hour load profile recorded by ESKOM for a household in Garagapola village, South Africa

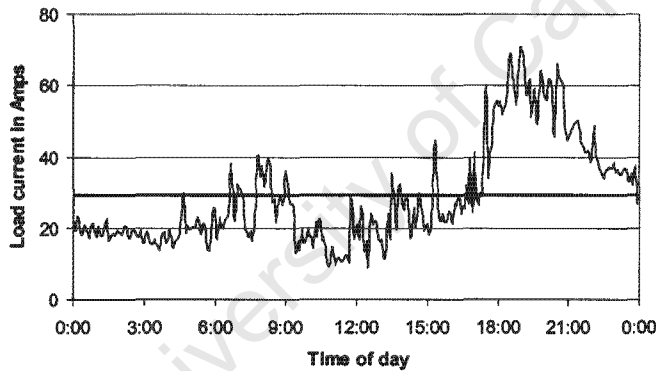


Figure 5.15. A typical 24-hour load profile for a group of 40 low income households in Garagapola village in South Africa

Let it be assumed that this was an off-grid community and that each household had a battery from which the required power was to be drawn on an autonomous day. The required battery capacity for this household for the (24-hour) duration would have been 15.84 Ah (at 230 V) = 3643 Wh with a peak load capability of 8A. The collective energy requirement for the community (during the same period) would be 698.16Ah or 160576.8Wh (at 230 V), with a peak load of about 75A. These figures would however be exclusive of power delivery losses as well as battery losses.

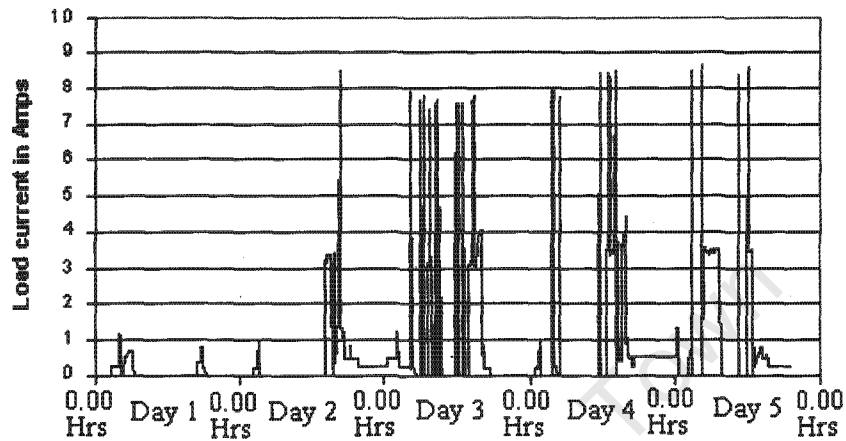


Figure 5.16. Load activity for an individual household over a period of 5 consecutive days

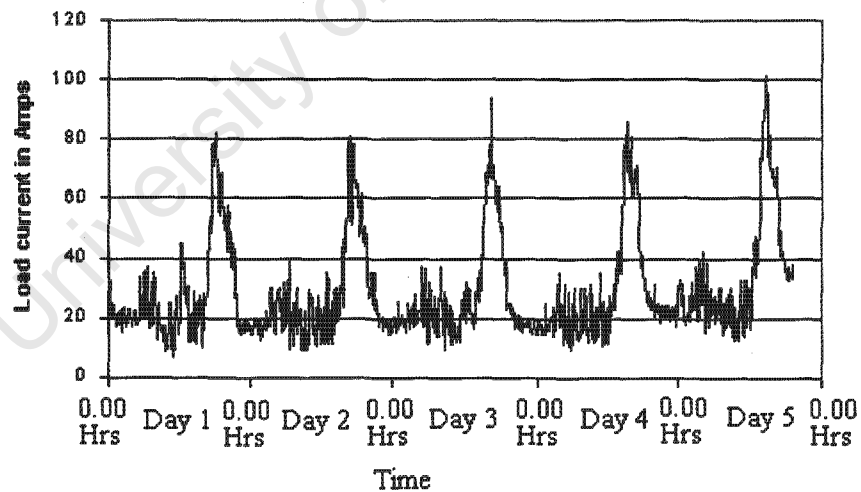


Figure 5.17. Load activity for a group of 41 households over a period of 5 consecutive days

Figures 5.16 and 5.17 are five-day load profiles for the aforementioned individual household and collective 41 household community respectively. The former appears quite unpredictable and would be quite problematic to model. In contrast, the collective profile of the village in figure 5.17 is fairly predictable. The plot in figure 5.18 is the average daily load

profile derived by summing up and averaging the profiles in figure 5.17. For convenience, this figure will be assumed to represent a typical daily load profile and will form the basis for the modelling of the daily load and hence the required storage. The various attempts that were made to characterise the above load profile are illustrated by the following models.

**Model 1:** The following description characterises the approximate dynamics of the aggregate load in figure 5.18. First there is a constant base load. Let  $B_b(t)$  be the constant base load. As household occupants wake up in the morning there is an increase in power consumption, which occurs between about 6.00 hours and 9.00 hours. It was assumed that this could be modelled as a normal distribution function, peaking above the base load at some 'mean' point in time,  $\mu$ . Let  $M_p(t)$  be this additional load demand profile referred to as morning demand. Thereafter, the load profile appears to resort back to the aforementioned base load until late afternoon when evening activity begins to pick up (again). This was also assumed to be approximately characterised by a similar but much bigger normal distribution function. From figure 8.18 this increase appears to span from about 15.00 hours to midnight (0.00 hours). Let  $E_p(t)$  be the additional load demand function referred to as evening peak demand. Therefore, the proposed overall daily load demand profile model  $L_{DL}$  can be described such that

$$L_{DL} = B_b(t) + M_p(t) + E_p(t)$$

$B_b(t) = 20 \text{ Amps}$  for all  $t$  and each of  $M_p(t)$  for  $6.00 \text{ hrs} \leq t \leq 9.00 \text{ hrs}$  and  $E_p(t)$  for  $15.00 \text{ hrs} \leq t \leq 0.00 \text{ hours}$ , can be described by a normal distribution function (for the defined duration).

$$M_p(t) = \frac{\exp\left(\frac{-(t - \mu)^2}{2\sigma^2}\right)}{\sigma\sqrt{2\pi}}$$

where  $\sigma$  is the standard deviation

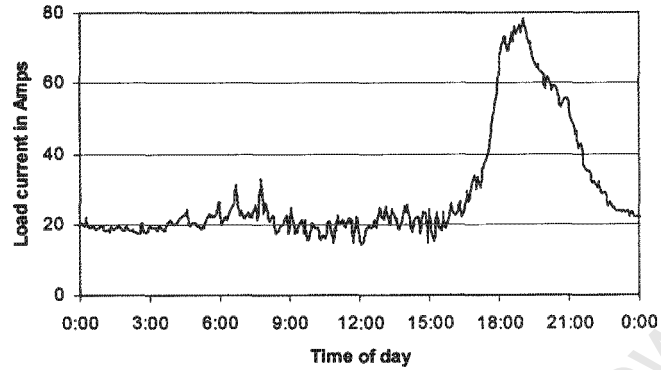


Figure 5.18. Average daily load profile

For practical purposes the load profile can be sampled at a convenient rate to get a total of  $T_N$  samples. From the available data,  $M_p(t)$  and  $E_p(t)$  were sampled at 5-minute intervals. So between 6.00 and 9.00 hours (inclusive) there are 37 samples and between 15.00 hours to 0.00 hours there are 109 samples.

In order to compute  $\mu$  (for the morning peak), the product of each sample coordinate pair  $(t_i, M_p(t_i))$  is computed and then they are all summed. The sum is then divided by the sum of all the current samples.

$$\mu = \frac{\sum_{t_i=1}^{T_N} M_p(t_i)t_i}{\sum_{t_i=1}^{T_N} M_p(t_i)}$$

Using this data the value of  $\mu = 18.37$  for the morning peak. Since each of the units used were sampled at five minute intervals beginning with one at 6.00 am, the actual time at which  $\mu = 18.37$  occurs is  $(17.37 \times 5 = 86.5)$  minutes after 6.00 am which is 30 seconds after 7.26 am.

For the evening session  $\mu = 54.7$ , which is equivalent to 53.7 five-minute intervals or 268.5 minutes after 15.00 hours. This is at 30 seconds after 19.28 hours.

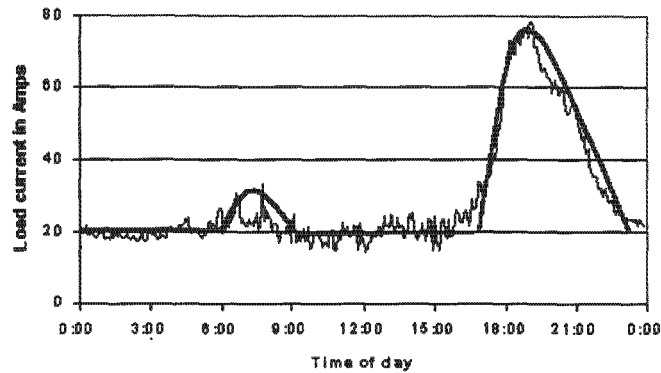


Figure 5.19. Sketch of the best fitted curve for the average daily load model

The standard deviation  $\sigma$  referred to earlier is given by

$$\sigma = \sqrt{\frac{\sum_{t_i=1}^{T_N} (t_i - \mu)^2}{T_N}}$$

From the data above the standard deviations for  $M_p(t)$  and  $E_p(t)$  were 4.2 and 31.5 respectively.

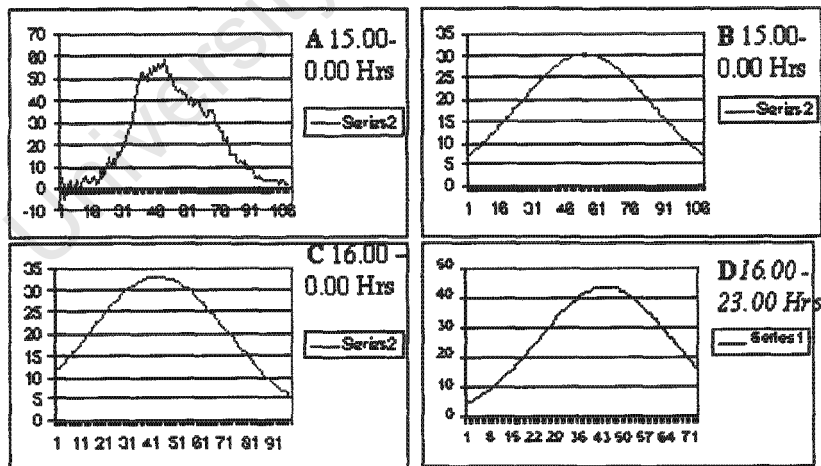


Figure 5.20. Plots of model results

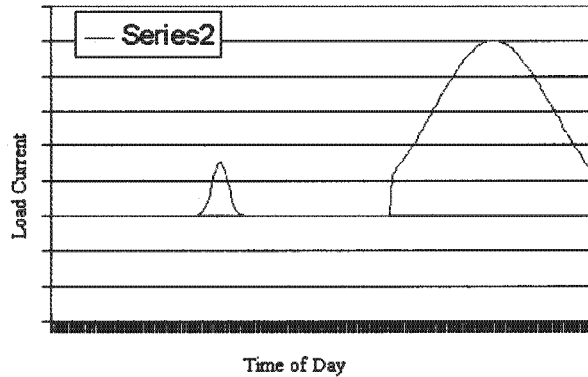


Figure 5.21. Overall Result of load profile using model 1

Using the above procedure, the results that were obtained did not compare favourably with the empirical plots. In figure 5.20 plot A is the actual portion of the evening load curve and B, C and D are the different normal distributions with slightly varying time intervals. Equally disappointing were the overall results as can be seen in figure 5.21. So a totally different approach was sought.

**Model 2:** The data for the load profile was compiled and plotted in Matlab. Then using a basic fitting tool function (in Matlab) the plot in figure 5.22 is one of several plots that were generated using various polynomial degrees, but were disappointing mismatches.

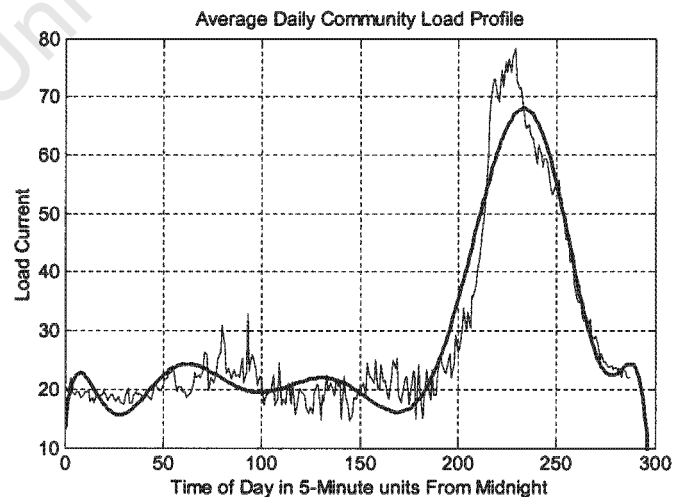
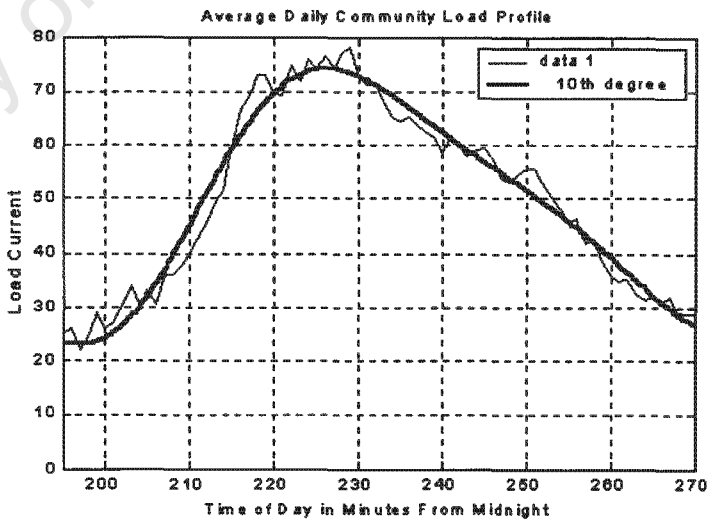
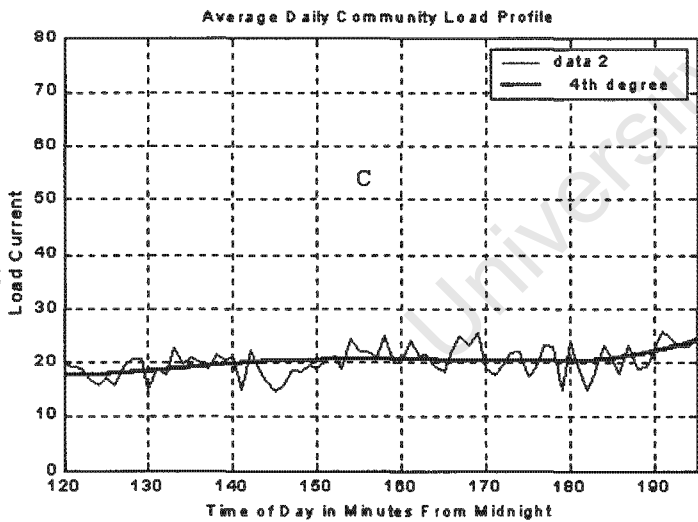
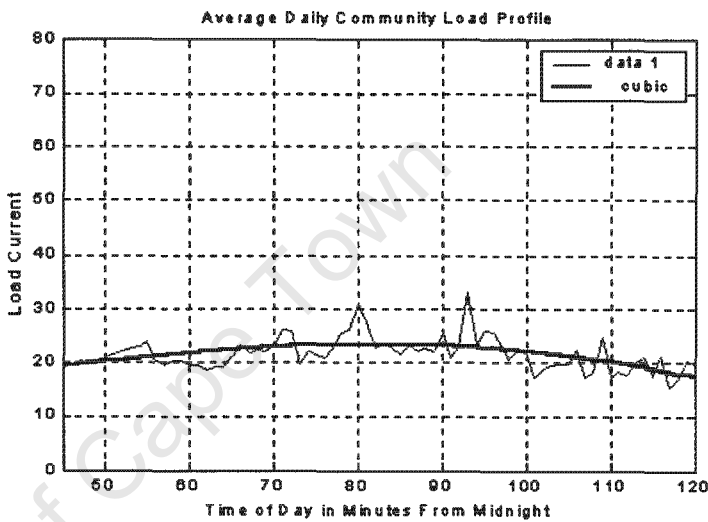
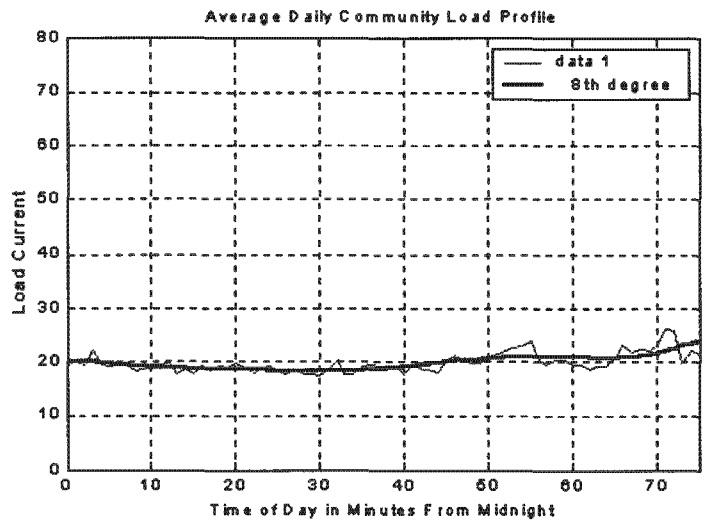


Figure 5.22. A basic fitting line generated by Matlab

Figure 5.23. Four segments of the same load profile treated with different polynomials



The load profile was then partitioned into four equal segments, which were fitted with various degrees of Matlab polynomial functions as illustrated in figure 5.23.

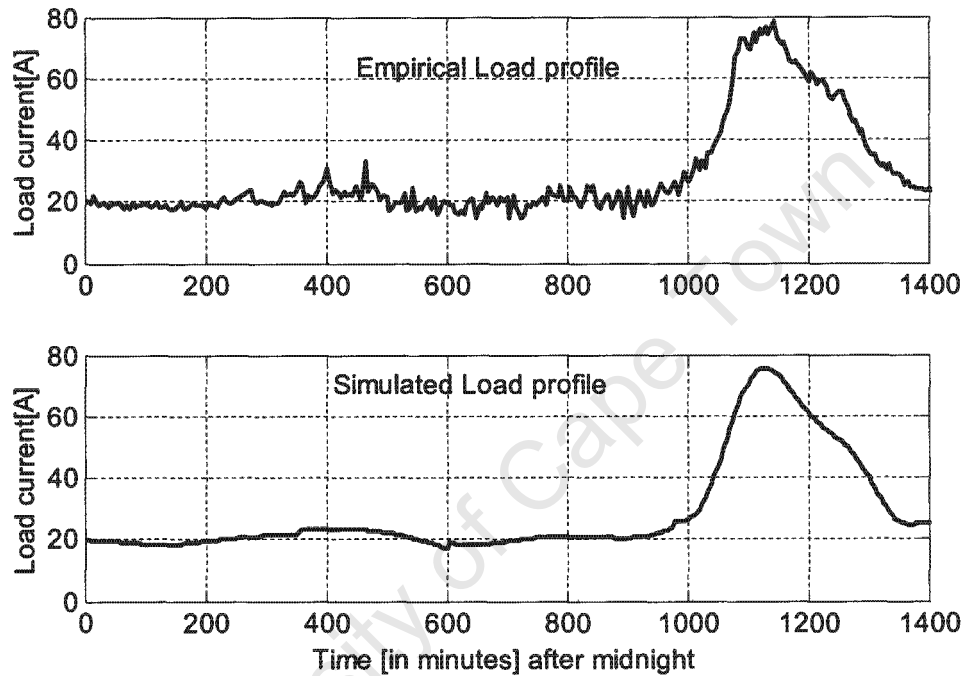


Figure 5.24. The Empirical and Simulated Load profile Curves

The following polynomial equations were generated by the Matlab basic fitting tool to mathematically describe the respective load profile segments, beginning from midnight.

The first period which spans for 6 hours 15 minutes from midnight is modeled by an 8<sup>th</sup> order polynomial,  $y_1(t)$  such that:

$$y_1(t) = -5.7 \times 10^{-12} t^8 + 1.7 \times 10^{-9} t^7 + -2.1 \times 10^{-7} t^6 + 1.3 \times 10^{-5} t^5 - 4.4 \times 10^4 t^4 + 8.2 \times 10^{-3} t^3 + 0.16t + 20$$

The second period begins at 6.15 hours up to 10.00 hours and is modeled by the following cubic order polynomial:

$$y_2(t) = -1.5 \times 10^{-5} t^3 + 2.7 \times 10^{-4} t^2 + 0.27t + 8.1$$

The third period begins from 10.00 hours and ends at 16.15 hrs and is modelled by a 4<sup>th</sup> order polynomial.

$$y_3(t) = 2.5 \times 10^{-6} t^4 - 1.5 \times 10^{-3} t^3 + 0.3 t^2 - 33 t + 1.2 \times 10^3$$

The fourth and last period of the day begins at 16.15 hrs up to midnight and is modeled by a 10<sup>th</sup> order polynomial:

$$y_4(t) = 4.1 \times 10^{-15} t^{10} - 9.7 \times 10^{-12} t^9 + 10^{-8} t^8 + -6.5 \times 10^{-6} t^7 + 2.7 \times 10^{-3} t^6 - 0.75 t^5 + \\ + 1.5 \times 10^2 t^4 - 2 \times 10^4 t^3 + 1.7 t^2 - 8.7 \times 10^7 t + 2 \times 10^9$$

Finally the data in each of these segments was compiled into a single table and the final load profile was plotted as seen in figure 5.24. The overall daily load profile function  $L_{DL}(t)$  can be described by the following equation,

$$L_{DL}(t) = y_1(t), \{for 0.00hrs \leq t < 6.15Hrs \\ = y_2(t), \{for 6.15hr \leq t < 10.00Hrs \\ = y_3(t), \{for 10.00Hrs \leq t < 16.15Hrs \\ = y_4(t), \{for 16.15Hrs \leq t < 0.00Hrs$$

#### 5.4 Concluding remarks

Load models for the critical rural functions of lighting, refrigeration and water pumping have been derived and plotted both in the transient and steady state. In addition, a new method of modelling a load profile by joining partial model algebraic functions created in Matlab has been devised and illustrated. Using the method, a typical 24-hour aggregate rural electric load has been mathematically modelled to replicate given empirical data.

With these models the necessary capacities for generation and storage devices can be designed optimally.

#### 5.5 References V

1. Lose C. M. and Frederick D. K., "Modeling and Analysis of Dynamic Systems," Houghton Mifflin Company, Boston, 1978.
2. Doebelin E. O., "System Dynamics: Modeling and Response," Charles Merrill Books, Columbus, Ohio, 1972.
3. Seely S., "Dynamic System analysis," Reinhold, New York 1964.

4. Laurent J C. Malhame R P, "A Physically-Based Computer Model of Aggregate Electric Water Heating Loads," IEEE Transactions on Power Systems, Vol. 9, No. 3, August 1994, pp. 1209 – 1217.
5. Gellings C. W., Taylor R. W., "Electric Load Curve Synthesis – A Computer Simulation of an Electric Utility Load shape," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 1 January 1981 pp. 60 –65.
6. Dolan P. S., Nehrir M. H., "Development of a Monte Carlo Based aggregate Model for Residential Electric Water Heater Loads," Elsevier (Electric Power System Research 36 (1996) pp. 29 – 35).
7. Lefebvre S., Desbiens C. "Residential Load Modeling for Predicting Distribution Transformer Load Behavior, Feeder and Cold Load Pickup," Elsevier (Electric Power and Energy Systems 24 (2002) 285 – 293).
8. Capasso A., Grattieri W., Lamedica R., Prudenzi A., "A Bottom-Up Approach to Residential Load modeling," IEEE Transactions on Power Systems, Vol., 9, No. 2 May 1994, pp. 957-964.
9. Mortensen R. E. and Haggerty, K. P., "A Stochastic Computer Model for Heating and Cooling Loads," IEEE Transactions on Power Systems Vol. 3 (1988), pp. 1213–1219.
10. Schneider K. C. and Hoad R. F., "Initial Transformer Sizing for Single-phase Residential Load," IEEE Transactions on Power Delivery, vol. 7 (1992), pp. 2074–2081.
11. Ihara S. and Schweppe F.C., "Physically Based Modeling of Cold Load Pickup," IEEE Trans Power Apparatus and Systems PAS-100 (1981), pp. 4142–4150.
12. Chong C., Malhamé R.P., "Statistical Synthesis of Physically Based Load Models With Applications to Cold Load Pick-up," IEEE Trans Power Apparatus and Systems PAS-103 (1984), pp. 1621–1628.
13. Athow D. and Law J., "Development and Applications of a Random Variable Model for Cold Load Pickup," IEEE Trans Power Delivery 9 (1994), pp. 1647–1653.
14. Leou R.C., Gaing Z.L., Lu C.N., Chang B. S. and Cheng C. L., "Distribution System Feder Cold Load Pickup Model," Elect Power System Researsh Vol.36 (1996), pp. 163–168.
15. Law J., Elliot L., Minford D. and Storms M., "Measured and Predicted Cold Load Pick up and Feeder Parameter Determination Using the Harmonic Model Algorithm," IEEE Transactions on Power Systems Vol.10 (1995), pp. 1756–1764.

16. McDonald J.E., Bruning A.M. and Mahieu W.R., "Cold Load Pickup," IEEE Transactions on Power Apparatus and Systems PAS-98 (1979), pp. 1384–1386.
17. Wilde R.L., "Effects of Cold Load Pickup at the Distribution Substation Transformer," IEEE Transactions on Power Apparatus and Systems, PAS-104 (1985), pp. 704–710.
18. Rau N.S. and Graham R.W., "Analysis and Simulation of the Effects of Controlled Water Heaters in a Winter Peaking System," IEEE Transactions on Power Apparatus and Systems, PAS-98 (1979), pp. 458–464.
19. Van Tonder J.C. and Lane I.E., "A Load Model to Support Demand Management Decisions on Domestic Storage Water Heater Control Strategy," IEEE Transactions on Power Systems Vol.11 (1996), pp. 1844–1849.
20. LaMeres B.J., Nehrir M.H. and Gerez A., "Controlling the Average Residential Water Heater Power Demand Using Fuzzy Logic," Electrical Power Systems Research Vol. 52 (1999), pp. 267–271.
21. Wakileh J.J., Pahwa A., "Optimization of Distribution System Design to Accommodate Cold Load Pickup," IEEE Transactions on Power Delivery Vol. 12 (1997), pp. 339–345.



## 6. Biogas as a Viable Renewable Electrical and Thermal Energy Source for Rural Energisation

### 6.1 Introduction

In rural Kenya, as is typical for most of sub-Saharan Africa, dry solid biomass [1] (wood, agricultural and animal waste) is burnt to provide fuel for thermal energy requirements as well as lighting. Apart from the low conversion efficiencies and health hazards to users, agricultural lands are deprived of nutrient replenishment, occasioning low food yields and deforestation, after the biomass is burnt.

With improving affluence, families may acquire small rudimentary electrical sources such as used car batteries and/or PV solar home systems [2]. Due to the limited capacities of such sources, consumers are only able to meet the most critical of loads like lighting and infotainment, leaving the energy intensive thermal loads to the same age-old biomass incinerating technologies. But even in cases where resources may be seemingly adequate, it is gradually being recognised that provision for thermal energy needs, (especially in remote rural areas), would be better served by energy forms other than electricity. For example, Eskom and Zesa [3], the South African and Zimbabwean power utilities respectively, are offering ampere-restricted services to some new rural grid consumers and encouraging them to use liquefied petroleum gas (LPG) for thermal loads. In Kenya, the infrastructure for retailing of LPG is only developed for urban centres.

Biogas, a methane rich fuel, has been used extensively in Asia and shown to address the above concerns cost-effectively [4-8]. Such developments are yet to be fully realised in sub-Saharan Africa. Biogas is a by-product gas produced by anaerobic decomposition (in the absence of oxygen) of organic matter by bacteria. It is also known as landfill gas [9-11] from urban garbage dumps or as marsh gas from swampy rural marshes, where it's known to cause spontaneous wild fires especially during hot seasons. In Uganda there are old folk tales of hunters being killed by mysterious fire flares in marshy swamps.

Apart from being a source of methane gas, wanton disposal of organic waste often harbour either disease carrying pathogens that end up in water resources or problematic weed seeds that find their way back into the farms. Livestock and poultry farms are also major emitters

of methane into the atmosphere. When released into the atmosphere methane is a green house gas (GHG) with the equivalent warming impact (TEWI) of 21 times that of an equivalent volume of carbon dioxide [12-14].

Early documented reports of generation of fuel gas from a bio-digester plant include an 1859 Indian leper colony where biogas was reportedly used for cooking [15]. Later in 1896 a street, in Exeter England, is reported to have used sewage gas for lights. At the close of the 19<sup>th</sup> century the French pioneered anaerobic treatment of biomass waste. This achieved the intended goal of neutralising offensive odours. The methane produced in the process would then be flared off.

The primary uses of biogas are cooking and lighting. When used directly in a burner to cook, a 65%/35% (methane/carbon dioxide) content biogas has an estimated heat calorific value of 5860 kilo-calories (24494.8 kilo-joules) per cubic meter (at 25°C and 1 bar) [4]. The gas can also be used directly in a combustion engine to run an electric generator. Successful use of modified spark ignition engines to run electrical and mechanical loads has been reported [16, 17].

The biggest promise however, is the emergence of fuel cell technologies with superior energy conversion efficiencies and low emissions. These have particularly been promoted by research in the automotive industry [18] among others. Their efforts are geared towards the direct use of hydrocarbon fuels as opposed to pure hydrogen. These fuels include methane and natural gas, which have a similar fuel ingredient to biogas. Moreover unlike natural gas, which is a fossil fuel, biogas is renewable and therefore the process of extracting energy from of it is zero emission rated.

In sub-Saharan Africa materials with potential to produce biogas are abundantly available and include animal, poultry and human waste, crop residues and household organic waste [19]. There are also modest quantities of biodegradable industrial waste. In the last decade an Amazon hyacinth weed invaded lakes in the Lake Victoria basin (so-called Great Lakes region of East Africa) with devastating consequences to the ecosystems and livelihoods of the fishing communities. Desperate efforts to rid the lakes of the weed have achieved mixed

results. In recent times such efforts have been expanded by encouraging economic ventures, such as handicrafts, as a viable incentive for community participation. The inclusion of biogas production to such efforts would be an added bonus.

Despite all these apparent opportunities, biogas production is virtually non-existent in our regions. Apart from cultural inertia to its use as cited by Akinbami [20] in Nigerian cases, instances abound of consumer frustration due to poor performance of trial digester projects [19]. In principle, the technology appears to be simple and is often misinterpreted as such, with resulting disappointments. Unfortunately this simplistic approach is promoted by much of the available literature that apparently relies on theoretical principles rather than proven experience. In fact as will be illustrated in section 6.2, obtaining good results involves both thorough knowledge and painstaking experience.

Secondly, the production of biogas should not be considered in isolation. The exclusion of other benefits, that include GHG mitigation, prevention of underground water pollution, control of foul smelling odours and recycling of soil nutrients in the cost equation could make the production of biogas appear uneconomical. The Food and Agricultural Organization (FAO) [4] has remarked that even in India and China where biogas programs are extensive, the results were mixed in the beginning. India has in fact decided to leave nothing to chance by creating a dedicated Ministry of Non-Conventional Energy Sources.

This chapter will cover the basic principles of biogas production and its potential for rural energisation. Some case studies will be cited, giving estimates of resources that are required to meet rural needs. Conclusions will then be drawn as to the benefits of these anaerobic processes in rural areas.

## **6.2 Basics of anaerobic decomposition**

The construction of a bio-digester for the production of biogas and fertilisers is well documented [21-35].

The process involves anaerobic decomposition of organic waste matter to produce methane and is dependent on a complex interaction of different groups of bacteria. In addition,

different mixtures of feedstock have optimum loading rates which need to be determined in an accurate analysis prior to a digester being built. Generally, the amount of biogas derived from waste depends on a number of factors [36-46] including:

- The ratio of dry matter to water in the digester
- The amount of grit and biologically inert material in the dry matter
- The nutrient content of feedstock
- The particle size of the material being digested (the finer the better)
- Environmental and climatic factors
- The previous storage history of the feedstock
- Digester temperature
- The pH (state of acidity or alkalinity) of the digester liquor
- The retention period (period from input of a feedstock to exit).

The essence of digester operation is the creation of conditions that are most favourable to bacteria since the gases are by-products of their metabolisms. For example, certain key nutrients are absolutely essential for the well being of bacteria. Carbon is responsible for keeping them active while nitrogen enables their cells to repair as well as multiply. Other elements that include phosphorus, magnesium, sodium, manganese, calcium and cobalt must always be available and slight deficiencies can result in total digester inhibition. Monitoring output gas composition can point to these deficiencies. For example, excess formation of ammonia could mean deficiency of nitrogen in the feedstock. Caution is sounded, though, that over-concentration of nitrogen, or any other such ingredients, could be toxic to bacteria. This is one reason why varied mixtures (cocktails) of feedstock types (like chicken and pig manure cocktail, or pig manure and corn stalks) are said to perform better than single types alone as they complement each other in nutrients. Additionally, most metals other than iron, nickel and cadmium as well as feedstock with antibiotics or any bactericide will poison the bacteria. Bacteria populations can be enhanced by external replenishment (seeding) to enhance digester metabolic rates.

Under neutral pH conditions, most microorganisms function optimally. However the products of bacteria that act on the raw input, for example, produce acetate and fatty acids,

thus lowering the system pH. The acidity trend can be halted or reversed by cutting down on the in-feed or by simply adding some appropriate amount of alkali, like bicarbonate or lime, directly to the digester. The system's ability to withstand acidity is referred to as its buffer. Extreme pH conditions can result in total stoppage of the digestion process. Caution must be taken when using lime so that the solid effluent, which must be used as fertiliser is not too alkaline.

Temperature generally promotes the metabolic rates, provided that the defined tolerances are not exceeded. There are two optional thermal operating regions namely, 36.7°C for mesophilic and 54.4°C for thermophilic bacteria. Opting to operate at thermophilic conditions will give faster results but the higher temperatures often require additional heating, which has cost implications. Under the warm climate that is prevalent in most of sub-Saharan Africa the mesophilic option is normally self-sustaining.

In basic terms the digestion processes can be summarised as follows. For the initial period some inevitable aerobic decomposition occurs, as the material originates from normal atmospheric conditions with relatively high oxygen levels. So the first lot of gas normally contains very high carbon dioxide levels. A typical carbohydrate molecule converts to carbon dioxide and water according to (6.1). In some cases this could be some 2 weeks in digester terms.



After stabilisation, with depletion of oxygen, a similar molecule decomposes to methane and carbon dioxide, instead. (See equation 6.2)



In practice however, a more complicated process (illustrated in figure 6.1) takes on multiple paths that will largely depend on the aforementioned environmental and operational conditions. In nature the most ideal conditions for bio-digestion exists in a cow's stomach.

In fact rumen from a freshly slaughtered cow is highly recommended for “kick-starting” a bio-digester. Finally, the typical composition of the gas leaving a digester is, 55-75% methane ( $\text{CH}_4$ ), 25-45% carbon dioxide ( $\text{CO}_2$ ), 1-5% nitrogen, up to 3% hydrogen ( $\text{H}_2$ ), up to 0.5% hydrogen sulphide ( $\text{H}_2\text{S}$ ), water vapour and traces of carbon monoxide, ammonia, sulphur and oxygen.

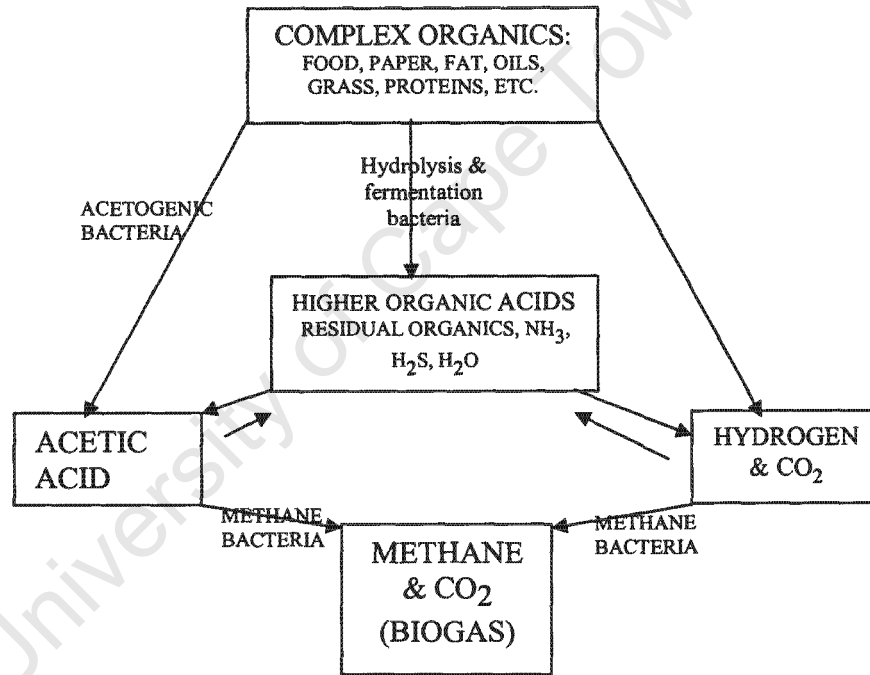


Figure 6.1. A Typical biodegradation pattern of biomass in a digester (Ref [4])

Hydrogen sulphide ( $\text{H}_2\text{S}$ ), though in apparently small percentages, has been cited as a major source of problems in the management of biogas. Apart from its offensive odour and toxicity to humans, it forms acids, which when mixed with water are very corrosive to equipment. In the digester it is a poison to the bacteria. There is therefore ample reason to scrub (remove)  $\text{H}_2\text{S}$  from biogas [47-50]. One technique is to let the gas react with a sacrificial material like steel wool stuffed in the delivery tube. A bio-scrubber technique proposed by Nishimura-Sosuke et al [47] uses bacteria and promises a more thorough and cost-effective remedy.

## **6.3 Case studies**

### **6.3.1 Background to the case studies**

A rural biogas study was done in Hambran village in Punjab, which was part of a Government of India program for the whole of Punjab State [51]. The overall aim was to save commercial energy, prevent deforestation, reduce soil erosion, preserve organic biomass for recycling and produce more food grain by using non-conventional energy.

Special emphasis was laid on the biogas program. Initially family size plants were constructed but it was later found to be more cost-effective to install community sizes. The study examined the Hambran village community biogas, to study aspects of the introduction of biogas technology into rural households. The village had 293 households, with a human and animal population of 1711 and 1400 respectively. An average family had 5 members. The households previously used cow dung cakes, fuel wood and agricultural waste as cooking fuel.

The specific objective of the study was to collect information about the technical, social and economic feasibility of a community biogas plant. The Hambran village complex had an average gas production capacity of 505 cubic meters per day. The biogas was supplied to individual households by a pipeline. The reported gas consumption for cooking was between 0.34 – 0.41 cubic meters and 0.15 cubic meters for lighting per capita per day. On average about 2.4 cubic meters per day was adequate for a household of 5.

### **6.3.2 Estimation of material requirements**

From the above and other similar studies in [52-56] it was found that for most organic waste types, the size of digesters is largely dependent on the mass of organic matter to be processed daily and confirm the factors stated in section 6.2. It was also found that biogas production could be increased, by dividing the daily slurry volume into two or more feedings, the more the better; as long as the total feed weight did not exceed the day's ration. Basically it is the digester feedstock itself that controlled the gas production for most systems, not the digester.

There are various ways of estimating the size of the digester, waste material loading rate and hydraulic retention time. For example, a 'rule of thumb' is that a daily loading rate of 6 kg of dry matter is used per cubic meter of digester. Generally, digester slurry (the operating solid-water mixture) should be eight to ten percent total solids or dry weight percentage. However, since in practice, plant or animal waste is already part liquid, it is more useful to specify the additional water required for a specific type of waste. The higher the water content of the original waste, the less additional liquid is needed.

As an example, the normal weight of fresh pig manure is about three times its theoretical dry weight. Cattle manure contains more water than pig manure, chicken manure contains less water than pig manure and plant waste generally contains less water than animal waste. Table 6.1 gives estimates of percentage dry matter content for different waste materials and the likely gas yield in cubic meters per ton of waste.

To make an estimate of the sizes for most high solids digesters, it is recommended to use an average residence time in the digester of 15 days with a limit of  $\pm 7$  days for a wide range of materials. This means that the required digester is 15 times the volume of the daily feed. This estimate, however, is contested by American authors [54-56] who argue that in order to make sure that the sludge that is taken out of the digester is free from disease carrying organisms, the slurry should stay in the digester for some 40 days. In that case, the daily slurry loading rate would be  $1/40$  (2.5%) of the digester capacity. It is also worth pointing out (as indicated earlier) that certain materials digest more easily than others. In general animal waste performs much better than plant waste. It has in fact been suggested that where circumstances permit, it would be more efficient to feed the plants to the animals and utilise the animal waste later, (perhaps the next day!).

The quantity of gas produced is determined by the efficiency of the digester, which is the fraction of dry matter that is converted into biogas. For most systems observed, approximately 50% of the dry matter was converted to biogas. For animal waste, which may have been subjected to composting such as broiler poultry manure, gas production was observed to reduce by up to two thirds, giving a digester efficiency of 16%. Oily wastes were found very digestible and almost 100% of the fat and oil converted to gas under suitable

conditions. The following table (Table 6.1) drawn up by *Practically Green* [52] is a useful guide. The figures given are for fresh wastes. Figures 6.2-6.5 also give estimates of biogas production by different feedstock types. It is also interesting to note that while storing animal organic waste for a week in hot weather, for example, may reduce the biogas potential by a half, pre-composting of plant waste enhances its gas productivity.

Table 6.1. Estimates of resources for biogas production

Feedstock	No. of Animals to Produce One ton per day	Dry Matter percentage content	Biogas Yield in Cubic Meters per Ton
Cattle Slurry	20 - 40	12%	25
Pig Slurry	250 - 300	9%	26
Laying Hen Manure	8,000 - 9,000	30%	90 - 150
Broiler chicken Manure	10,000 - 15,000	60%	50 - 100
Food Processing Waste	-	15%	46

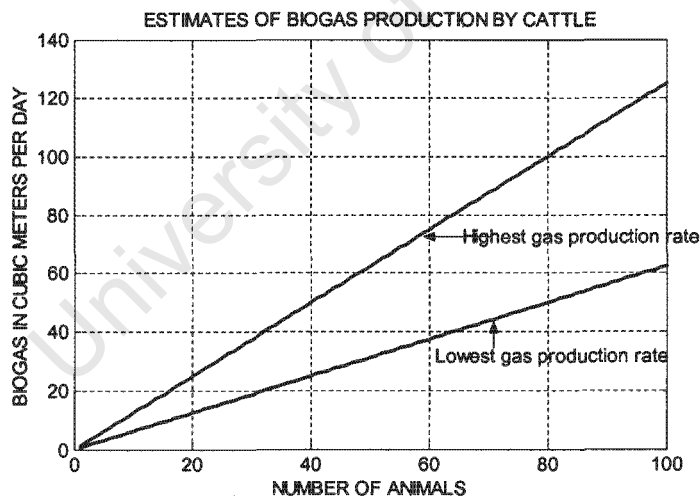


Figure 6.2. Estimates of biogas production from cattle manure

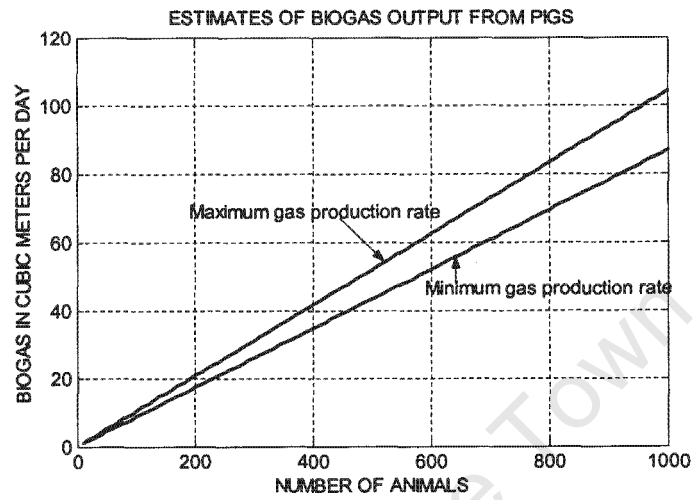


Figure 6.3. Estimates of biogas production from pig manure

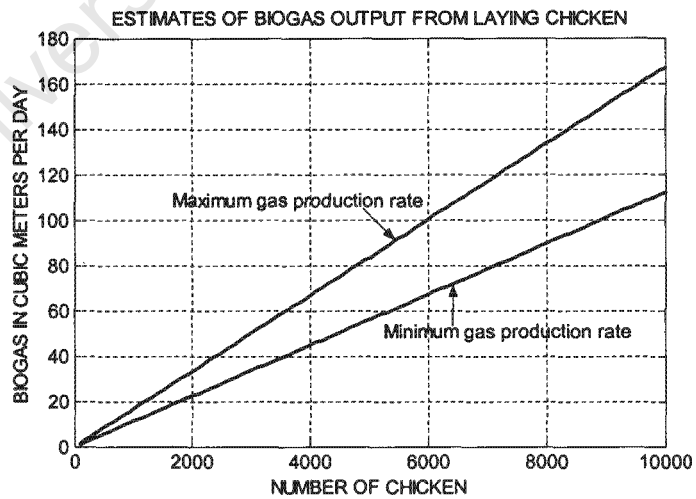


Figure 6.4. Estimates of biogas production from poultry manure

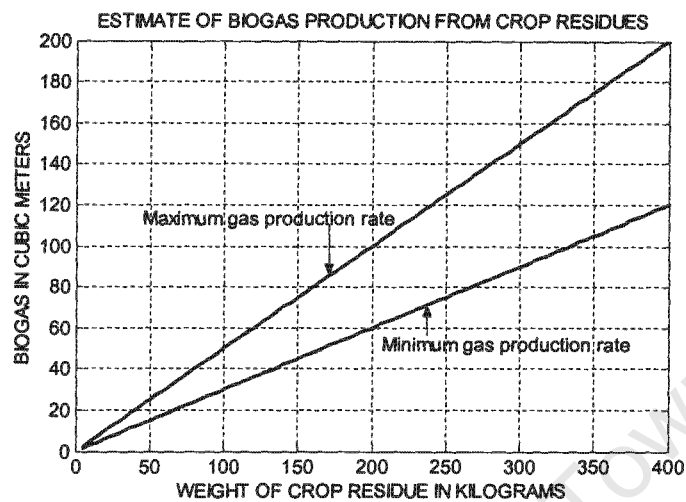


Figure 6.5. Estimates of biogas production from crop residue

Table 6.2. Percentage of dry matter in stock-feed types

Material	% Solid matter
Water hyacinth	11%
Plant waste (average)	75%
Grass	30 – 80%
Kelp	11%
Seaweed	33%
Chicken manure (fresh)	35%
Chicken manure (day old)	90%
Pig manure	14%
Human excreta	27%
Newspaper	93%

## 6.4 Concluding remarks

The basic principles of biogas production and its potential for rural energisation have been discussed. In order to comprehend the value or cost-effectiveness of biogas production, one must look at the value of the collective benefits of the process.

For African rural communities the processing of biogas is both necessary and beneficial. The anaerobic process controls underground water polluting and disease carrying pathogens as well as destroying unwanted weed seeds while providing rich farm fertilisers. Additionally, the collection of the digester gases serves to stem landfill green house emissions and preempts possible fire hazards while providing an inexpensive energy source. Moreover, biogas is a renewable resource and the process of extracting energy from it is zero emission rated. Therefore, the combined benefits of anaerobic processes in rural areas are both desirable and environmentally essential.

## 6.5 References VI

1. Karekezi S., "Poverty and Energy in Africa," *Energy Policy* vol. 30, pp. 915-919, 2002.
2. Agumba M., Osawa B., "Kenya's PV market," The ISES International Solar Energy Society, 2000
3. Mangwengwende S., "Tariffs and subsidies in Zimbabwe's reforming electricity industry steering a utility through turbulent times," *Energy Policy* vol. 30, pp. 947-958, 2002.
4. Uri Marchaim, "Biogas Processes for Sustainable Development," Migal Galilee Technological Center Kiryat Shmona, Israel. ISBN 92-5-103126-6, FAO 1992.
5. Tietjen C., "From Biodung to Biogas-Historical Review of European Experience", *Energy, Agriculture, and Waste*, p 274, 1975.
6. Bungay, H. R., 1928-. "Energy, the biomass options," New York, Wiley 1981.
7. Lewis, C. "Biological fuels." Arnold, London 1983.
8. White, L. P., Plaskett L. G., "Biomass as fuel." London New York, Academic Press. (1981).

9. Rodriquez-Iglesias J. et.al. "Characterisation of Extraction wells and recovery of Biogas in Municipal Solid Waste Sanitary Landfills," Sardinia.99, Cagliari, 4-8 October, p. 457-464.
10. Thorup C. et al. "Landfill Gas Generation Rates Estimated From Pressure Rebound in Extraction Systems." Sardinia.99, Cagliari, 4-8 October, p. 449-456.
11. Willumsen H. C "Automated control of landfill gas abstraction at small landfills." 20th Annual Landfill Gas Symposium. SWANA GR-LG0020, p. 177-183,1997.
12. Klingler B., "Environmental Aspects of Biogas Technology," German Biogas Association. Results from GTZ-Project "Promotion of Anaerobic Technologies, 1998" TBW GmbH. Frankfurt.
13. Cassada M. E., Safley L.M.Jr., "Global Methane Emissions from Livestock and Poultry Manure," EPA CX-816200-010, 1990.
14. "Methane Emissions and Opportunities for Control." Workshop of Intergovernmental Panel on Climate Change, Response Strategies Working Group. Japan Environment Agency, EPA, 1990.
15. Paul Harris, "History of Biogas."  
<http://www.ees.adelaide.edu.au/pharris/biogas/History.html>
16. Thunman H., Leckner B., "Ignition and propagation of a reaction front in cross-current bed combustion of wet fuels" Fuel Vol. 80, pp 473 – 481, 2001.
17. Huang J., Cookes R. J., "Assessment of simulated biogas as a fuel for spark ignition engine," Fuel Vol. 77, No. 15, pp. 1793-1801, 1998.
18. Sebitosi A. B., Pillay P., "Applications of Advances in Automotive Electronics to Rural Electrification: The 42 V Power-net for Rural Power Distribution," Proceedings of the IEEE PES General Meeting, July 2003, Toronto, Canada.
19. Kavaisi A. K., Rubindamayugi M. S. T., "The Potential of Agro-Industrial residues for production of Bio-gas and Electricity in Tanzania," WREC, 1996.
20. Akinbami J. F.K., Ilori M.O., Oyebisi T.O., Akinwumi I.O., Adeoti O., "Biogas energy use in Nigeria: current status, future prospects and policy implications," Renewable and Sustainable Energy Reviews 5 (2001) 97–112.
21. Khandelwal K. C., Maithani P. C., "Guide to family size Biogas plants," Department of Non-Conventional Energy Sources, New Delhi, 1989.
22. Meynell, P. J., "Methane: Planning a Digester," Schocken Books, New York 1976.

23. Myles, "A Practical Guide to Janta Biogas Plant technology." Action for Food Production, New Delhi, 1985.
24. Singh J. B., Myles R., Dhussa A., "Manual on Deenhandhu Biogas Plant," Tata McGraw-Hill, New Delhi, 1987.
25. Aburas R., Hammad M. A., Hiary S. E., Qousous S., "Construction and operation of a Demonstration Biogas plant, Problems and Prospects," Energy Conversion Management, Vol. 37, No. 5, pp. 611-614, 1996.
26. An, B. X., Rodriguez L., et al. (1997). "Installation and performance of low-cost polyethylene tube digesters on small-scale farms." World Animal Review. 88((1)): 38-47.
27. Mång H., Lund H., Hvelplund F., "Biogas plants in Denmark: technological and economic developments." Denmark Applied Energy 64 (1999) 195±206.
28. Shannon R., (Australia), "Biogas," IPC – VI, Designing for a sustainable future, Conference Proceedings. Chapter Eight - Technology Stream, 1997.
29. Kanwar S. S., Guleri R. L., "Performance Evaluation of a Family Size Rubber Balloon Plant Under Hilly Conditions," Bioresource Technology, vol. 50, pp.119-121.
30. Dekker M., Fry, L. J. "Practical Building of Power Plants for Rural Energy Independence." Andover, Hampshire, Chapel River Press (1975).
31. Lapp, H. M., Schulte D. D., et al. "Methane Production from Animal Wastes. Fundamental Considerations." Canadian Agricultural Engineering 17(2): 97-102, (1975).
32. Meuhling, A. J. "Producing Methane Gas from Pig Effluent." Adelaide, Department of Agriculture, South Australia, (1981).
33. Meynell, P. J. "Methane: Planning a Digester." Old Working, Surrey, The Gresham Press, (1976).
34. Pharaoh, D. M., "Manure digesters and methane gas production." Sydney, New South Wales Dept. of Agriculture, Agricultural Engineering Section (1976),
35. Meynell, P.J. Methane: "Planning a Digester." Dorset, England: Prism Press, 1978.
36. Zelunder A.J. et al. "Microbiology of Methane Bacteria in Anaerobic Digestion." Elsevier Biomedical Press. London UK, 1982.
37. Backus, B.D., Clanton C.J., Goodrich P.R., Morris H.A., "Carbon-to-nitrogen ratio and hydraulic retention time effect on the anaerobic digestion of cheese whey," Transactions of the ASAE 31 (4): pp. 1274-1283, 1988.

38. Dangoggo S. M., Aliyu M., Atiku A. T., "The effect of seeding Bacteria on Biogas Production rate," WREC, 1996.
39. Uribe, M., Juan, M., "Evaluation of the production of biogas from the vegetative material of prickly pear, through a methanic fermentation process," Chile University, Santiago, Esc, De Agronomia, pp. 51. 1993.
40. Al-Masri M.R., "Changes in biogas production due to different ratios of some animal and agricultural wastes," *Bioresource Technology* 77 (2001) 97±100.
41. Al-Masri, M.R., Guenther, K.D., "The effect of gamma irradiation on in vitro digestible energy of some agricultural residues," *Das wirtschaftseigene Futter* 41, 61±68, 1995.
42. Singh S. P., Vatsa D. K., Verma H. N., "Problems with Biogas Plants in Himachal Pradesh," *Bioresource Technology* 99, pp. 67-71 (1997).
43. Chen, Y. R. Hashimoto A. G., "Kinetics of Methane Formation." *Biotechnology and Bioengineering Symposium No 8, Gatlinburg, Tennessee, John Wiley & Sons Inc. (1978).*
44. Elefsiniotis P., Oldham W.K., "Influence of pH on the acid-phase anaerobic digestion of primary sludge," *Journal of Chemical Technology and Biotechnology* 60 (1): 89-96, 1988.
45. Boodoo A., Delaitre C., Preston T.R., "The Effect of Retention Time on Biogas Production From Slurry Produced by Cattle Fed with Sugarcane," *Animal production Division, Ministry of Agriculture, Natural Resources and the Environment, Reduit, Mauritius, vol. 4, pp. 21-25, 1979.*
46. Ranade D. R., Dighe A. S., Bhirangi S. S., Panhalkar V. S., Yeole T. Y. , "Evaluation of Sodium molybdate to inhibit Sulphate reduction during anaerobic digestion of distillery waste," *Bioresources Technology* 68 (1999) 287-291.
47. Nishimura-Sosuke, Yoda-Motoyuki, "Removal of Biogas From an Anaerobic Gas Using a Bio-Scrubber," *Water Science and Technology, Vol. 36 No. 6-7, pp 349-356, 1997.*
48. Gadre R. V., "Removal of Hydrogen Sulphide from Biogas by Chemoautotrophic Fixed-film Bioreactor," *Biotechnol-Bioeng. Vol. 34, No. 3, pp. 410-414, Jul 1989.*
49. Chou-Tse-Chuan et al, "Selective Removal of Hydrogen Sulphide From Biogas by a Packed Silica Gel Adsorber Tower,"

50. Henning- Klaus-Dirk et al, "Hydrogen Sulphide Removal from Biogas by an Activated Carbon Method," GWF-das-Gas und Wasserfach: Gas-Erdgas, Vol 126 No. 1 Jan 1985, p 19-24.
51. Vyas S.K., Sandhar NS, Singh A, Gupta RK and Jindal U, "Generation of Energy through anaerobic digestion – Experience of full scale at Hambran, Punjab" Inc. Acta Volume of 5th Int. Symp. On Anaerobic Digestion, (1988), Bologna, Italy.
52. Practically Green Environmental Services. Solar House, Magherafelt, Co. Londonderry, BT45 6HW, Northern Ireland. (<http://www.practicallygreen.com>)
53. Chan, U Sam, "State of the art review on the integrated use of anaerobic processes in China." Internal report prepared for IRCWD.1982.
54. Pond B. et al, "Tropical Animal Production," Volume 6, Number 2, 1981. Mexico.
55. Arnott M., "The Biogas/Biofertilizer Handbook," Peace Corps Information Collection and Exchange, Washington DC, 1985. <http://www.peacecorps.gov>
56. Fry, Merrill, R., "Methane Generators for fuel gas and fertilizer." New Alchemy Institute, Newsletter No. 3. Santa Barbara, pp. 45, 1973.)

## 7. The Possibility of Fuel Cells for Rural Electrification in Rural sub-Saharan Africa

### 7.1 Introduction

A fuel cell is an electrochemical dc generator and was invented by William Grove back in 1839 [1]. The first successful application was, however, not until nearly 100 years later by Francis Bacon. The first large-scale use was extraterrestrial in the 1950's for the Apollo Space Programme. In 1967, General Motors reportedly developed a passenger car for use on company property but serious research for vehicular and other commercial applications did not occur until the 1990's.

The fuel cell consists of an anode and a cathode with an electrolyte separating them. Gaseous or liquid fuels can be converted directly into electricity. This eliminates the conventional processes of combustion and conversion of heat using mechanical means to electricity and thus offering a more efficient and less polluting alternative. Fuel utilisation flexibility as well as their environmental friendliness have enhanced recent interest in this technology. In addition, the combined heat and power (CHP) capabilities of certain fuel cell types make them ideal candidates for that comprehensive so-called TES (total energy system) that can deliver both electrical and thermal energy from a single source; an attribute that is desirable for off-grid applications [2-4].

There are two main categories of fuel cells (FCs) namely, those that operate at low temperatures (<200°C) and those that operate at relatively high temperatures (500 - 1000°C). The former includes polymer electrolyte (PEFC), alkali (AFC) and phosphoric acid (PAFC) and have aqueous electrolytes made of the same materials as the cell names. The latter are molten carbonate (MCFC) and solid oxide (SOFC).

The fuel cell was originally conceived to use hydrogen as the fuel and the following equation describes the basic concept of the electrochemical energy conversion process ( $H_2 \rightarrow 2H^+ + 2e^-$ ). In practice, however, the use of pure hydrogen has shortcomings due to various reasons that include its availability, low energy density as well as safety concerns. Consequently, automotive and other industry stakeholders have developed fuel cells that can

use the more easily available and portable fuels like methanol, methane and natural gas [6-9]. Such fuels must be pre-processed through reformers to liberate the hydrogen necessary for the ultimate electrochemical reaction.

These developments are particularly important for African rural electrification (energisation) where biogas, a fuel that largely consists of methane, can be inexpensively produced by the action of anaerobic bacteria on organic waste. In fact, laboratory tests have been carried out for a number of years [10-16] on tubular solid oxide fuel cells (SOFC) using various grades of natural gas, landfill and digester biogas as well as pure methane with very encouraging results. The gases consistently performed with good efficiency ratings, particularly, in CHP applications. In [10], for example, it was discovered that at extremely low methane concentration levels, that could not possibly operate any type of combustion engine, a SOFC could still run reasonably well.

Just as rural Africa completely bypassed the use of traditional landline telephone infrastructure to cellular phone systems, this chapter looks at yet another possible technological leap in rural Africa: the use of fuel cells with biogas. Section 7.2 will cover the basics of fuel cell operation. Section 7.3 will examine a rural electric load and evaluate the amount of biogas that would be required to operate a fuel cell generator to satisfy it. Using this result and data from chapter 5, a graph plot will show the numbers of animals and/or weight of crop residue resources that would be required for the running of such a fuel cell to satisfy different village sizes. Section 7.4 will briefly discuss a transient model and some empirical results from National Renewable Energy Laboratories (NREL). The future outlook on fuel cells will be discussed in section 7.5. Conclusions will then be drawn as to the possibility of adopting this technology in rural Africa.

## 7.2 Fuel cell basics

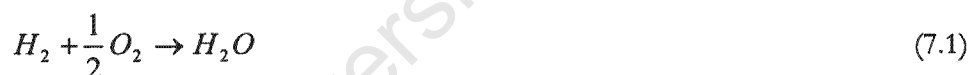
The electrical power output of a fuel cell can be easily derived from the product of the load current,  $I$  and the operating voltage,  $V$ . However, the net thermal power output is the sum of both chemical and electrical activities. The internal ohmic heating, as the load current flows, is added to the sum of the exothermic and endothermic chemical and electrochemical reactions to give the net thermal output. In CHP applications this net thermal power output

complements the electrical output to improve overall fuel cell efficiency.

Every substance has a Gibbs free energy of formation ( $G$ ). It is a state function [17]. The values are given in standard thermodynamic tables [18, 19]. For example the Gibbs free energy of formation for hydrogen,  $(G)_{H_2} = 0 \text{ kJ/mole}$ , for oxygen,  $(G)_{O_2} = 0$ , and for water  $(G)_{H_2O} = -237.18 \text{ kJ/mole}$ . The negative (-) sign means that the formation process releases energy. The values are given as 'energy per mole' and are referred to as molar Gibbs free energy of formation.

During a reaction there is a change  $\Delta G$  in the Gibbs free energy of formation from reactants to products. This change can be worked out using Hess's law [17] and is equal to the difference between the sums of Gibbs free energies of formation of the products and the reactants ( $\Delta G = \sum n_p (G)_{\text{Products}} - \sum n_r (G)_{\text{Reactants}}$ ). If the process occurs at constant temperature and pressure, then  $\Delta G$  is equal to the maximum possible useful work obtainable from the process.

Consider the basic electrochemical reaction in equation (7.1).



The energy produced by the reaction is the change in the Gibbs free energy  $\Delta G$  from reactants to product. Therefore

$$\begin{aligned} \Delta G &= (G)_{H_2O} - \left[ (G)_{H_2} + \frac{1}{2}(G)_{O_2} \right] \\ &= -237.18 - (0 + 0) = -237.18 \text{ kJ} \end{aligned}$$

It must however be noted that the Gibbs free energy of formation is dependent on temperature and whether the substance concerned is in liquid or gaseous state. In the example above, the values given are only valid at standard temperature (25°C or 298K) and for the standard states of liquid water and gaseous hydrogen and oxygen. The value obtained under these standard conditions is designated  $\Delta G^0$  (the change in Gibbs standard free energy of formation).

In the case of a fuel cell,  $\Delta G$  is the energy available to drive the electrons through an external load. In an ideal situation (without losses) all this energy will be converted to electrical energy. For each gram mole of hydrogen used,  $2N$  electrons are driven through the external load and a charge of  $2F$  coulombs is moved. ( $N$  is Avogadro's number =  $6.22 \times 10^{23}$  and  $F$  is Faraday's constant = 96845 coulombs/gram mole). The charge of an electron =  $-e$ . Therefore  $-2Ne = -2F$ .

One molecule of hydrogen produces 2 electrons. One gram mole of hydrogen ( $H_2$ ) is 2.016 gram and since one coulomb flowing per second constitutes a current of one amp, it can be shown that 0.037605 gm of ( $H_2$ ) are required to produce an electric current of 1 amp for 1 hour.

If  $E$  is the fuel cell voltage, then the electrical work done to move a given amount of charge in the circuit is the product of the voltage and the charge. Therefore electric work =  $-2FE$  joules. Without any losses therefore,  $-2FE$  will be equal to the change in the Gibbs free energy. So,  $\Delta G = -2F \cdot E$  and thus is defined the fundamental ideal ('reversible') fuel cell emf  $E$ , also called the ideal open circuit voltage.

$$E = \frac{-\Delta G}{2F} \quad (7.2)$$

Additionally, fuel cells use materials whose energy can be released by burning. The energy released this way (after total combustion) is termed the change in enthalpy of formation,  $\Delta H$ . Like  $\Delta G$ ,  $\Delta H$  is given in standard thermodynamic tables, is negative when energy is released and dependent on the gaseous or liquid state of a substance. For example, in the burning of hydrogen ( $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ ) the tables [18, 19] give the values of  $\Delta H$  as  $-241,820$  J/mole for steam and  $-285,830$  J/mole for water. The former is called the 'lower heating value' (LHV) and the latter 'higher heating value' (HHV).

The efficiency  $\eta$  of a fuel cell can then be viewed in terms of what the emf would have been if the change in enthalpy of formation had been used for the electrical energy conversion instead of the change in Gibbs free energy of formation. Thus ideally the maximum possible electrical efficiency =  $\frac{\Delta G}{\Delta H} \times 100\%$ . In practice however other issues have to be taken into

account. For example fuel cells do not use up all the fuel that they are supplied with and the ratio between the fuel utilised and the fuel supplied, which is the fuel utilisation ratio  $\mu$ , must be included when working out the efficiency. So when  $\mu$  is considered the maximum possible efficiency of a cell  $\eta$ , is given by

$$\eta = \mu \frac{\Delta G}{\Delta H} \times 100\% \quad (7.3)$$

In addition to being affected by temperature, the Gibbs free energy is also affected by the 'activity' levels of the reactants and products. In cases of gases behaving 'ideally' their activity is proportional to their partial pressures. So to work out the total change in Gibbs free energy of formation  $\Delta G$  of a reaction the Nernst equation is used [20-22]. If the reaction in equation (7.1) were to take place at pressure P and temperature T (where P is in bar and T in Kelvin) then

$$\Delta G = \Delta G^0 - RT \ln \left[ \frac{P_{H_2O}^1}{P_{H_2}^1 \cdot P_{O_2}^{\frac{1}{2}}} \right] = \Delta G^0 - RT \ln(Q) \quad (7.4)$$

P is the partial pressure of the reactant or product with the exponent of P being determined by the number of moles in the balanced equation. Q is the reaction quotient. R is the ideal gas constant = 8.314J/gram mol-K and  $\Delta G^0$  is the change in molar Gibbs standard free energy of formation.

In practice a chemical reaction takes the general form shown in equation (7.5).



where A, B and C, D are the reactants and products respectively while  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  are their respective number of moles in a balanced equation.

The reaction can run both in the forward and reverse directions at some rate and hence the  $\rightleftharpoons$  sign. If one starts with only the reactants A and B and no products C or D, the reaction may proceed to the right (under favourable conditions). As the concentrations of A and B decrease, the rate of this 'forward' reaction will slow down. Similarly, as the concentrations of C and D increase, the rate of the reverse reaction will increase. Eventually, these rates will

be equal and the concentrations of the various species will not change. This is the Equilibrium State for that reaction under those conditions. In [17] it is shown that when a reaction is in equilibrium

$$\Delta G^{\circ} = -RT \ln(K_p) \quad (7.6)$$

where  $K_p$  is the equilibrium constant of the reaction at the given temperature.  $\ln(K_p)$  is also given in thermodynamic tables.

Likewise, the potential  $E$ , of a cell under any random conditions can be found by using the Nernst equation.

$$E = \frac{-\Delta G^{\circ}}{2F} + \frac{RT}{2F} \ln(Q) = E^{\circ} + \frac{RT}{2F} \ln(Q) \quad (7.7)$$

where  $E^{\circ}$  is the cell potential at standard conditions

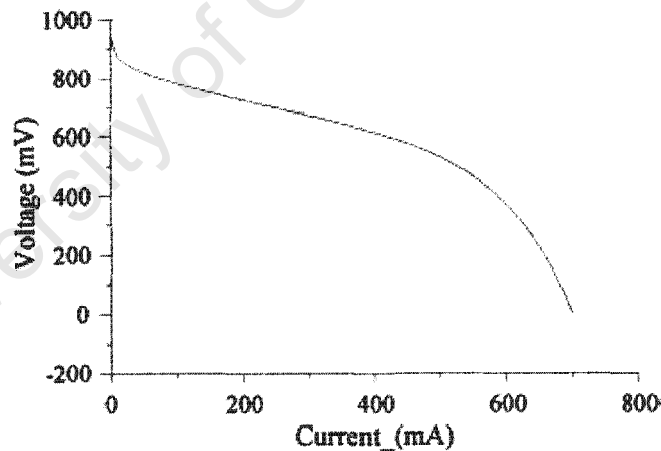
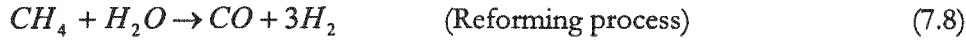


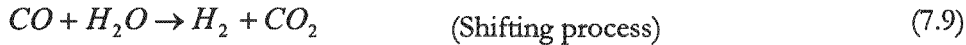
Figure 7.1. A typical shape of I-V characteristics of a PEM fuel cell

In practice, current-voltage (I-V) characteristics are supplied by the fuel cell manufacturer, with recommended operating points and fuel utilisation ratios. At these recommended points of operation the behaviour of a fuel cell is practically linear with respect to changes in fuel, load current and voltage. (Figure 7.1 is a typical shape of PEM fuel cell I-V characteristics.) Despite the apparent restriction it is shown in [23-26] that using the same manufacturers' characteristics, alternative operating points can be selected to obtain a range of desired power and/or efficiency levels.

In a SOFC using methane gas the following reactions take place. Initially methane must be reformed to liberate the required hydrogen.



The carbon monoxide (CO) is in turn converted by steam to carbon dioxide and hydrogen.

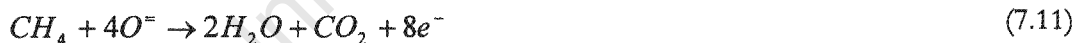


For an ideal (100% effective) reformer, the effective result of equation (7.8) and (7.9) can be written as equation (7.10). This reaction consumes heat energy (endothermic). The amount of heat required is equal to the change in enthalpy of the reaction,  $\Delta H$ .



In practice, however, the recycled gases, relevant equilibrium constants and fuel cell geometry (among others) would compound the situation and it is more reliable to use empirical data.

Additionally, it is technically possible for methane and carbon monoxide to undergo direct electrochemical reactions (without prior conversion to hydrogen) as shown in equations (7.11) and (7.12). Test data [23] have however shown that conditions are predominantly in favour of the reformation process as shown in equations, (7.8) (7.9) and (7.10).



Finally, the heat generated during the electrochemical conversion of hydrogen is the difference between the Gibbs free energy for water vapour which is available for electrical work and the total change in enthalpy of formation ( $\Delta H - \Delta G$ ).

### 7.3 Rural loads and biogas requirements for fuel cell operation

Figure 7.2 is an electrical load profile from a database of the South African NRS (National Rationalised Specifications) Load Research Project. It was for a group of 41 rural households in Garagapola village in South Africa over a 24-hour period on the 5<sup>th</sup> July 2002, beginning

from midnight. If this were assumed to be the typical daily consumer load profile, then the daily total load demand for the village would be 160.5 kWh, with an average power demand of 6.7 kW and a peak power demand of 16.3 kW. Thus the load factor would be 41%. If all this load were to be supplied directly from a fuel cell, then the fuel cell capacity would have to be rated at 16.3 kW (or more) instead of 6.7 kW. This would be in addition to meeting the transient loading (as well as a possible cold load pickup), which would escalate the capital cost. A more cost-effective alternative would be to use the fuel cell as a base load generator rated slightly above the average load capacity of 6.7 kW. An appropriate storage device would then be used to shave the transient and peak load demands. If the efficiency of the storage device were assumed to be 80%, then the required generator capacity would have to be increased to compensate for this. From figure 7.2 the required storage is 32.3 kWh. If this is 80% of the energy used to charge the battery then the source must supply a total of  $(1 \div 80\%) = 125\%$  of this. So the additional energy required =  $32.3 \times \left[ \frac{1}{80\%} - 1 \right] = 8.075 \text{ kWh}$ .

Therefore the required fuel cell power rating = 7.024 kW

Let the generator be an SOFC using biogas. In order to produce 7.024 kW of electric power from an SOFC fuel cell stack, some amount of usable thermal power will be produced as well.

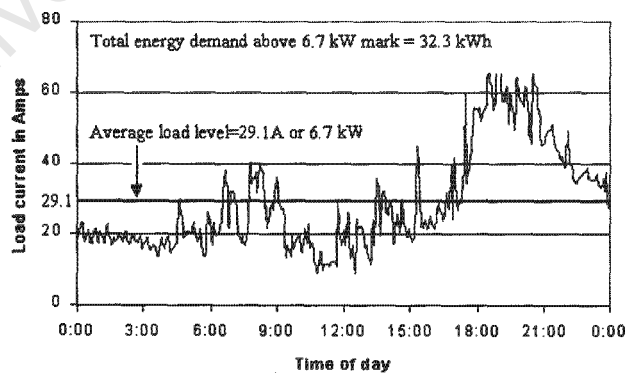


Figure 7.2. A 24- hour village load profile

To begin with, if the fuel used were pure hydrogen then the only electrochemical reaction in the cell would be  $(H_2 + \frac{1}{2}O_2 \rightarrow H_2O)$ . Using the manufacturer's I-V (current-voltage) characteristics an operating point can be selected. Assume that selected operating voltage per unit cell was 700mV at a cell temperature of 1000°C (1273.2 K), an operating pressure of 1

bar and a 75% fuel utilisation ratio. To ease the calculations it will be assumed that the cells are in parallel, since power is a collective contribution of individual cells. In order to deliver an electric load of 7.024 kW, the total current produced would

$$\text{be: } I = \frac{P}{V} = \frac{7024}{0.7} = 10034.3A$$

From the above in order to produce 1 amp for 1 hour one requires 0.037605 gram of hydrogen. So, in this case  $0.037605 \times 10034.3 = 377.34$  gm/hour will be used. So the amount of hydrogen gas used per sec =  $(377.34 \div 3600) = 0.105$ gm.

In an SOFC cell at 1273.2K, steam can be assumed to behave like an ideal gas [17, 22] and the electrochemical reaction be assumed to be in equilibrium, since 25% of the fuel remains unutilised. Therefore, the change in specific Gibbs energy for hydrogen and oxygen to water, electrochemical reaction at 1273.2K is given by equation (7.4)

$$\text{Work out per gram mole of hydrogen} = -\Delta G = -\Delta G^0 + RT \ln \left[ \frac{P^{H_2O}}{P^{H_2} \cdot P^{\frac{1}{2}O_2}} \right] \text{ joules}$$

From the tables the logarithmic values of the equilibrium constant = 18.182 for 1200K and 14.609 for 1400K. By interpolation the required value for 1273.2K can be found as follows.

$$\ln K_p = 18.182 - \left[ \frac{3.573}{200} \times 73.2 \right] = 16.874. \text{ And } \Delta G^0 \text{ can be found using equation (7.6).}$$

From equation (7.4),

$$\Delta G = \Delta G^0 = -(8.314 \times 1273.2 \times 16.874) = -178617.8 \text{ Joules/gram mole, since for the}$$

$$\text{chosen operating pressure of 1 bar } \ln \left[ \frac{P^{H_2O}}{P^{H_2} \cdot P^{\frac{1}{2}O_2}} \right] = \ln 1 = 0.$$

1-gram mole of H<sub>2</sub> is 2.016 gram.

$$\text{Work out per gram of H}_2 = -178617.8 \div 2.016 = -88600.1 \text{ Joules/gram}$$

But amount of hydrogen utilised per second = 0.105g

Therefore, amount of heat produced in the fuel cell exothermic reaction (assuming that the Gibbs change is all converted to electrical energy)

$$= 0.105 \times \frac{1}{2.016} \times (\Delta H - \Delta G)$$

Where  $\Delta H$  is molar enthalpy of formation for the reaction.

From the tables, molar enthalpy of formation for water vapour (steam) = -241820 joules/gram mole.

$$= 0.105 \times \frac{-(241820 - 178617.8)}{2.016} = -3244.9W. \text{ It will be assumed that the means to}$$

recover it is 100% efficient.

From the above the open circuit voltage E is given by

$$E = \frac{\Delta G^0}{2F} = \frac{RT}{2F} \ln K_p + 0 = \frac{RT}{2F} \times 16.874 = 0.925V$$

R=8.314 kJ/kmol-K and T=1273.2K.

Since the operating voltage is 0.7 V and the current is 10034.3 amps, the amount of heat generated due to internal ohmic resistances =  $(0.925 - 0.700) \times 10034.3 = 2257.7W$ .

If it is assumed that the efficiency of recovering this heat is 80%, then  $(2257.7 \times 0.8) = 1806.1W$  will be available.

If the fuel should be changed to 100% methane, then an additional reformation stage to generate hydrogen would be required. The fuel utilisation ratio is 75%. Therefore, the amount of hydrogen received from the reformer is  $(0.105 \div 75\%) = 0.140 \text{ gm/sec}$ . Let it be assumed that the reformer is 100% efficient; meaning that reformation and gas shift reactions are completed in the reformer and only hydrogen enters the fuel cell proper. So equations (7.8), (7.9) and (7.10) will be applied.

The overall reformer reaction  $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

One mole of  $CH_4$  produces 4 moles of  $H_2$ . One gram mole of methane is  $(12.01 + (4 \times 1.008)) = 16.04 \text{ gm}$  and 4 gram moles of hydrogen are 8.064gm. But the amount of hydrogen required is 0.140g/sec. This corresponds to  $(16.04 \div 8.064) \times 0.140 = 0.28 \text{ gm}$  of methane per sec.

Reactions in the reformer are endothermic (consume heat).

The following figures were obtained from enthalpy of formation tables for the respective gases.

One mole of methane @ -74850 J/gram mole = -74850

2 moles of Water (vapour) @ -241,820 J/ gram mole = -483,640

One mole of carbon dioxide @ -393,520 J/gram mole = -393,520

One mole of hydrogen @ 0 J/mole = 0

Total change in enthalpy of formation = 164,970 J/gram mole of methane (16.04 g).

The amount of methane processed is 0.28g/sec and will require 2880 W of heat to reform.

Total heat generated earlier = 3244.9 + 1806.1 = 5051.0 W

Net thermal energy available from fuel cell = (5051.0 – 2880) = 2171 W. This does not take into account the 25% unutilised fuel at the outlet of the fuel cell. This could be burnt at the exhaust and could potentially produce 1/3 of the power produced by the utilised 75%. When recycled, it reduces the thermal demand of the reformer or it could run additional thermal loads.

In the case of biogas the required amount will depend on its methane concentration. For example for a 65%: 35%, methane: carbon dioxide mixture, the gas volume will have to be increased by  $((100 \div 65) - 1) \times 100\% = 53.8\%$  as compared to methane.

The same problem could be looked at in an alternative way. If one wishes to purchase off-the-shelf commercial equipment for use with biogas, one is bound to find those that are calibrated to run on methane. Since the concentration of methane in biogas is diluted, it is advisable [6, 7] that the equipment capacities be de-rated in order to operate properly. That means that using the same volume of biogas as methane one should expect to generate a fraction of energy in proportion to the fraction of methane in the biogas. So in order to generate 7.024 kW of electric power (kWe) using the same biogas grade, one would require a machine rated for  $(7.024 \div 65\%) = 10.806$  kWe when running on pure methane.

From the above, the average amount of methane required for the 41 rural households in Garagapola village is 0.28 g/sec. At standard temperature and pressure one gram mole of a gas occupies 22.4 liters. The gram mole of methane is 16.04. Therefore the volume of gas required per second is  $0.28 \times \frac{22.4}{16.04} = 0.39$  liters. If the composition of biogas were 65:35%, then 0.39 liters would represent 65% of the biogas volume. The required biogas volume =  $(0.39 \div 65\%) = 0.60$  liters/sec. Total amount of gas per day =  $(0.6 \times 3600 \times 24) = 51,840$  liters = 51.84 cubic meters. We can therefore derive the required animal resources to meet the needs for various sizes of villages. This is illustrated in figure 7.3.

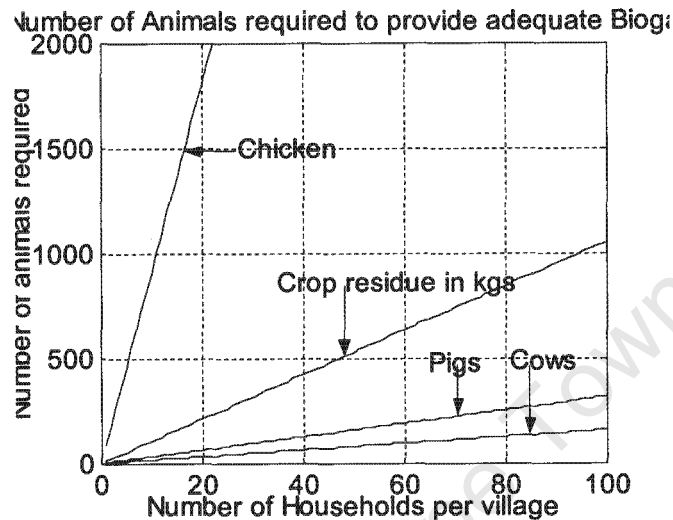


Figure 7.3. Numbers of animals or weight of crop residue for different village sizes

#### 7.4 Transient response of a fuel cell

The performance of a given fuel cell stack is largely dependent on manufacturer construction technology. Because this is an emerging and highly competitive field much of detail passes as proprietary, with scanty revelations. This problem when combined with the non-linearity of the fuel cell subsystems and their interaction, makes it problematic to obtain a mathematical model that is valid for a full range of circumstances and is still a subject of intense research. It is therefore advisable to use empirical data.

The transient model used here has been used in [34-37]. The fuel cell considered is comprised of a reformer, a stack and a DC-DC converter. The reformer and stack are each represented as first order time delay elements as depicted in figure 7.4. A non-linear resistance is used to represent miscellaneous voltage drops in the stack. An inductor is inserted to account for the time constant associated with the load current. The input voltage represents the input fuel to the reformer and the output is the stack output DC voltage prior to the power conditioner. Power conditioning is achieved by a DC-DC converter whose time constant is deemed negligible compared to the rest of the system.

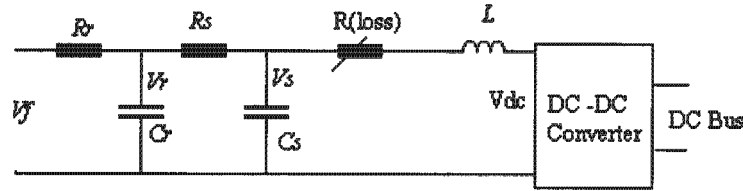


Figure 7.4. The dynamic equivalent electrical circuit of a fuel cell system

$V_f$  is the input fuel rate

$V_r$  is the reformer output (stack input)

$V_{dc}$  is output DC voltage from the stack

$R_{(loss)}$  is a non-linear internal resistance obtainable from the fuel cell I-V characteristics

The Transfer functions of the reformer and the stack are given by equations (7.13) and (7.14) respectively.

$$\frac{V_r}{V_{in}} = \frac{\frac{1}{S \cdot C_r}}{R_r + \frac{1}{S \cdot C_r}} = \frac{1}{1 + S \cdot R_r C_r} \quad (7.13)$$

$$\frac{V_{cs}}{V_r} = \frac{\frac{1}{S \cdot C_s}}{R_s + \frac{1}{S \cdot C_s}} = \frac{1}{1 + S \cdot R_s C_s} \quad (7.14)$$

Where,  $R_r C_r = \tau_r$  and  $R_s C_s = \tau_s$  are the reformer and stack time constants respectively.

The transient demand is assumed to be initiated by the electric load but the ratio of electric to thermal output power is a constant. According to the study in [36], the reformer time constant ranges from 0.8 – 1.7 s and for the stack it is 80 – 180 ms, depending on unit ratings. In [35] typical fuel cell V-I characteristics are used to derive the loss resistances as functions of load currents (at steady state) depending on a particular fuel cell type.

The simulation results in Figure 7.4 were obtained in [36] for the system response to a step increase in load current of a linear load. The system time constant was 3.6 seconds.

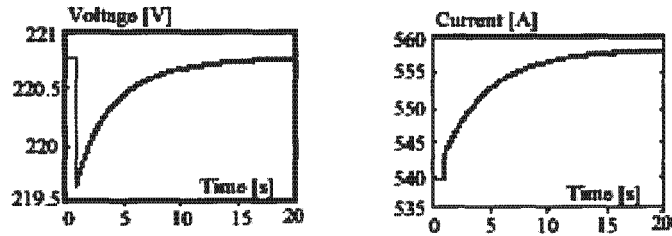


Figure 7.4. Current and voltage responses of a fuel cell source to a step load increase

A system with such a lag in response time would require a storage device to fill in the initial void. The minimum amount of energy that must be stored is the difference between the amount of energy required by the load for the duration of the transient and the total amount of energy that the source is able to deliver during the same period. This would also require that the final total load is less than or equal to the existing power rating of the fuel intake to the reformer. If this should be exceeded then the reformer would have to increase its fuel intake and its time constant would have to be considered as well.

The choice of storage device is normally between an electrolytic capacitor, lead acid battery and ultra capacitor. The parameters that one considers before making a choice are, the amount of energy to be stored, cost of storage device, charge/discharge cycle efficiency, power capability, self discharge rate, recharge rate, recycle life and maintenance requirements.

Figures 7.5 and 7.6 show empirical results from a report sanctioned by the National Renewable Energy Laboratories (NREL) [37] for the transient behaviour of a fuel cell system when compensated by an ultra capacitor.

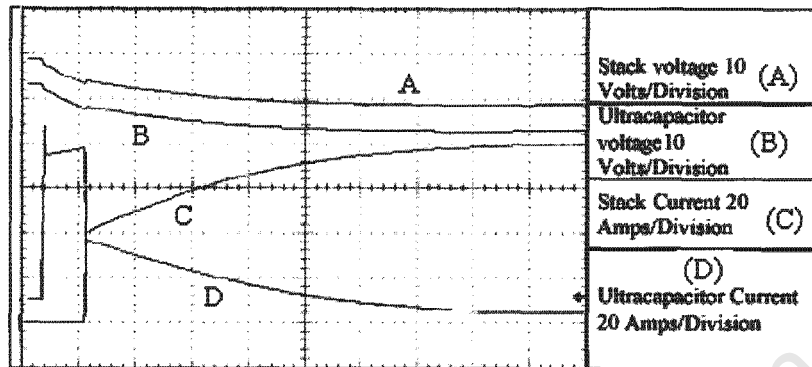


Figure 7.5. Step load (linear) to full load (3kW) and maintain load for 100 sec (time base is 10 sec per division)

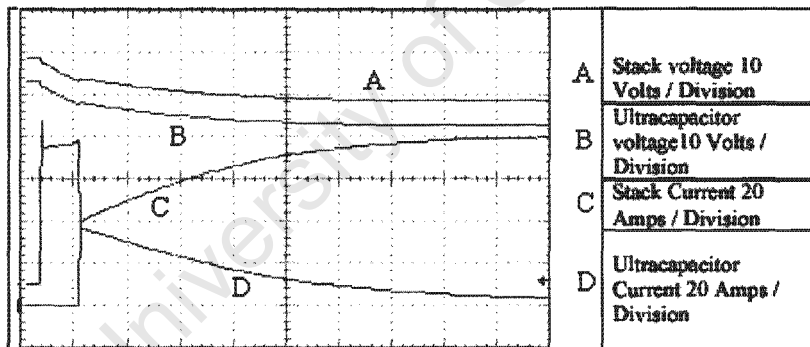


Figure 7.6 Start up of a 1.5 hp motor driving air fan (Time base 10sec/division). (Note that air fan motors draw the same current characteristics as water pump motors)

## 7.5 The future of fuel cells

In the course of the last decade the level of interest and investment in fuel cells has grown exponentially [38-45]. On the automotive front, every major manufacturer is working on fuel cell technology and intending to commercialise 'as soon as is practical'. The Bush Administration (in the US) has designated fuel cell vehicles as central to federal automotive research and development (R&D) efforts [38]. Appendix VI is a table providing facts for fuel

cell auxiliary power units (APU) from a selection of automotive manufacturers as published in [39]. There are, in addition, hundreds of other power industry players. Capacities ranging from milliwatts to megawatts are being developed for applications including laptops, cellular phones, homes, automobiles, remote telecommunication sites, forklifts, construction equipment and wheelchairs. The issue about fuel cell is not 'if' but when it does happen it will revolutionise energy. It is estimated for example that if the 17 million vehicles sold in the USA in a year were powered by fuel cells, it would equal the stationary electric generating capacity of the entire country.

One of the current technological challenges of fuel cells is durability. The technologies are still in the process (but steadily improving) of proving they can operate over long periods of time without failure in a wide variety of operating conditions. Durable materials need to be produced cheaply. More work also needs to be done on reformers so that conveniently available fuels can be used. The good news for rural Africa is that more progress seems to have been achieved with reforming natural gas and methanol than for other fuels. Additionally, contrary to what had been assumed in the past, SOFCs can operate efficiently even at low capacities of 1 kW. According to [41] Sulzer Hexis is leading the world in the commercialisation of the technology with a 1kW SOFC residential system. It is expected that economies of scale will enable price reduction, which is another major issue.

At the same time, SOFC technology is beginning to make inroads into the automotive Auxiliary Power Unit (APU) market, hitherto traditionally the preserve of PEMFCs. Renault and BMW are both looking at SOFC APUs for cars and trucks. SOFC components are potentially cheaper and easier to manufacture than their PEM counterparts and notable achievements have already been made in reducing costs. Rolls Royce, for example, says that it has already cut its stack costs to US\$300 per kW. This is a much better cost when compared to the 1.1 kW pico hydro at Kathamba, which was priced at US \$ 58 per household for the total of 65 households. Moreover, the SOFC being portable would be located closer to the consumers and hence require a much smaller distribution infrastructure.

In the business of pure hydrogen fuel, leading storage technologies include hydrides, nano-carbon tubes and compressed and liquid (cryogenic) storage. One of the more promising avenues of research is the use of microscopic nano-tubes. This technology stores hydrogen

in microscopic cavities, absorbing the atoms like a sponge. In theory, one could put together a storage technology that would address the safety concerns and also get not hundreds but conceivably thousands of kilometers of range.

## 7.6 Concluding remarks

The potential benefits of biogas in rural energy delivery have been discussed extensively in literature. This chapter has explored that potential further, by using a state-of-the-art automotive technology, the fuel cell. The basic relationships that govern the operation of a fuel cell have been discussed. Using these relationships, the fuel requirements of a SOFC running with biogas to supply an electric load in a South African rural village have been derived, under idealised conditions. Moreover, the application has been shown to produce a complementary amount of usable thermal energy. From these results the varieties and quantities of resources needed to process the required quantities of biogas for different sizes of villages have been estimated and graphically illustrated. As has been indicated, these resources are largely available in rural sub-Saharan Africa.

## 7.7 Appendix VI

TABLE VI Major Fuel Cell APU R&D Initiatives

Participants	Application	Size	Fuel cell system
BMW, International Fuel Cells	Passenger car, BMW 7-series	5 kW	Hydrogen, PEM
Ballard, Daimler-Chrysler	Class 8 Freightliner Century Class S/T	1.4 kW	Hydrogen, PEM
BMW, Delphi, Global Thermoelectric	Passenger car	1-5 kW	Gasoline, SOFC
Delphi, CALSTART, Aerovironment	Class 8 truck	5 kW	Diesel, SOFC
SunLine Transit, Southwest Research Institute	Class 8 International Truck	5 kW	
EXCELLSiS,	Military Class 8 vehicle		Diesel, PEM
DaimlerChrysler, EXCELLSiS		3 kW	Hydrogen, PEM
Virginia Tech Univ., Energy Partners	Hybrid-electric passenger car	20 kW	Hydrogen, PEM

## 7.8 References VII

1. Tse L., Bong D., "A Brief History of Fuel Cell," Vision Engineer.  
[http://www.visionengineer.com/env/fc\\_history.shtml](http://www.visionengineer.com/env/fc_history.shtml)
2. Krist K., Wright J. D., Gleason K. J., "Solid Fuel Oxide Fuel Cell Residential Cogeneration," Joint DOE / EPRI / GRI, Fuel Cell Technology Review Conference, August 3-5, 1999 Chicago, IL
3. Crosbie G. M., et al, "Application of Direct Oxidation of Liquid Hydrocarbon Fuels in Solid oxide Fuel Cells to Automotive Auxiliary Power Units." SAE 2002-01-2545.
4. Hartvigsen J. et al, "Solid Oxide Fuel Cells." PV 93-4 pp. 878, The Electrochemical Proceedings Series, Pennington, NJ 1993.
5. Drienckhahn W., "SOFC in Dispersed Power Generation," Journal of European Ceramic Society, Society 19 (6-7) (1999) pp. 861-863
6. Keegan K., Khaleel M., Chick L., Recknagle K., Simmer S., Deiber J., "Analysis of a Planar Solid Oxide Fuel Cell Based Automotive Auxiliary Power Unit," Society of Automotive Engineers, 2002-01-0413.
7. Zizelman J., Shaffer S., Mukerjee S., "Solid Oxide Fuel Cell Auxiliary Power Unit- A Development Update," SAE 2002-01-0411.
8. Nakagawa N., Sagara H., Kato K., "Catalytic Activity of Ni-YSZ-CeO<sub>2</sub> Anode for the Steam Reforming of Methane in a Direct Internal-Reforming Solid Oxide Fuel Cell." Journal of Power Sources Vol. 93, 88-94, 2001.
9. Aguir P., Chadwick D., Kershenbaum L., "Modeling of an indirect reforming solid oxide fuel cell," Chemical Engineering Science vol. 57 (2002) p. 1665 -1677.
10. Staniforth J., Kendall K., "Biogas Powering a Small Tubular Solid Oxide Fuel Cell," Journal of Power Sources, Vol. 71, pp. 275-277, 1998.
11. Siegel R. J., Trocciola J. C., Preston J. L., "Test results for Fuel-Cell Operation on Landfill Gas," Energy, Vol. 22, No. 8, pp. 777-786, 1997.
12. Spiegel R. J., Preston J. L., Trocciola J. C., "Fuel Cell Operation on landfill gas at Penrose Power Station," Energy, Vol. 24, pp. 723-742, 1999.
13. Spiegel R. J., Preston J. L., "Test Results on Fuel Cell Operation on Anaerobic Digester Gas," Journal of Power Sources, Vol. 86, pp. 283-288, 2000.
14. Roe S. et al, "Emerging Technologies for the management and utilization of Landfill Gas." U S Environment Protection Agency, EPA-600/R-98-021, Feb 1998.

15. Staniforth J., Kendall K., "Cannock Landfill Gas Powering a Small Tubular Solid Oxide Fuel Cell-A Case Study." *Journal of Power Sources*, vol. 86 pp. 401-403, 2000.
16. Xantha Bruso, "The Coming of Age of a Waste-to-Energy Technology: Implementing Biogas-Powered Fuel Cells." 11.369J: *Industry, Technology and Ecology*, December 2001.
17. Zumdahl, S. S., "Chemistry, 4<sup>th</sup> Edition" Houghtom Maffli Company, 1997.
18. Chase M. W., et al, "JANAF Thermodynamic Tables - Third Edition," American Chemical Society and The American Institute of Physics for National Bureau of Standards, 1985.
19. Çencel Y. A., Boles M. A., "Thermodynamics – An Engineering Approach – 4<sup>th</sup> Edition," McGraw-Hill Higher Education, 2002.
20. "Fuel Cell Handbook," U S Department of Energy, National Technical Laboratory, 2000.
21. Campanari S., "Thermodynamic Model and Parametric Analysis of a Tubular SOFC Module." *Journal of Power Sources*, Vol. 92, pp. 26-34, 2001.
22. Larminie J., Dicks A., "Fuel Cell System Explained," John Wiley and Sons, Ltd., 2000.
23. Khandkar A. et al, "Selection of SOFC Stack Operation Point for Optimal balance of Efficiency and Power." *Third European Solid Oxide Fuel Cell Forum*, June 1998.
24. Hartvigsen J. et al, "Development of an SOFC Stack Performance Map for Natural Gas Operation." *Sixth International Symposium on Solid Oxide Fuel Cells*, October 1999.
25. Khandkar A. et al, "Status and Progress of SOFCo's Planar SOFC Development," *Sixth International Symposium on Solid Oxide Fuel Cells*, October 1999.
26. Föger K., "Fuel Cells as Distributed Energy generators," Ceramic Fuels Ltd, 170 Browns Road, Noble Park, Vic3174, Australia.
27. Vyas SK ,Sandhar NS, Singh A, Gupta RK and Jindal U, "Generation of Energy through anaerobic digestion – Experience of full scale at Hambran, Punjab" Inc. *Acta Volume of 5th Int. Symp. On Anaerobic Digestion*, (1988), Bologna, Italy.
28. Uri Marchaim, "Biogas Processes for Sustainable Development," Migal Galilee Technological Center Kiryat Shmona, Israel. ISBN 92-5-103126-6, FAO 1992.
29. Chan, U Sam, "State of the art review on the integrated use of anaerobic processes in China." Internal report prepared for IRCWD.1982.

30. Fry, Merrill, R., "Methane Generators for fuel gas and fertilizer." New Alchemy Institute, Newsletter No. 3. Santa Barbara, 45 pp, 1973.
31. Pond B. et al, "Tropical Animal Production," Volume 6, Number 2, 1981. Mexico.
32. Arnott M., "The Biogas/Biofertilizer Handbook," Peace Corps Information Collection and Exchange, Washington DC, 1985. <http://www.peacecorps.gov>
33. Ramakumar R., Abouzahr I., Ashenayi K., "A knowledge-based Approach to Integrated Renewable Energy Sytems," IEEE Transactions on Energy Conversion, Vol. 7, No. 4, pp. 648-659, December 1992.
34. Yoon-Ho Kim and Sang-sun Kim, "An Electrical Modeling and Fuzzy Logic Control of a Fuel Cell generation System," IEEE Transaction on Energy Conversion, Vol. 14, No. 2, June 1999.
35. Hall D. J., Colclaser J. G., "Transient Modeling and Simulation Of a Tubular Sloid Oxide Fuel Cell," IEEE Transactions on Energy Conversion, Vol. 14, No. 3, September 1999.
36. Azmy A. M., Erlich I., "Dynamic Simulation of Fuel Cells and Micro-turbines Integrated with a Multi-Machine Network," Proceedings of IEEE Bologna PowerTech, Bologna, Italy, June 2003.
37. Key T. S., Sitzlar H. E., Geist T. D., "Fast Response, Load-Matching Hybrid Fuel Cell," EPRI PEAC Corp. Knoxville, Tennessee. Final Technical Progress Report National Renewable Energy Laboratory, June 2003 • NREL/SR-560-32743.
38. Sperling, D., "Updating Automotive Research." Issues in Science and Technology, Spring 2002, pp. 85-89.
39. Lutsey N., Brodrick C-J, Sperling D., Dwyer H. A., "Markets for Fuel Cell Auxiliary Power Units in Vehicles: A Preliminary Assessment," Institute of Transportation Studies University of California, Davis. July 31, 2002. <http://www.its.berkeley.edu/publications/>
40. "The Future of Fuel Cells: An Interview with Bob Rose, Executive Director Fuel Cell 2000," E V World. <http://evworld.com/view.cfm?section=article&storyid=120>
41. Cropper M, "Solid Oxide Fuel Cell Technology in Europe: Trends and Developments." Fuel Cell Today 4 October 2001. <http://www.fuelcelltoday.com>
42. "DaimlerChrysler Delivers the First Fuel Cell Bus to the City of Madrid," Madrid, Spain, May 05, 2003. <http://www.daimlerchrysler.com/dccom/0,,0-5-7145-1-66124-1-0-0-0-0-0-9-0-0-0-0-0-0-0,00.html>

43. Roberts B., "The Promise of Hydrogen, Is it the Super Power of the Future?" IEEE Power and Energy, vol. 2, No. 2, March/April 2004.
44. Andrews C. J., Weiner S. A., "Visions of a Hydrogen Future," IEEE Power and Energy, vol. 2, No. 2, March/April 2004.
45. Gurney J. H., "Building a Case for the Hydrogen Economy," IEEE Power and Energy, vol. 2, No. 2, March/April 2004.

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## 8. Other Energy Resources

### 8.1 Introduction

While the focus of the thesis is on automotive sources and loads, both solar and wind can be used with vehicles. For example the SunRay [1], manufactured by Sunetra in Hawaii, is powered by solar energy, has an average range of 100 kilometers and a top speed of 100km. Micro wind turbines have also been used on recreational boats for battery charging [2]. As such, a discussion for small wind and solar is not inappropriate. For the sake of completeness micro hydro will be discussed as well. These resources are indeed free in their natural form but the conversion technologies are not. Among other factors, the power density of the available energy resource greatly influences the sizing and hence the cost-effectiveness of the conversion equipment. Therefore resource assessment is necessary.

There are various methods of resource assessment. Some methods involve the use of climatic databases often spanning several years, at hourly intervals and requiring considerable computer storage and simulations. While such methods eventually give accurate results, the massive resource requirement renders them impractical for rural African circumstances. Moreover, such designs are often one-of-a-kind and the same costs must be incurred again for a different project. The meager capital and manpower resources available must be shared between this necessity for resource assessment and the ability to finally harness it. It has in fact been remarked in [1] that, "in the case of micro hydro, quite often the feasibility study alone costs more than the total amount for implementation." Additionally, time is often of essence as issues tend to get overtaken by other events, leading to abandonment of projects. In an attempt to avoid such shortcomings, methods using approximate monthly or annual climatic data have been used in the past. Unfortunately, these almost invariably result in very inaccurate designs and consequent under-sizing or over-sizing of systems as has been cited in the Kenya PV cases. Therefore there is need for a compromised approach.

Analytical modelling has been found to be a reliable and cost-effective option. In the case of radiation data for example, using monthly global radiation values (which are otherwise inadequate alone) stochastic models are used to generate intermediate data having the same statistical properties (including, average value, variance, and characteristic sequence

(autocorrelation)) as the measured data. Thus the generated data approximates the natural characteristics as far as possible. Recent research [4-5] has shown that data generated this way can be used satisfactorily in place of long-term measured data. In addition, software [6] using a combination of validated models and new interpolation techniques to enable the generation of data for virtually any location (at any latitude and altitude) is now commercially available.

These developments are very important for rural Africa where lack of up-to-date resource databases especially at micro level is a major problem for any potential renewable energy designer.

This chapter will look at the harnessing of insolation, wind and micro hydro resources for rural energy needs. Basics of resource-to-electrical energy conversion technologies currently used in Kenya as well as appropriate resource assessment models and/or methods will be discussed. Examples of possible rural applications will be given in each case. Additionally section 8.2 will give a brief example on the application of commercially available state-of-the-art PV design software for a fictitious installation in Thika town in Kenya. Then finally section 8.5 will briefly highlight the possibility of converting human muscle power to electric power in possible emergencies.

## **8.2 PV Generation**

### **8.2.1 Background on photovoltaics**

The photovoltaic effect was first reported way back in 1839 by Becquerel. The first practical silicon type solar cells were however only produced in 1954, by Bell Laboratories. Initial applications were in extraterrestrial missions. The first earthly uses were in remote and inaccessible installations that required little or no maintenance, mainly in signal and telecommunications applications.

In the decade leading up to the end of the millennium the spirit of the Rio Earth summit promoted a fresh awareness of environmental sustainability. Consequently, the use of PV technology was among programs promoted by the Global Environment Fund (GEF), among others. Beneficiaries in sub-Saharan Africa included Zimbabwe and Uganda. At the

same time some modest commercial consumption of solar PV panels was gradually picking up for off-grid applications in a few other sub-Saharan African countries. Notable among these was Kenya [7-11].

A PV cell is a dc generator [12, 13]. Using semi-conductor technology the cells convert sunlight into electricity by a quantum process. Technically the light does not have to originate from the sun but since the basic aim is to harness a renewable energy only the sun could be such a source. A photon from the sun's ray strikes the material and if the energy content of the photon is at least as high as the band gap energy,  $E_g$ , of the material then an electron is elevated from its normal valence band location to the conduction band. The above action by the sun results in electron-hole charge carriers called photo-carriers. When an external electrical load is connected, a dc current (called the photo current) flows. Thus, the process is called the photovoltaic effect.

The power generated increases with increased sunlight, but is also negatively affected by temperature. The amount of energy absorbed by an electron being equal to a specific value,  $E_g$ , means that the balance energy of photons that do not satisfy this condition (in a particular material) must be discarded. This energy is converted to heat, which constitutes conversion inefficiency.

In an effort to address this shortcoming, manufacturers exploit the fact that photons with different wavelengths of the sun's radiation spectrum have different energy levels. So multiple band gap materials are now being used to utilise a wider range of the spectrum [14]. For example, whereas the average efficiency of a solar cell is currently of the order of 15%, multi-junction cells have been produced with efficiencies of over 30%.

Currently a wide variety of PV technologies are commercially available. These include, crystalline silicone, multi-crystalline silicone, polycrystalline silicone, amorphous silicone, copper indium diselenide (CIS), cadmium telluride (CdTe) and concentrators with silicon cells.

Like other semiconductor components, manufacturer's datasheets are normally used to describe the behaviour of a given product. Typical manufacturer's open-circuit voltage ( $V_{OC}$ ) as well as short-circuit current ( $I_{SC}$ ) as functions of light intensity exposure of a PV cell are shown in figure 8.1. These are however only valid for the test conditions as indicated [15, 16]. Likewise I-V (current-voltage) characteristics are for specific test conditions of light intensity and temperature. These are referred to here as  $G_{ref}$  and  $T_{ref}$ , and are typically 1kW per square meter (irradiance) and 25° Celsius respectively (at wind speeds < 1 m/s). Using the following expressions, currents and voltages can be derived for different conditions.

The change in temperature is given by

$$\Delta T_C = T_C - T_{ref} \quad (8.1)$$

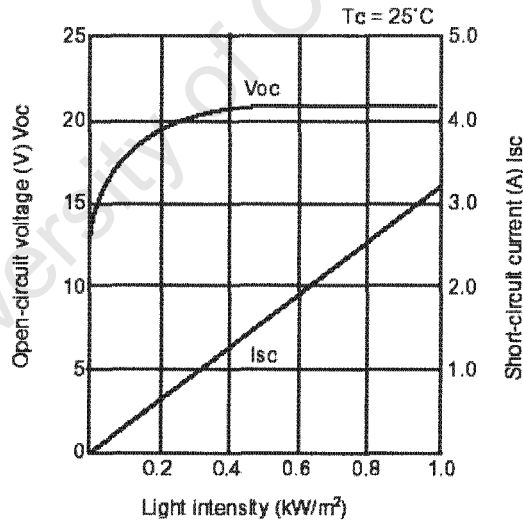


Figure 8.1. Open circuit voltage and short circuit current as functions of light intensity (Ref [16])

The change in current is given by

$$\Delta I = \alpha_{scT} \left( \frac{G}{G_{ref}} \right) \Delta T_C + \left( \frac{G}{G_{ref}} - 1 \right) I_{sc,ref} \quad (8.2)$$

$\alpha_{scT}$  is the short circuit temperature coefficient

$I_{sc,ref}$  is the data sheet specified short circuit current

The change in voltage is given by

$$\Delta V = -\beta_{ocT}\Delta T_C - R_S\Delta I \quad (8.3)$$

where  $\beta_{ocT}$  is the open circuit temperature coefficient.

Finally the new voltage and current values are given by

$$V_{new} = V_{ref} + \Delta V \quad (8.4)$$

$$I_{new} = I_{ref} + \Delta I \quad (8.5)$$

It should be born in mind that these terms for temperature refer to actual cell temperature and not the ambient temperature. Figure 8.2 is a typical I-V characteristic of operating current as a function of operating voltage at a standard irradiance of 1 kW per square meter at cell temperatures of 25°C and 56°C.

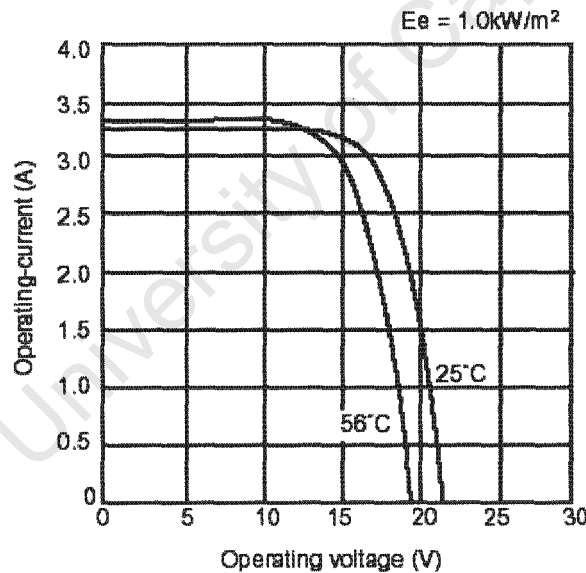


Figure 8.2. Operating-current versus operating voltage at 25°C and 56°C (Ref [16])

### 8.2.2 Solar resource assessment

A single PV cell has a very small capacity. To obtain a tangible amount of output power a number of cells are combined to form a module. The performance of a PV module is often characterised by a commercial label giving its peak output power (Wp) (valid at the aforementioned standard conditions). The primary requirement for an effective design, however, is an understanding of the expected energy production by an installation over a

given period, (say, daily, monthly or annually). Irradiance is the amount of solar power per unit area on a surface, while insolation refers to the amount of radiant energy per unit area in a given period (often in kWh per square meter per day). Insolation values are especially important for PV, since the total energy production of a module over a period is proportional to the cumulative exposure to solar energy. Additionally, since the energy that can be generated by a PV module is not only proportional to the available insolation but affected by ambient conditions as well, a complete resource assessment for a location must include both the solar resource and other weather conditions.

The maximum amount of solar power emitted by the sun per unit area perpendicular to the sun's ray in near-earth space (or immediately outside the atmosphere) is the solar constant,  $I_{SC}$ . The average value of  $I_{SC} = 1367$  watts per square meter. This radiation corresponds to the maximum possible radiation that would occur at the earth's surface if it were unhindered. The actual levels experienced on the earth's surface are lower due the following factors.

There are two main variables that affect the irradiance reaching a specific location on earth namely, geometric (including the earth's rotation on a tilted axis and its orbital revolution around the sun) and atmospheric factors. These factors can be further enumerated as, geography of location (altitude and latitude), orientation, time of day (sunrise and sunset hours have longer reddish radiation wavelength while midday have shorter bluish radiation), season of the year and cloud cover. The effect on the solar spectrum, at a location by the time of the day is specified by a spectrum index called optical air mass (AM). When the sun is overhead at sea level AM=1 and at sunrise/sunset AM=10. It should be noted that AM is also related to the relative path length traversed by the radiation from the outer rim of the atmosphere to a particular location on the earth's surface. For example at sunrise this path will be longer than at noon. By the same token, AM will be affected by altitude and latitude.

From the above, all the listed impediments to the propagation of radiation from the outer rim of the atmosphere to a terrestrial location can be reasonably predicted, except cloud cover. For a given location they can therefore be factored into the PV cell performance as constants. Consequently, the only phenomena of significance that can unpredictably restrict

the availability of solar radiation at the earth's surface are clouds and their accompanying weather patterns.

Due to the stochastic nature of cloud patterns, an appropriate database or probabilistic model is necessary to predict the available solar energy. As stated earlier the trend is the use of a bit of both. For designers in the USA, the National Solar Radiation Data Base (NSRDB) is the most common source but this covers only American locations. A viable reprieve for African designers can be found from the Swiss Federal Office of Energy [6], which maintains one of the international bases recommended by Sandia National Laboratories. The base has also developed commercially available solar resource-modelling software METEONORM. This tool combines several solar radiation models [17-21] and worldwide monthly global radiation data to generate hourly insolation data for known locations around the world. In addition interpolation techniques are used to generate data for virtually any other location. Currently due to the availability of inexpensive geo-positioning technology, any terrestrial location could be identified in terms of latitude, longitude and altitude fairly easily.

From the interpolation and radiation generation procedure, hourly values of global radiation and monthly temperature required for temperature generation for any location in sub-Saharan Africa should be now possible. Using these, hourly temperature values may be calculated in METEONORM. The idea underlying the model is based on the assumption that the amplitude of the temperature variation during daytime is approximately proportional to the amplitude of the daily global radiation profile. Thus the temperature profile is calculated by transforming the radiation profile.

### **8.2.3 PV power rating and annual energy output**

Section 8.2.2 has outlined the assessment of solar energy resource. In addition to resource assessment, manufacturing characteristics and environmental factors in general influence the annual energy produced by a PV module. According to a Sandia report [17] the most significant performance factors are, cumulative insolation, modules power rating (at Standard conditions), operating temperature (temperature coefficient), maximum power voltage rating ( $V_{mp}$ ) dependence on insolation level, variation of solar spectrum, soiling and optical losses

when the sun is incident at high angle-of-incident (AOI). Performance degradation [22, 23] factors constitute the PV module's combined effective inefficiency factor (also referred to as de-rate factor). Therefore the available PV module output power  $P_S$  is given by

$$P_S = P_o \cdot A_e \cdot \eta_a \quad (8.6)$$

where,  $A_e$  is the effective array surface area,

$P_o$  is the initial un-glassed and un-degraded PV cell output at normal incidence at one solar constant intensity and reference temperature and  $\eta_a$  is the combined effective efficiency of the module.

In [23] this factor is estimated by the following expression.

$$\eta_a = \frac{P_S}{P_o \cdot A_e} \approx \eta_r [1 - 0.0045(T_c - T_r)] \quad (8.7)$$

$\eta_r$  is the panel efficiency at reference conditions

$T_r$  is the reference temperature

$T_c$  is the cell temperature, which is generally dependent on insolation and wind velocity

$$T_c = T_a + k \cdot I_t$$

$T_a$  is the air temperature and  $k$  is an exponential function of the wind velocity

$$k = f(w_t) = c_1 + c_2 \cdot \exp(c_3 w_t)$$

( $c_1$ ,  $c_2$  and  $c_3$  are constant coefficients).

#### 8.2.4 System level influences on PV performance

The foregoing sub-sections have developed a basic understanding of what influences the performance of a PV module on its own. In practical installations the module must combine and interact with other components, (including other PV modules to form arrays), as well as loads that have a significant influence on the overall performance, reliability and cost effectiveness of the system.

The factors that can emerge from these system interactions include, module mismatch, wiring and terminal resistance, inverter efficiency versus load, maximum point tracker efficiency, charge controller efficiency, degradation of system performance due to overall

aging, battery charge and discharge characteristics and array to load ratio. In [17] it had been estimated that even in well designed systems, each of the above factors could cause an energy production degradation of up to 5%. It would therefore follow that even when the PV modules themselves may individually be performing well, system failure could easily occur if poor attention were paid to system design. However, according to more recent Sandia field studies [18], module mismatch and spectral variation are the two least influential factors on system energy production. The dominant factors include BOS (balance of system components) and module orientation. For the capacities of systems used in Kenya, no sun tracking devices are used to avoid parasitic losses. Since Kenya is astride the equator it has been established that maximum annual insolation is picked up by a horizontally positioned module. The group of components that include inverters, charge controllers and batteries, which are collectively referred to as “power conditioning hardware” have been found in field studies to be by far the biggest causes of system failure. This concurs with a separate Kenyan field report cited in chapter 1. In the case of Kenya however, only the batteries were involved, as the current rural Kenyan systems are still fairly simple and do not include the rest of the otherwise ‘standard’ power conditioning hardware.

For over a decade concerted collaborative efforts have been made by various researchers [18-21], including Sandia National Laboratories, to develop and document outdoor test procedures that quantify the performance characteristics of PV for virtually all commercial technologies. Subsequently a performance model has been created, improved and validated [24]. It has further been made available by Sandia at [25] where they also maintain and continually expand an access database of performance parameters for over 150 commercial PV modules. In addition, a software design company has incorporated the model in commercially available PV system design software [26] that carries a global radiation database, which includes major cities across Africa. It also permits the use of externally acquired radiation data. Once equipped with climatic data for a location and a type of commercial PV module, entries can be made into the software. Appropriate module capacities can be selected, as well as the necessary BOS components to predict the energy production of an installation over a given period.

### 8.2.5 Rural application examples

In the most basic installation a PV module can be connected directly to a load. The method has the advantage of using power directly from the panel and avoiding storage losses but its scope is limited to water pumping as other loads are not as consistently available. Moreover, since the motor must operate over a wide speed-torque range, as irradiance levels fluctuate, its performance efficiency can never be optimised. Consequently the panel is often oversized by 2 to 3 times, which may reverse the apparent cost gains of avoiding a battery. In the solar home systems (SHS) commonly found in Kenya a single panel directly charges a battery, which in turn runs fluorescent lights and basic infotainment appliances. No charge controllers or maximum power point trackers are involved.

Consider a simple rural consumer who uses a 20W black and white TV for 4 hours, a 5W radio for some 10 hours together with three 10W fluorescent lights for 4 hours, each day. The daily amount of energy required is  $(20 \times 4) + (5 \times 10) + (3 \times 10) = 160\text{Wh}$ . If the dc bus used were the automotive 42V and the panel were to deliver this over a period of 8 hours, then the necessary average power would be 20W. In order to charge at a rate of 20W the panel would have to operate at  $(20 \div 42) = 476\text{mA}$ . This is however the ideal figure. In reality there are deterioration factors (as seen earlier) both for the solar panel and the battery [22, 23]. Let  $K_1$  be the deterioration factor for the panel based on the aforementioned effects. Let  $K_2$  be the deterioration factor based on the aging performance for battery which systematically decreases the charge discharge efficiency of the stored energy. In [16] these have been estimated at 0.85 and 0.95 respectively, for purposes of specifying an appropriate panel capacity. The required charging current would therefore have to be upgraded by a factor equal to the reciprocal of the product of  $K_1$  and  $K_2$ , which in this case is

$\frac{1}{0.95 \times 0.85} = 1.24$ . So the correct specification of the solar panel should be an operating

current  $I_p = 476 \times 1.24 = 590\text{mA}$ .

In order to specify the correct PV cell operating voltage  $V_p$  one must make provision for

- an additional reverse blocking diode often included to protect the cells from reverse current from the battery at times of low or no insolation ( $\sim 0.5\text{V}$ )
- some cable voltage drop leading to the battery (0.1-0.5V)
- some additional voltage allowance due to temperature ( $\sim 1.3$ ).

In this case  $V_p$  would come to about  $(42 + 0.5 + 0.4 + 1.3) = 44.2V$ . An appropriate panel would therefore be of peak power  $W_p = V_p I_p = 44.2 \times 0.590 = 26.1W_p$  or better.

This example assumes the availability of all the sunlight required at a constant rate, and without any spectral variation. The load is also assumed to be constant. In addition, hardly anything is known about the battery or panel itself and a host of other relevant factors. In a simple household depicted, the assumption of loading holds reasonably true but not the insolation. The answer will at best be a mere guide.

The use of Solar Design Studio (SDS) [26] software using the aforementioned Sandia performance model takes into account a more detailed picture as briefly explained below. A series of menus allow the user to enter the appropriate data for a particular situation and the results should be much closer to reality.

**Climate selection-** loads details of hourly climatic data for a location spanning for a year. This can be from any appropriate default or external weather data file.

**System shading-** allows the loading of relevant typical (or empirical) system shading effects for the loaded climate or an alteration of the default parameters.

**System load-** allows the loading of a relevant daily load profile (including possible load profile changes during weekends).

**PV array configuration** -allows the loading of a datasheet of a PV module from a database in the package containing 150 (Sandia compiled) known commercial modules (but also permits use of an external file) plus the appropriate configuration in the installation (like number of parallel and series modules)

**PV array wiring** -allows the user to enter the distance between the array and the battery, and permissible percentage voltage drop and wire diameter.

**System battery bank** - allows the entry battery manufacturer's full data and details of configuration of the installation.

**Inverter option** -allows the entry of details about the required inverter.

When the data has been entered, one clicks 'calculate' and obtains various results including charts of monthly output power, battery states of charge and annual cost analysis among others.

In appendix VIII at the end of this chapter are graphic results of a simulation using SDS[26] for a sample fictitious load but a real Kenyan location, Thika town which is 40 km from Nairobi. Because the distance is less than 50 km and being at nearly the same altitude as Nairobi the default global radiation data file for Nairobi in the design software was deemed to be adequate and was used. Figure APVIIIa are daily and weekend load profiles to be met. Figure APVIIIb is the datasheet for the selected commercial PV module to be used (ASE-300-DGF/50). The menu allows for size of array to be specified. (In this case 200 modules in parallel by 1 in series). Figures APPVIIIc and APPVIIId show specifications for wiring and battery storage for the installation. Some typical default parameters like shedding are used. When 'calculate' is activated, figure APPVIIIe gives a display of the expected monthly performance of the PV installation in clearly and self explanatory bar charts. A variety of other results not shown in the appendix are also selectable. Since the method uses field validated weather models and real component data, the prediction of the energy production should be more accurate than by any other method to date. In fact from the author's anecdotal experience figure APPVIIIe appears very consistent with the normal Nairobi weather pattern, as June is normally relatively overcast while December is a full bright sunny season.

## **8.3 Wind power**

### **8.3.1 Background on wind power**

A wind turbine converts wind motion into rotary mechanical power that can, in turn, be used to operate mechanical tools or an electric power generator. Wind power is the least exploited resource in sub-Saharan Africa. This could be due to unproven negative speculation that may have resulted from lack of facts. For example, whereas it is generally assumed that wind speeds for landlocked trans-equatorial locations are low and hence not viable for electric power generation, power utilities in Rwanda and Kenya have successfully operated pilot projects of wind electric installations connected to their grids for a number of years [27]. Rural exploitation of wind energy for water pumping can however be encountered in some scattered locations in Kenya, Rwanda, Burundi and Tanzania. There are similar installations scattered elsewhere particularly in Southern as well as West Africa.

### 8.3.2 Wind turbine basics

A simple model for the power extractable by a turbine in a stream of air, utilises a momentum theory developed in the 19<sup>th</sup> century to predict the performance of ship propellers. The adaptation of the theory by Bilau in 1925 assumes the air stream flow to be steady and axial [28-33]. In addition, the air is assumed to be incompressible and inviscid (with negligible viscous effects), with a downstream flow that is constant over the particular stream tube section and having no discontinuity across the stream tube boundary. In this model the turbine is represented by a uniform disc actuator which creates discontinuity of pressure in the stream tube of air flowing through it.

The model (see figure 8.3) therefore permits the application of Newtonian mechanics. Using momentum and energy relationships the effective axial velocity,  $V$ , at the disc is given by equation (8.8)

$$V = \frac{1}{2}(V_1 + V_2) \quad (8.8)$$

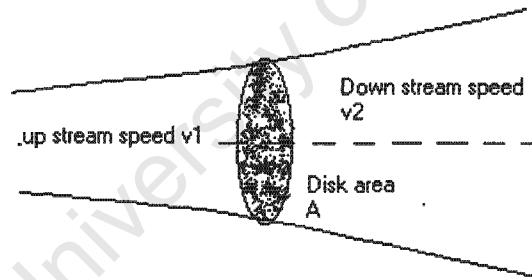


Figure 8.3. A stream tube representation of flow through a horizontal-axis tube (Ref [28])

In other words, equal retardation of the flow is imposed upstream and downstream of the disc. The power output,  $P$ , from the disc must therefore be the rate of change in kinetic energy of the stream. The kinetic energy of a mass  $m$  at a velocity  $V$  is  $\frac{1}{2}mV^2$ .

$$P = \frac{1}{2}m(V_1^2 - V_2^2) \quad (8.9)$$

where,  $m = \rho AV$  ( $\rho$  is the air density and  $A$  the area swept by the actuator).

The density of air,  $\rho$ , is affected by altitude and slightly by temperature and standard ratings are normally based on a temperature of 15° Celsius at sea level. A density correction is therefore needed for computation of power output at higher altitudes. Figure 8.4 is a plot of estimated changes in air density with altitude. In addition wind speeds increase with taller masts. A dimensionless number, the wind shear exponent, typically ranging from 0.10 to 0.25, gives the rate at which the wind speed varies with mast height above the ground. A low exponent corresponds to a smooth terrain while a high exponent is typical of a terrain with sizeable obstacles. A value of 0.14 (or 1/7) is frequently used as a first approximation.

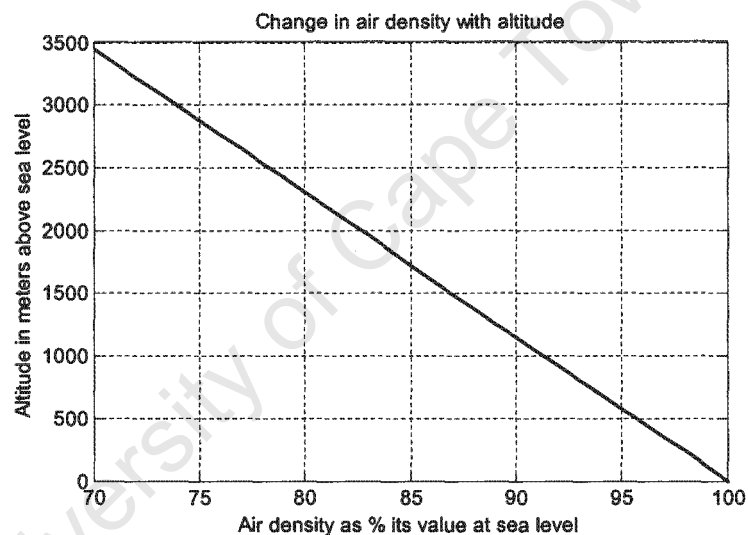


Figure 8.4. Estimate of air density as a percentage of its value at sea level against altitude in meters above sea level

From the above it is shown in [28] that power,  $P$ , can be expressed in terms of upstream velocity,  $V_1$  alone.

$$P = \frac{1}{2} C_p \rho A V_1^3 \quad (8.9)$$

The power coefficient,  $C_p$ , which is the ratio of the actual power delivered by the disc to the power of the free flowing stream prior to interference by the disc. The maximum theoretically extractable power (using this model) occurs when  $C_p = \frac{16}{27}$ .

$A = \pi R^2$  is the area swept by the turbine blades having a radius of  $R$  meters.

This ideal maximum however, can only be realised in an unrealistic boundary case where the turbine has a very large number of blades operating at a very high rotational speed and with its axis aligned in the direction of the wind. In practice the losses that this model ignores do in fact reduce the maximum power coefficient to between 0.25 and 0.45.

Among the myriads of turbine designs there is a major distinction between the centuries old types characterised by low speed and high solidity (large blade to sweep area ratio) and the high speed and low solidity types that have recently emerged. The former had poor tip speed ratio,  $\lambda$  values and high drag losses.  $\lambda$  is the ratio of the turbine peripheral speed to the free stream wind speed,  $V_1$ .

$$\lambda = \frac{\omega r}{V_1} \quad (8.10)$$

where,  $\omega$  is the angular velocity of the turbine,  $r$  is its tip radius.

The latter closely resemble aircraft propellers and achieve higher  $C_p$  and  $\lambda$  values.

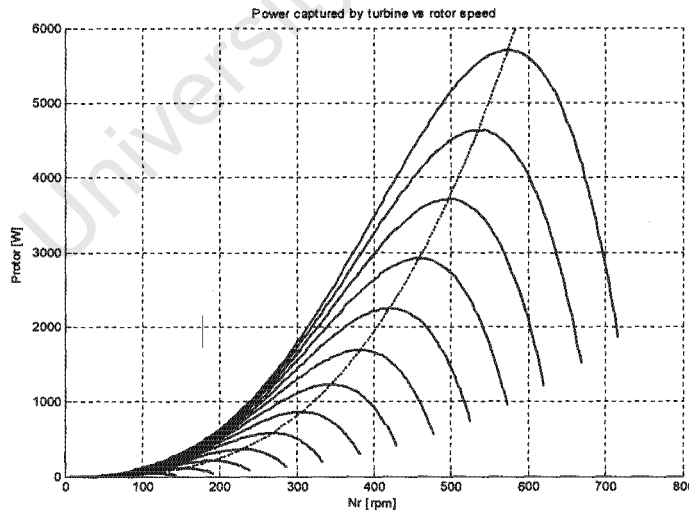


Figure 8.5. A family of curves for output turbine power at different rotor speeds

The shaft power delivered by a wind turbine can be influenced by the matching of torque speed characteristics of the prime mover and the load. The most general description of a turbine characteristic is the power/tip speed ratio curve.

Torque x angular speed = Power

$$\text{Torque} = \frac{\text{Power}}{\omega} = \frac{1}{\omega} \cdot \frac{1}{2} C_p \rho A V^3 \quad (8.11)$$

$$\text{But from (8.10)} \omega = \frac{\lambda V_1}{r}$$

Therefore

$$\text{Torque} = \frac{\pi r^3 \rho}{2} \cdot \frac{1}{\lambda} \cdot C_p \cdot V^2 \quad (8.12)$$

A family of curves for torque versus speed for a range of permissible wind speeds (Figure 8.5) can then be drawn. On each of these curves is a point of maximum output power for each wind speed. Joining these points creates a maximum power point locus. A load having a load line to match this locus will always draw maximum power.

### 8.3.3 Wind resource assessment

Equation (8.9) gives the turbine output power as a function of wind speed. It would be convenient if the average wind power could be computed from the average wind velocity at a location. But the wind power is proportional to the cubic power of the speed and relatively small changes in speed result in much larger power differences. In fact, the most frequently occurring wind speed may not necessarily have the highest energy content. So one way to solve the problem is by separately treating each wind speed and its duration time and summing up the results. This means that in practice, (due to the stochastic nature of wind) a method using a probabilistic model that predicts the frequency of occurrence of different wind regimes at a location must be used. A generally used method is a Weibull distribution model expressed in terms of a scale parameter and shape parameter [34, 35]. The two parameters are obtained from the mean and standard deviation of a sample set of data for a location.

In brief, a Weibull distribution can be characterised by its cumulative distribution function  $F(V)$  and probability density function  $f(V)$  where

$$F(V) = 1 - \exp\left(-\left(\frac{V}{c}\right)^k\right) \quad (8.13)$$

$$\text{and } f(V) = \frac{dF}{dV} = \frac{k}{c} \left(\frac{V}{c}\right)^{k-1} \cdot \exp\left(-\left(\frac{V}{c}\right)^k\right) \quad (8.14)$$

k and c are the shape and scale factors. These can only be determined from very detailed data of wind characteristics for a given location. So in its simplified version the shape factor k is assumed to be 2 and the model becomes known as the Rayleigh distribution. In this case the only requirement is the average wind velocity of the location for the period under consideration. The method has been validated by among others the American Wind Energy Association. It can then be shown that the cumulative distribution and probabilistic density functions simplify to equations, (8.15) and (8.16).

$$F(V) = 1 - \exp\left[-\frac{\pi}{4} \left(\frac{V}{V_m}\right)^2\right] \quad (8.15)$$

and

$$f(V) = \frac{\pi}{2} \frac{V}{V_m^2} \cdot \exp\left[-\frac{\pi}{2} \left(\frac{V}{V_m}\right)^2\right] \quad (8.16)$$

where  $V_m$  is the mean wind velocity for the location over the period under consideration.

If P is the power available per unit cross-sectional area at a given wind speed in a wind stream then the average wind energy density  $E_d$  at a site is given by

$$E_d = \int_0^{\infty} P f(V) dV \quad (8.17)$$

It is shown in [35] that  $E_d = \frac{3}{8} \frac{\rho \sqrt{\pi}}{K^{1.5}}$  watts/unit area.

Where  $K = \frac{\pi}{4V_m^2}$

In addition, small wind turbines (below 100 kW) are designed to operate within a range of wind speeds where a minimum cut-in speed ( $V_o$ ), is required to activate the turbine. As the wind speed increases further the turbine power output increases according to equation (8.9) until rated speed, ( $V_R$ ), when the maximum power output is achieved. As wind speed increases the power output is maintained at this maximum value until a design cut-off speed,  $V_1$ . For wind speeds higher than  $V_1$  a shut down is effected to avoid turbine damage. Figure 8.6 illustrates a typical small turbine power output as a function of wind speed. Under such circumstances therefore, evaluating the available wind energy density for a location must take into account the characteristics of the conversion technology.

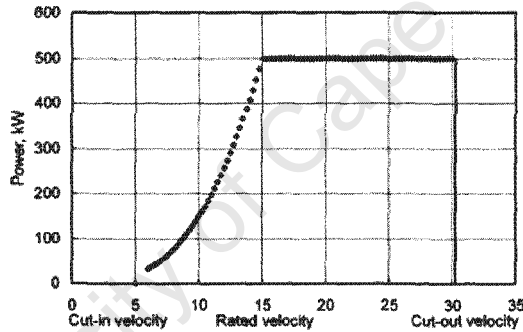


Figure 8.6. Output power as a function of wind speed for a small wind turbine (Ref [35])

From equation (8.17) and figure 8.6 the total useful power density  $E_{dm}$  available at a location is given by

$$E_{dm} = \int_{V_o}^{V_R} P(V)f(V)dV + TP_R \int_{V_R}^{V_1} f(V)dV \quad (8.18)$$

It is shown further in [35] that

$$E_{dm} = TK\rho \int_{V_o}^{V_R} V^4 \exp(-KV^2)dV + \frac{1}{2} \rho V_R^3 T [\exp(-KV_R^2) - \exp(-KV_1^2)] \quad (8.19)$$

T is given as the time period in hours.

Therefore the average power density  $P_{dm}$  for a location is given by equation (8.20),

$$P_{dm} = \frac{E_{dm}}{T} \quad (8.20)$$

Equation (8.19) is solvable by numerical integration using Simpson's rule.

Section 8.3.4 is a worked out example. The function in the variable term of  $P_{dm}$  is sampled at increments of 0.1 m/s over the interval from cut-in speed to rated speed and tabulated. The result is plotted and a best fitting polynomial is generated in Matlab. The final solution of the required power density is then obtained by analytically integrating the Matlab generated polynomial over the interval.

### 8.3.4 Rural applications of wind power

Consider a rural location with average wind speeds of 5 meters per second and a consumer with a daily requirement of 3kWh of electric energy. Assume that the available wind equipment has a cut-in wind speed of 3.5 m/s, a rated speed of 10 m/s and a cutout speed of 22 m/s. Let the turbine power coefficient be 0.35 with generator efficiency of 80%. Assume that the air density,  $\rho = 1.225$  [kg/m<sup>3</sup>].

From the above the available average wind power density can be estimated.

$$K = \frac{\pi}{4V_m^2} = \frac{\pi}{4 \times 5 \times 5} = 0.0314$$

$$\begin{aligned} P_{dm} &= 0.0314 \times 1.225 \int_{3.5}^{10} V^4 \exp(-0.0314V^2) dV + \\ &+ \frac{1}{2} \times 1.225 \times 10^3 [\exp(-3.14) - \exp(-0.0314 \times 22^2)] \\ &= \int_{3.5}^{10} f(V) dV + 26.5 \end{aligned}$$

The function  $f(V) = 0.0385V^4 \exp(-0.0314V^2)$  was tabulated at increments of 0.1m/s over the interval [3.5, 10.0], plotted in Matlab and a best fitting polynomial  $f'(V)$  was generated out as (see figure 8.7)

$$f'(V) = -0.12V^3 + 1.5V^2 - 1.1V - 6.2$$

Therefore the wind power density can be found by analytical integration of  $f'(V)$

$$P_{dm} = \int_{3.5}^{10} f'(V)dV + 26.5 = 121 \text{ Watts per square meter.}$$

The consumer requires 3kWh per day. But the generator is 80% efficient and the turbine power coefficient is 0.35. So the amount of wind energy required daily =  $\frac{3}{0.35 \times 80\%} = 10.7 \text{ kWh/day}$ . If this is assumed to be spread evenly round the clock it requires an average wind power supply of  $10.7 \div 24 = 0.45 \text{ kW}$ .

From the above, 1 square meter has an average of 121 watts. To get 450 watts the required area will be  $450 \div 121 = 3.69$  square meters.

If R is the radius of the turbine propeller then

$$\pi R^2 = 3.69$$

$$R = \sqrt{\frac{3.69}{\pi}} = 1.1 \text{ Meters}$$

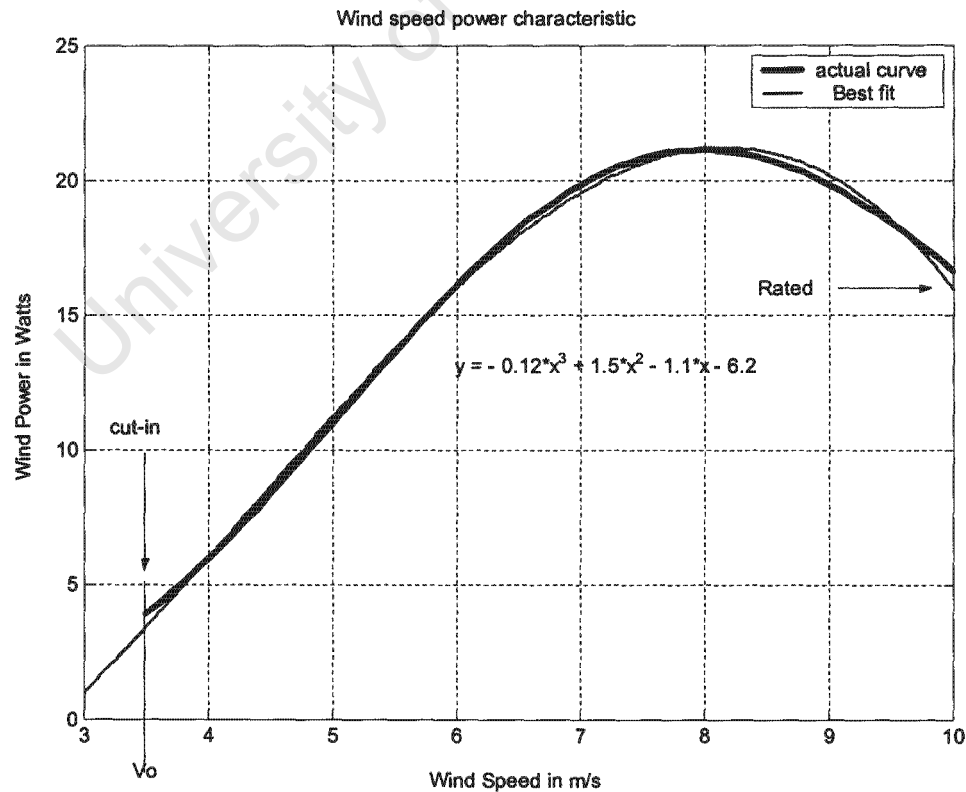


Figure 8.7. A plot of a tabulated wind energy as a function of speed with a best fitting function superimposed

Figure 8.8 shows a model of the wind distribution derived from figure 8.7 by evaluating and plotting the function  $\frac{f'(V)}{V^3}$  over the interval  $[3.5, 10.0]$ .

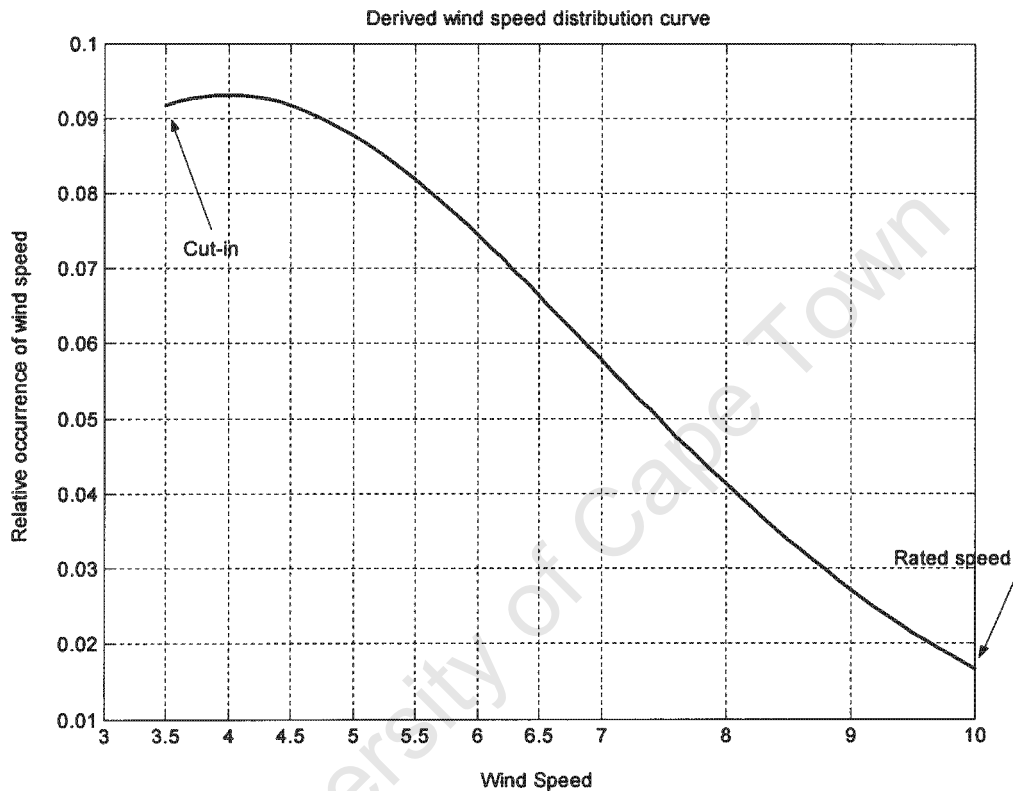


Figure 8.8. Wind speed profile derived from figure 8.7

## 8.4 Micro-hydro power

### 8.4.1 Background micro-hydro

The use of water wheels dates back to a few thousand years [36] when wooden wheels provided power mainly for grain milling. The industrial district of Sheffield in England is one example where the use of grinding stones for the fabrication of knives virtually predates history. The first use of moving water to produce electricity was reportedly a waterwheel on the Fox River in Wisconsin in 1882.

The dawn of the 20<sup>th</sup> century saw further evolution of falling water power as the prime mover in mainstream electric power production, mainly with large dams connected to cross country grid networks in Europe and the USA. This is however in sharp contrast with sub-Saharan Africa where such networks are largely absent. But even the few cases where they are, rural communities do not always benefit from grid electricity and hence the importance of developing small distributed resources [37-41]. This point is well illustrated in the case of South Africa which has a surplus grid capacity that could run several sub-Sahara African countries but has found it necessary to serve some rural communities with off-grid power systems, while a large number of communities still remain in darkness.

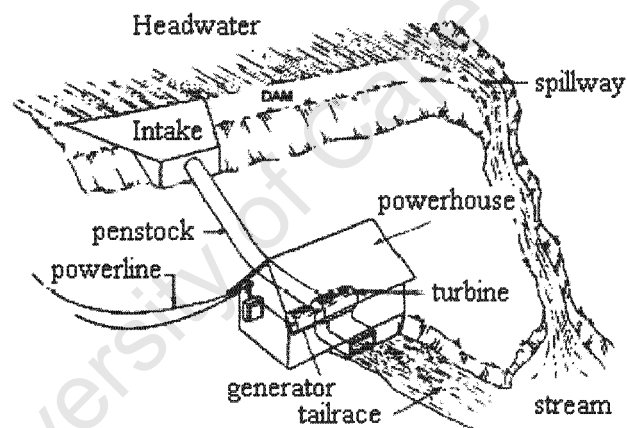


Figure 8.9. An over view of a micro-hydro site (Ref [38])

The term micro-hydro is defined differently in different parts of the world. In fact what may be referred to as micro-hydro in countries with grid capacities of orders greater than 50 gigawatts may pass as one of the main national utility generators in a country like Uganda which has a national grid capacity of just a few hundred megawatts! In the context of this chapter the term will refer to anything from 100 kW down to a small stream capable of a few tens of watts. The very low end is sometimes referred to as pico-hydro. Experience has shown that micro-hydro is one of the more cost-effective, reliable and environmentally-sound means of energy conversion especially, as it does not have the shortcomings of the big hydro systems like flooding and interference of river flows among others. In addition it is

a much more concentrated energy resource and is more predictable than either wind or insolation power.

Its comparative major shortcomings include its site dependence. In some climates severe droughts may result in the drying up of streams and hence total stoppage of generation. In the great lakes region of East and central Africa there is quite a good deal of small rural water resource potential for micro-hydro but like most other resources their exploitation is yet to be fully realised.

#### 8.4.2 Hydro technology

Hydro turbines convert moving water momentum into rotary shaft power, which can then be used either to power a machine directly such as a grain miller or run an electric generator [42-47]. The power extracted by the turbine is proportional to the height through which the water falls (pressure head  $H$ ), and the volume of water falling per second ( $Q$ ). There are two types of hydro turbines, the reaction and the impulse. In the reaction turbine, the fluid fills the blade passages, and the head change or pressure drop occurs within the runner. On the other hand an impulse turbine first converts the water head through a nozzle into a high-velocity jet, which then strikes the buckets at one position as they pass by. The runner passages are not fully filled, and the jet flow past the buckets is essentially at constant pressure. Impulse turbines are ideally suited for high head and relatively low power and are hence the choice for micro and pico hydro applications.

The Pelton turbine is one such type. It is comprised of three basic components namely, a stationary nozzle, a runner and a casing as illustrated in figure 8.10.

Momentum is imparted to the turbine as the water jet strikes the buckets. If it is assumed that the entire head is converted into velocity and that there are no losses in the turbine then all the kinetic energy of the jet will be converted into rotary mechanical power.

$$P = QH \quad (8.21)$$

Where  $Q$  is the available discharge per sec and  $H$  is the head on the nozzle.

Turbines have unique power-speed, as well as efficiency-speed characteristics and hence perform differently under different conditions. One must therefore consider the desired range of power production for the available water flow rates. In general the efficiency of a turbine is provided by the manufacturer's specifications. Figure 8.11 shows typical iso-efficiency curves, for a Pelton turbine for a variety of flow rates and impeller speeds. In the case of electric power generation the generator efficiency must also be included to get the actual electric power output.

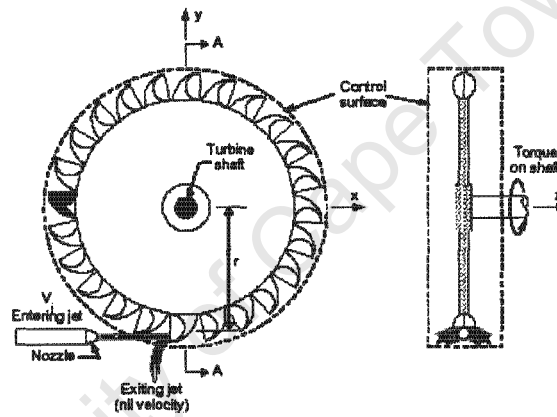


Figure 8.10. A Pelton type of turbine (Ref [39])

So the electrical power output is given by

$$P_e = \eta_t \rho g Q H_a \quad (8.22)$$

where  $P_e$  is the electrical power produced by the generator (Watts),

$\eta_t$  is the combined turbine hydraulic and generator efficiency

$\rho$  is the density of the water in  $kg/m^3$

$g$  is the gravitational acceleration in  $m/s^2$

$Q$  is the volume flow rate through the turbine in  $m^3/s$

$H_a$  is the available pressure head on the nozzle (m).

In a typical modern micro-hydro scenario, water is taken from a river by diverting it through an intake barrier across the river, called a weir, which maintains a continuous flow through the intake. The water then passes through a settling reservoir (forebay) in which it is slowed

down sufficiently for suspended particles to settle out. A rack of metal bars usually protects this, which filters out water-borne debris. A sluice gate (valve) then lets the water into a pressure piping (penstock) that finally leads to the turbine. During maintenance the valve is closed and the water is diverted back to the river down a spillway.

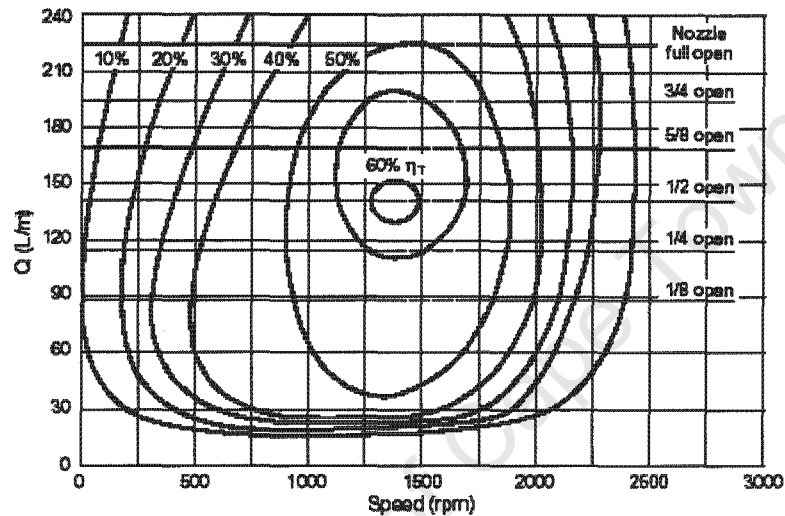


Figure 8.11. Typical iso-efficiency curves for a pelton turbine (Ref [39])

### 8.4.3 Micro-hydro resource assessment

From the above, the factors determining the power content of a small river are the head and the rate of water discharge. Three reasonably affordable ways have been suggested for assessment of the head.

- Using a surveyor's leveling instrument and scale
- Using a carpenter's level together with scale, wooden boards and plugs.
- Using a pressure gauge.

As for the flow rate, several options are also available. In the case of a small stream the time taken to fill up a bucket of known volume can be measured. For a larger river the cross sectional area of the stream can be estimated and multiplied by the speed of a floating object placed on the water surface. Finally an estimate of seasonal variations in the river flow rates is essential. In the likely absence of records, sample rates may have to be taken several times

during the course of a year. Information from the inhabitants of an area has been used in the past.

#### **8.4.4 A case study of a rural of micro-hydro application in Kenya**

The Micro-Hydro Centre of Nottingham Trent University in the United Kingdom implemented a Pico-hydro scheme in Kathamba village in Kirinyaga District in Kenya in 2002[48, 49]. The water source was a small village spring. The flow rate had been assessed to be at least 5 liters per second during 90% of the year with a net head of 28 meters. A reservoir of 80 cubic meters was constructed at the intake and fed through a penstock of 158m in length and 110mm in diameter, constructed out of PVC piping and leading to a Pelton turbine. A flow rate of 8.4 liters per second through the turbine was realised.

The turbine was directly coupled to an induction generator. The electrical output was 1.1kW and corresponded to a turbine-generator efficiency of 48%. The single-phase 230 volts ac supply was distributed to 65 households within a radius of 550m. An Induction Generator Controller to regulate the voltage and frequency during conditions of changing consumer load was installed. A 2kW cooking ring was used as a ballast load to dump excess power during low load demand hours.

### **8.5 The possibility of human power for electric generation**

Most of rural sub-Saharan Africa is not mechanised and manual labour plays a crucial role as a source of power for many activities, especially in agriculture and will most likely continue for some time to come. It would therefore be reasonable to suggest the possibility of generating electric power 'manually', at least for the most critical of functions like charging of cell phones and provision of reading light. This could present real life saving possibilities in certain emergency situations.

Humans (and animals) perform their physical activity by muscular work or exercise. This is achieved by transforming stored energy into mechanical work [50]. There are parallels that can be drawn between this human energy transformation process and automotive internal combustion engine. In either case the main source of power is the oxidation of hydrocarbon

fuel resulting in the release of energy, carbon dioxide and water. Equation (8.25) represents the oxidation of a sugar molecule.



Like the case of the automobile, humans store their energy in some high-energy battery pack-like cell phosphates. The most popular of these are the ATP (adenosinetriphosphates).

The challenge however is to develop appropriate conversion devices to harness this energy. It is important to access the energy at optimal power rates that are neither so demanding as to create undue human strain nor so weak as to take long and boring sessions.

Currently there is not much of precedent or literature about manual electric generation. An Indian pedal generator (Bijli bike) has been reported to operate lights in some remote off-grid rural Indian schools with finance from AID (Association for India's Development). A humanitarian organisation, Light Up The World (LUTW) [51] founded in 1997 by Dave Irvine-Halliday operates in Nepal and is reported to use, among other technologies, pedal generators to charge up batteries for lighting in remote villages. More recently Cable News Network (CNN) reported Laos villagers [52] operating laptops using pedal power. At the amateur level a number of gadgets have been suggested that include utilising human power in everyday hand or foot actions (swinging, walking, and pedaling).

The pedalling mechanism is low-tech and can be designed as a bicycle accessory. The generator portion has however some interesting aspects. In order to operate at moderate power rating (sustainable by an average human) the generator should operate at low speeds, perhaps in the range of 200 rpm. This can be realised by a machine with many poles, which could have cost implications due to commercial unavailability. There is however a machine type that could fit such a description, namely a stepper motor [53-54]. The only problem that may be encountered however is the poor efficiency at which the generator mode of this motor may operate. This has been estimated in the range of 20 - 30%.

## 8.6 Concluding remarks

The most common renewable energy resources and their state-of-the-art resource-to-electrical energy conversion technologies have been described. The importance of accurate resource assessment has been highlighted. In addition, various resource assessment methods using physical and/or software techniques suitable for sub-Saharan African rural locations have been described. Using worked out examples the practical usefulness of these methods has been demonstrated. Therefore it is possible to design accurate and hence cost-effective renewable energy installations even in data-deficient environments like rural sub-Saharan Africa.

## 8.7 Appendix VIII

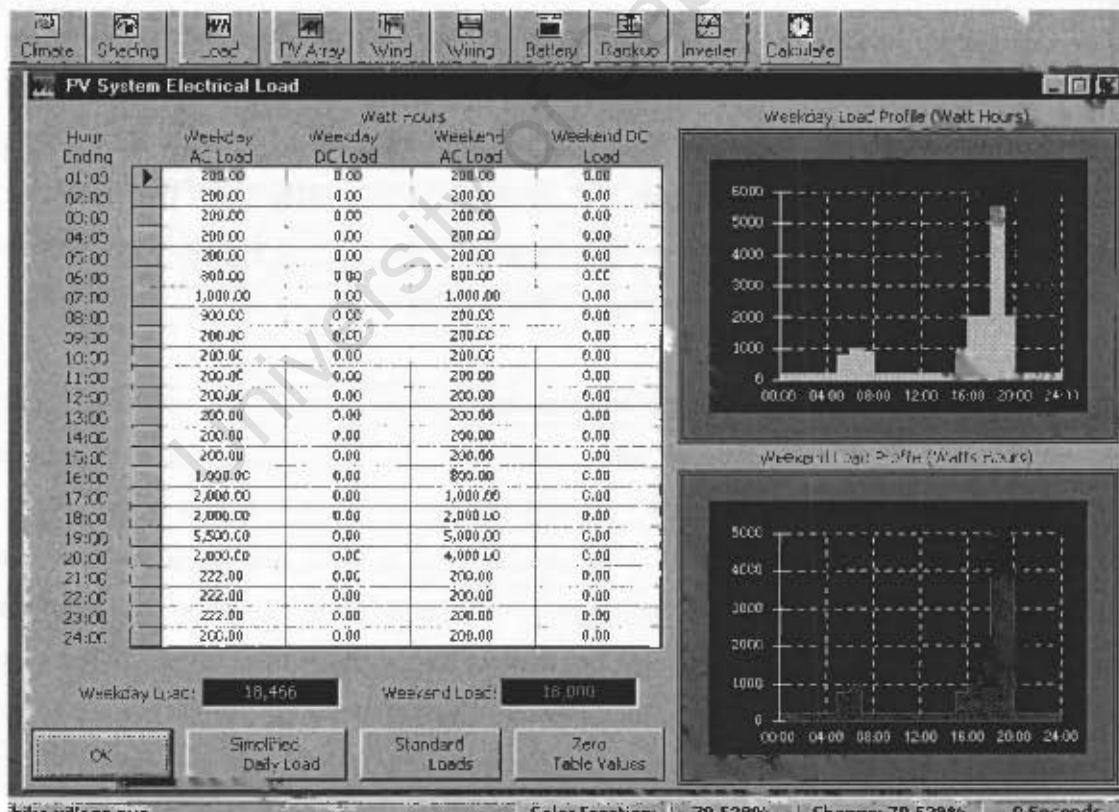


Figure VIIIa. A daily and weekly load profile for a household at Thika (Kenya)  
(from a worked out example in section 8.2.5)

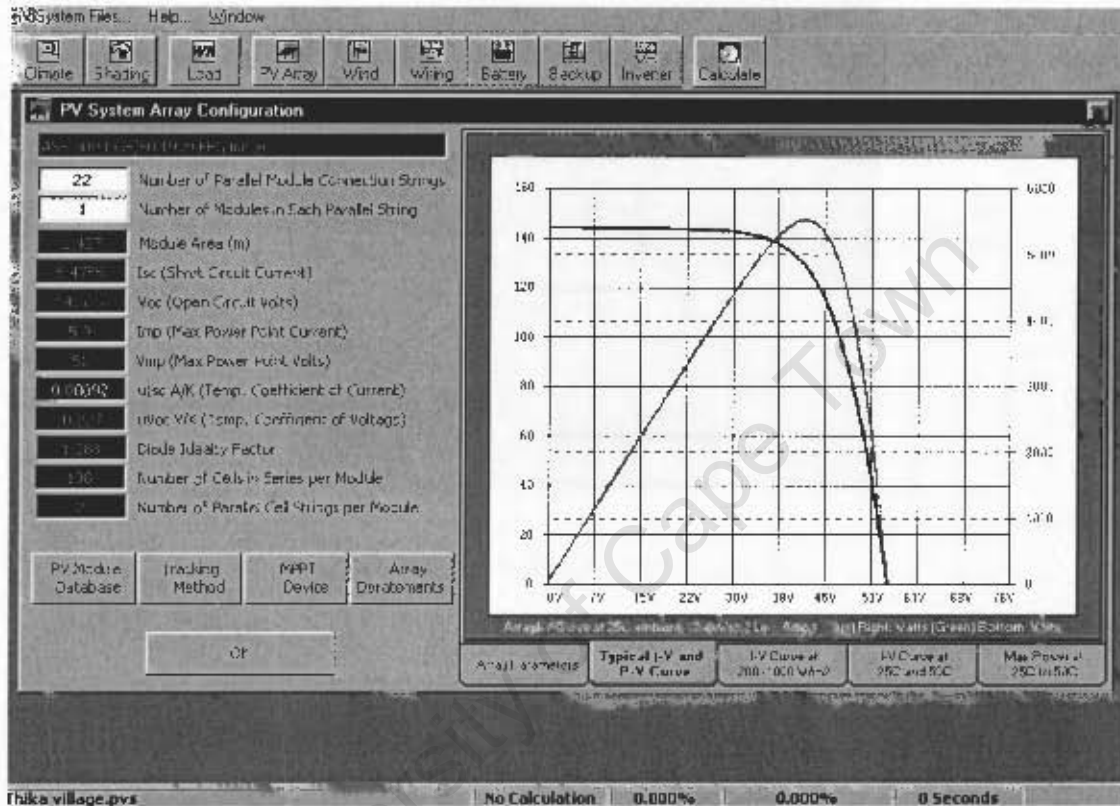


Figure APPVIIIb. Datasheet for the selected PV module (ASE-300-DGF/50) to be used (The menu allows for sizing of array)

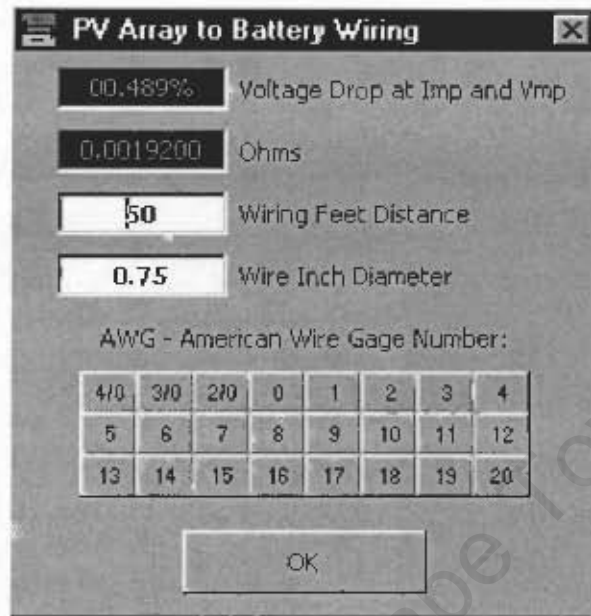


Figure APPVIIIc. Specification for wiring

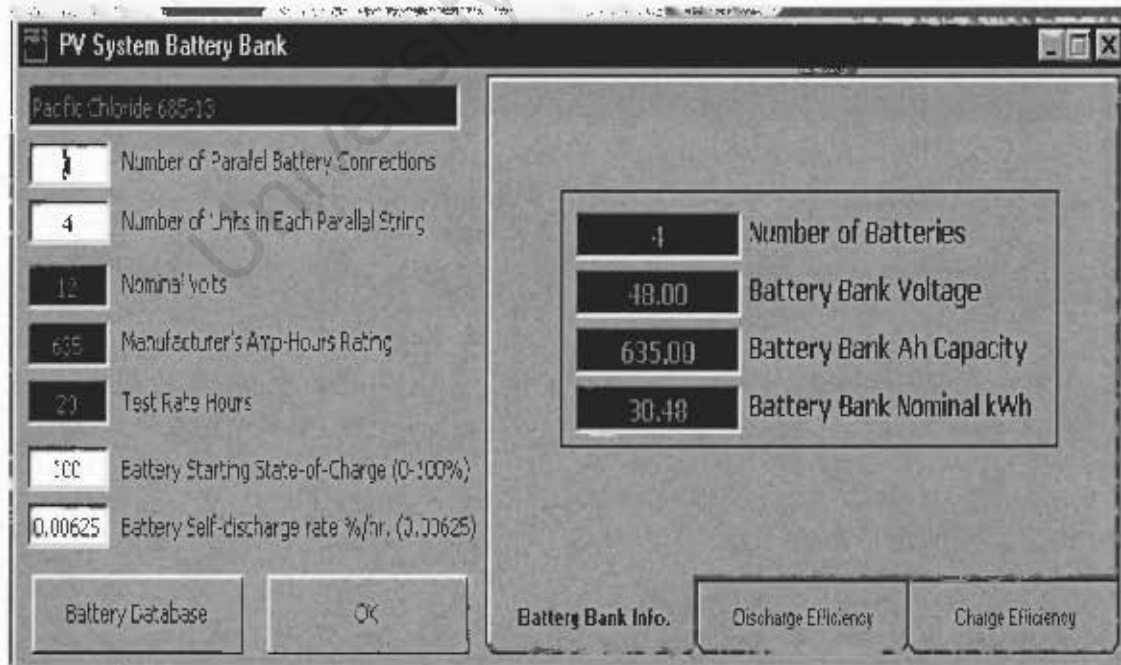


Figure APPVIIIId. The specification for the storage battery (Type Pacific Chloride 685-13)

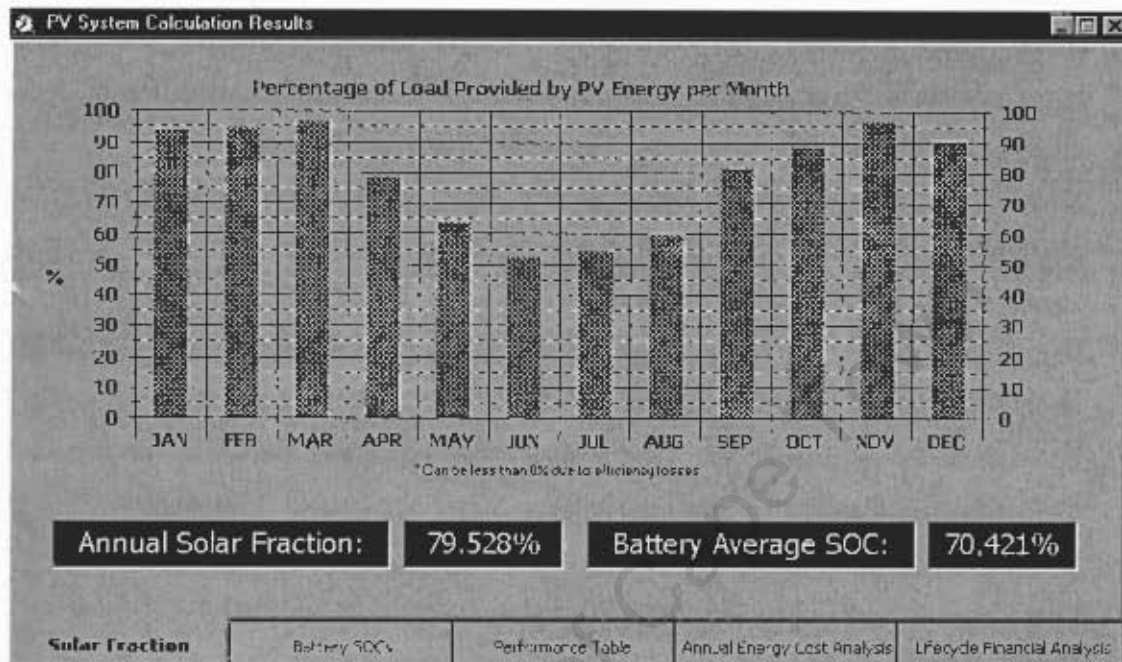


Figure APPVIII. A plot of the monthly performance as percentage of the load met by the installation

## 8.8 References VIII

1. "SunRay," <http://www.ream.net/www/krud/sunray.html>
2. Ryck Lydecker, "Fuel cells set sail," Boat/US magazine, Jan 2004  
[http://articles.findarticles.com/p/articles/mi\\_m0BQK/is\\_1\\_9/ai\\_112350800](http://articles.findarticles.com/p/articles/mi_m0BQK/is_1_9/ai_112350800)
3. Kristoferson L. A., Bakalders V., "Renewable Energy Technologies: Their Application in Developing Countries," Intermediate Technology Publications, 1991.
4. Gansler R. A., Klein S. A. and Beckman W. A., "Assessment of the accuracy of generated meteorological data for use in solar energy simulation studies," Solar Energy Vol. 53, No. 3, pp. 279-287, 1994.
5. Remund J., Salvisberg F., Kunz S., "On the Generation of hourly Short-wave Radiation Data on Tilted Surfaces," Solar Energy Vol. 62, No. 5, pp. 331-344, 1998

6. METEONORM, Global Meteorological Database for Solar Energy and Applied Climatology, Ver. 5.0, Edition 2003. <http://www.meteoest.ch/en/firma>.
7. Hankins M. "A case study on private provision of photovoltaic systems in Kenya." World Bank Energy Report 2000, Ch.11. ESMAP 2000 Washington <http://www.worldbank.org/html/fpd/esmap/energy--report2000/ch11.pdf>
8. Ochieng F. "The amorphous question." SolarNet 1999;1(1) Nairobi, Kenya.
9. Kammen DM. "Household power in a new light: policy lessons and questions for photovoltaic technology in Africa." *Tiempo*, vol. 20 pp. 1-8, 1996.
10. Jacobson A et al., "Field Performance Measurements of Amorphous Silicon Photovoltaic Modules in Kenya," Proc. (ASES), Madison, Wisconsin, June 16-21, 2000 <http://socrates.berkeley.edu/~dkammen/ASES-2000-aSi-paper.pdf>
11. ESMAP Technical Paper 012, "The Kenya Portable Battery Pack Experience: Test Marketing and Alternative for Low-Income Rural Household Electrification." The World Bank, 2001, Washington.
12. Green M. A. "Solar Cells – Operating Principles, Technology, and System Applications," Prince Hall, New Jersey, 1982.
13. Rauschenbach H. S., "Solar Cell Array Design Handbook: The Principles and Technology of Photovoltaic Energy Conversion." Van Nostrand Reinhold, New York, 1980.
14. "High-Efficiency Triple Junction Amorphous Silicon Alloy Photovoltaic" Technology, Annual Technical Progress Report, United Solar Systems Corp., July 1999.
15. Roger J. A. and Maguin C., "Photovoltaic Solar Panels including Thermal Effects." *Solar Energy*, vol.29, p.245–256, 1982.
16. "Solar Cell Handbook," Panasonic, August 1998. <http://www.solarbotics.net/library/datasheets/sunceram.pdf>
17. King D. L., "Modelling Annual Energy Production from Photovoltaic Modules," Highlights of Sandia's Photovoltaics Program December 2000
18. King D. L., Kratochvil J. A., Boyson W. F., "Photovoltaic System Performance Characterization Methodologies," Sandia National Laboratories Albuquerque, New Mexico 87185-0752 (NCPV and Solar Program Review Meeting 2003).
19. Whiraker C. et al, "Application and Validation of a New PV Performance Characterization Method," 26<sup>th</sup> IEEE PV Specialists Conference, 1997, pp. 1253-1256.

20. Kroposki B., et al, "Comparison Of Module Performance Characterization Methods," 28<sup>th</sup> IEEE PV Specialists Conference 2000, pp. 1407-1411.
21. Fanny A. II., et al, "Short-term Characterization of Building Integrated Photovoltaic Modules," Proceedings of Solar Forum 2002, Reno, NV, June 15-19, 2002.
22. Cahen D., Gartsman K., Hodes G., Rodevy O., Visoly-Fisher L, Dobson K., "Overcoming Degradation Mechanisms in CdTe Solar Cells." First Annual Report. February 2000. Weizmann Institute of Science, Rehovot, Israel.
23. Gavanidou E. S., Bakirtzis A. G., "Design of Stand Alone System with Renewable Energy Sources using Trade-off methods," IEEE Transactions on Energy Conversion, Vol. 7, No. 1, 1992.
24. "Photovoltaic Power Systems and the National Electrical Code: Suggested Practices" SAND2001-0674 Unlimited Release Printed March 2001.
25. <http://www.sandia.gov/pv>
26. Solar Design Studio. <http://www.manisolarsoftware.com>
27. Karekezi S, Rauja T., "Renewable energy technologies in Africa." Zed Books Ltd. in association with AFREPREN, London and New Jersey 1997.
28. Warne D. F., "Wind Power Equipment." E. & F. N. Spon Ltd, 1983.
29. Wegley, J. Ramsdell, M. Ongill and R. Drake, "A Siting Handbook for Small Wind Energy Conversion Systems." Report No. PNL-2521 Rev.1, 1980; National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22151.
30. Gipe P., "Wind energy basics -A comprehensive guide to modern small wind technology." White River Junction, Vermont. 1999.
31. Gipe P., "Wind Power for Home and Business - A comprehensive guide to modern small wind technology." White River Junction, Vermont. 1999.
32. Piggott II., "Wind Power Workshop" The Center for Alternative Technology, Wind Resource Assessment Handbook: Fundamentals for Conducting a Successful Monitoring Program"—National Renewable Energy Laboratories.  
<http://www.nrel.gov/publications>.
33. "Small Wind Electric Systems," National Renewable Energy Laboratories, DOE/GO-102001-1293, May 2001.
34. Dorvlo Atsu S. S., "Estimating Wind Speed Distribution," Energy conversion Management, vol., 43, pp. 2311-2318, 2002.

35. Mathew S. Pandey K. P., Kumar A. V., "Analysis of Wind Regimes for Energy Estimation," *Renewable Energy*, vol. 25, pp. 381-399, 2002.
36. <http://www.waterindustry.org/Water-Facts/story-of-water.htm>
37. Thornbloom M., Ngbangadia D., "Using Micro-hydro power in the Zairian Village," *Solar Energy*, vol.59, No. 1-3, pp. 75-81, 1997 (Elsevier).
38. Paish O., "Small hydro power: technology and current status," *Renewable and Sustainable Energy Reviews*, vol. 6 (2002) pp.537-556 (Pergamon).
39. "Principles of Hydraulics: Pelton Turbine Experiment," Fluids Laboratory, University of Iowa. <http://css.engineering.uiowa.edu/fluidslab/pdfs/53-071/lab4.pdf>
40. Waddell R., Bryce P., "Micro hydro systems for small communities," *Renewable Energy* 16 (1999) 1257-1261 (Pergamon).
41. Maher P., Smith N.P.A., Williams A. A., "Assessment of pico hydro as an option for off-grid electrification in Kenya," *Renewable Energy* 28 (2003) 1357-1369 (Pergamon).
42. Fraenkel P, Paish O, Bokalders V, Harvey A, Brown A, Edwards R., "Micro-Hydro Power: a guide for development workers". London: IT Publications Ltd, 1991.
43. "International Journal of Hydropower and Dams: World Atlas". Sutton: Aquamedia Publications, 2000.
44. Fulford S., Mosley P., Gill A. "Recommendations on the use of micro-hydro power in rural development". *Journal of International Development*, vol. 12, pp. 975-983, 2000.
45. "The EU-China Small Hydro Industry Guide". Chincham: IT Power Ltd., 1999.
46. Harvey A. et al., "Micro-Hydro Design Manual". London: IT Publications Ltd., 1993.
47. Khennas S, Barnett A. "Best Practices for Sustainable Development of Micro-Hydro in Developing Countries," ESMAP Technical Paper 006, IBRD, World Bank, 2000.
48. Maher P., Smith N.P.A., "Pico hydro for village power — a manual for schemes up to 5 kW in hilly areas" Internet-published training document, 2001.  
<http://eee.ntu.ac.uk/research/microhydro/picosite>.
49. Smith N.P.A., Maher P., Williams A. A., "Strategies for sustainable and cost effective village electrification using Pico hydro power". *World Renewable Energy Congress V1*. Elsevier Science Ltd.; 2000, pp. 1490-1496.
50. Christensen E. H., "Textbook of Work Physiology," McGraw-Hill Inc. 1977
51. <http://www.lightuptheworld.org/>

52. CableNewsNetwork, "Pedaling onto the Information Superhighway: Laos villagers to get online with bike-powered PCs." Tuesday, February 18, 2003 Posted: 10:21 AM EST (1521 GMT)  
<http://www.cnn.com/2003/TECH/internet/02/18/laos.onlinbybicycle.ap/index.html>
53. <http://www.c-realevents.demon.co.uk/steppers/stepmotor.htm>
54. <http://www.bioelectrifier.com/mini.htm>

University of Cape Town



## 9. A Specification of a Flywheel Battery for Rural Electric Energy Storage

### 9.1 Introduction

Kenyan rural electric loads are characterised by poor load factors with virtually no coincidence between generation and consumption. In the case of PV, for example, power generation is by daytime, while the lighting and infotainment dominated loads are almost entirely by night. Cynics have aptly likened operating such a system, without adequate storage, to milking a cow without a bucket. Energy storage remains by far the biggest challenge in rural electrification.

Electrical energy storage technology in sub-Saharan Africa is almost exclusively by chemical batteries, particularly the automotive lead acid type [1]. The batteries have low initial prices but this is deceptive, as their short lifespans imply routine replacement expenses. This increases the burden on the environment due to the frequent disposal of toxic materials. In addition, they have low depth of discharge capabilities and thus larger than necessary capacities are required, which further erodes their apparent cost advantage. There are certain battery types, which have labels like “solar batteries” with somewhat enhanced depths of discharge but this often comes with trade offs.

Gary Hunt [2] refers to an inextricable link between power, energy and lifespan (in both age and charge/discharge cycles) that continues to baffle chemical battery researchers. Whenever any one of these three functions is enhanced, at least one of the remaining two deteriorates. For example, in order to deliver a required peak transient power, the design must offer high electrolyte to plate exposure but this in turn increases self-discharge rates and hence reduces the available energy. Ambient temperatures also affect charging characteristics and general performance. Other issues range from simple ones like water loss (or drying up) to more abstract ones like electrolyte stratification. In renewable energy installations, batteries are often connected in series strings and charged while in use. Due to disparities in chemistry, different cells charge at different rates and the necessary equalization to allow the slow charging sections to top up cannot be carried out feasibly. Moreover due to the stochastic nature of resources, many generators are fitted with maximum power point trackers which

often conflict with the set 'optimum' battery charging rates and results in dumping of excess power even when batteries are not fully charged. In addition, if battery cells should be kept at overcharge (say above 2.45volts in case of lead acid) for long periods, grid corrosion results. On the other hand, in cases of sustained low insolation and high load demand, the batteries will have to be exposed to long periods of deep discharge. This could lead to (the aforementioned) sulfation: a state that renders recharging difficult and at times impossible [1]. Moreover, all chemical batteries suffer from high discharge shock, which compromises their lifespans. Consequently, chemical batteries require expensive and highly skilled maintenance in order to yield maximum life. Skilled manpower and disposable income are rare commodities in African rural areas.

The flywheel [3-18] is an age-old technology that has seen recent revival and could subsequently evolve to address the above concerns. The use of flywheels as reaction wheels (like porter's wheels) dates back to biblical times. The first electromechanical battery was however only reported in a late 1940's in the urban Swiss vehicle called the gyrobus. Even then further research did not pick up until the 1970's, mainly for outer space programs but still kept a relatively low profile. The early 1990's saw a new revival as international political pressure increased demand for environmentally benign technologies. This was augmented by developments in strong lightweight materials, magnetic technology and solid-state electronics. Subsequently, flywheel battery technology was shortlisted as one of the candidate technologies by the Partnership for a New Generation of Vehicles (PNGV) in mid 1990's [19, 20].

Potential attributes of the technology include long lifespans, ability to charge or discharge at very high power rates through very deep cycles, no deterioration in performance with number of charge/re-charge cycles and freedom from most of the chemical battery encumbrances. This technology has the potential to challenge the energy density of petroleum.

This chapter will examine the possibility of using the environmentally benign electromechanical flywheel battery in rural sub-Saharan Africa. Section 9.2 introduces the basics of kinetic energy storage. Section 9.3 provides the design equations of a flywheel

motor generator. Section 9.4 discusses the role of power conditioning electronics. Section 9.5 develops a specification for a suitable flywheel battery, under near idealised conditions, for a rural household load and illustrates the usefulness of the machine design equations. Section 9.6 examines the current status, some pending research issues and the projected future of the flywheel battery. Conclusions will then be drawn as to the possibility of adopting the flywheel battery as electrical energy storage for rural requirements.

## 9.2 Kinetic energy storage

In principle, a flywheel stores energy in kinetic form, in a rotating wheel that is suspended on frictionless bearings in an aerodynamically drag free vacuum enclosure.

The kinetic energy stored in a moving body is proportional to its mass and the square of its linear velocity.

$$KE = \frac{1}{2}mv^2 \quad (9.1)$$

When transformed into rotational motion one must consider the moment of inertia  $J$ . For the solid cylinder (figure 9.1) rotating about its axis, the moment of inertia is defined as  $J = \sum m_i r_i^2$ , the sum of all elemental masses multiplied by the square of their distances from the rotational axis. As the sizes of these particles tend to zero they are virtually cubic with dimensions  $\delta\omega$ ,  $\delta r$  and  $h$ .

$$J = \int_{\theta=0}^{2\pi} \int_{r=0}^R \rho h \cdot d\omega \cdot dr \cdot r^2 \quad (9.2)$$

It is shown in appendix VIII at the end of the chapter that

$$\text{For a solid cylinder } J = \frac{1}{2}mr^2 \quad (9.3)$$

(Equation (9.4) is in the appendix)

And that for a hollow cylindrical system, as is typical of flywheels

$$J = \frac{1}{2}m(r_o^2 + r_i^2) \quad (9.5)$$

Where  $r_i$  and  $r_o$  are the inner and outer radii respectively and the kinetic energy stored  $KE$

is given in equation (9.6)

$$KE = \frac{1}{2} J \omega^2 = \frac{1}{4} m(r_o^2 + r_i^2) \omega^2 \quad (9.6)$$

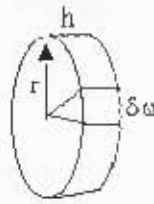


Figure 9.1. A solid cylinder with radius  $r$  and height  $h$

The energy grows in proportion to the flywheel mass and the square of the angular velocity. So there is more emphasis on angular velocity rather than mass.

Consider a special case of a thin rotating ring. Its moment of inertia,  $J$  is given by equation (9.5). But as the thickness tends to zero  $r_i = r_o = r$  and  $J = \frac{1}{2} m(r_i^2 + r_o^2) = mr^2$ .

But  $v = r\omega$

So kinetic energy,

$$KE = \frac{1}{2} mv^2 = \frac{1}{2} mr^2 \omega^2 = \frac{1}{2} J \omega^2 \quad (9.7)$$

where  $v$  is the linear velocity of a particle,  $r$  is the mean radius of the ring,  $m$  is its mass and  $\omega$  its angular velocity.

The spinning subjects the rotor to stresses in proportion to the square of the angular velocity. These stresses can lead to failure. So, the maximum speed and therefore the maximum amount of energy storage attainable by the rotor is governed by its tensile strength.

$$KE = \frac{1}{2} m \frac{\sigma_h}{\rho} = \frac{1}{2} J \omega^2 \quad (9.8)$$

where,  $\sigma_h$  is the maximum allowable hoop stress for the ring,  $\rho$  is the density of the

material.

The above expressions are only true for a thin ring. To get the total kinetic energy of a composite disk one would, in theory, have to sum up the energy in the nearly infinite thin rings. It will however be shown in section 9.6 that in practice the factors that determine rotor failure are much more complex. There is still lack of adequate experience and test data and much is still the subject of intense research. For example, while different composite flywheel designs may exhibit clearly different types of failure, similar designs may not necessarily fail in a similar manner.

### 9.3 The motor-generator

In order to transfer energy to and from the spinning disk a motor generator is used. The most popular choice is a permanent magnet synchronous machine, with an outer rotor design largely due to its high efficiency. The heart of this machine is an ironless magnetic array: an innovation by Klaus Halbach [20] which reduces the stator losses to just the copper losses. The outer rotor is integrated into the flywheel, forming one unit instead of a machine with an attached flywheel.

An ideal Halbach cylinder is defined as an infinitely long structure where the magnitude of the magnetisation is constant and its orientation turns continuously. At an angular position  $\phi$  in the cylinder, measured clockwise from the  $y$ -axis, the magnetisation has an orientation  $2\phi$ . The collective result is a uniform magnetic field,  $B_y$  in the  $y$  direction within the cylinder bore and a zero field outside the cylinder. The field is dependent only on the ratio between the inner  $r_i$  and outer  $r_o$  radii of the cylinder (or the difference between their natural logarithms) as given by equation (9.9).

$$B_y = J_r \ln\left(\frac{r_o}{r_i}\right) = J_r (\ln r_o - \ln r_i) \quad (9.9)$$

where  $J_r$  is the remanent field of the magnetic material of the cylinder.

In practice however, approximations of this ideal design are constructed from a finite

number,  $N$ , of short segments of high quality (rare-earth) magnets and systematically rotated to form an array as shown in figure 9.2. It has the advantage of cutting down on cost of magnetic material as well as improving their stress performance. They can be arranged depending on the number of poles required. These magnets form the inner part of the motor rotor as illustrated in figure 9.3. Unlike the ideal case, however there's a finite stray field on the outside. There is also a possibility of some mild eddy current in the array magnets due to the current in the stator winding. In the illustrated practical dipole (figure 9.2) the magnetic field  $B$  (in the bore) is dependent on the number of magnet elements used, as well. It is given by Halbach's theoretical treatment as equation (9.10),

$$B = J_r \ln \left( \frac{r_o}{r_i} \right) \eta \quad (9.10)$$

$$\text{where } \eta = \left[ \frac{\sin(2\pi / N)}{(2\pi / N)} \right]$$

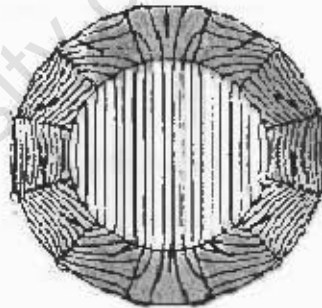


Figure 9.2. Magnetic field distribution of a dipole Halbach array

As illustrated in figure 9.3, the winding is on the inner core which forms the stator, while the magnet array is moulded with the composite rotor with which it spins. The losses to be expected from the configuration in figure 9.3 are, copper losses in the stator windings, rotor bearing losses and no air drag losses in the vacuum chamber. Therefore, the deceleration torque on no load (which is the self-discharge factor for the battery) is constant and not dependent on rotor speed. Bearing losses are minimized by the use of magnetic rather than mechanical bearings. The copper winding for the armature is sometimes made from tubing

to enable the circulation of cooling oil.

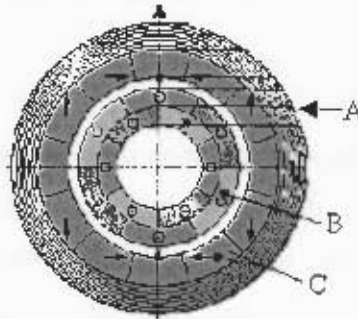


Figure 9.3. A cross-section of an ironless motor generator (complete) with the composite rotor

*A is the composite ring,*

*B is the electrical winding 3 phase 4 pole*

*C is the magnet array*

The performance of the machine can then be summarised as follows. Since the field strength,  $B$  and the depth of the magnetic ring,  $l$  are constant, the torque developed during charging will depend on charging (armature) current.

So for the dipole above, with  $I_{eff}$  as the effective current and  $l$ , as the magnetic depth, the torque  $T$  is given by

$$T = B \frac{\sqrt{2}}{3} q I_{eff} \sin\left(\frac{\pi}{q}\right) \quad (9.11)$$

where,  $q$  is the number of phases for the machine.

The choice of a dipole version of the Halbach's magnet arrangement has been further supported in [5] on the grounds that it makes the inductive coupling between the magnets and the windings relatively insensitive to the radial gap between them. This eases the mechanical clearance between them.

In [18] Ofori-Tenkorang et al showed that the torque developed by a permanent magnet

synchronous motor using the Halbach array (with an ironless core) is much higher than for a conventional array using the same weight and type of magnets.

## 9.4 Power Electronics

The function of this sub-system is to condition the power to and from the generator [21, 22]. This is necessitated by the fact that the flywheel motor generator has a continually variable voltage and frequency. Likewise, the levels of power from an external source like a wind turbine or a PV generator often vary with time. Currently the most popular drive components are insulated gate bipolar transistors (IGBT). These are driven by appropriate control electronics. Figure 9.4 illustrates a typical 3-phase flywheel battery /power conditioner scenario.

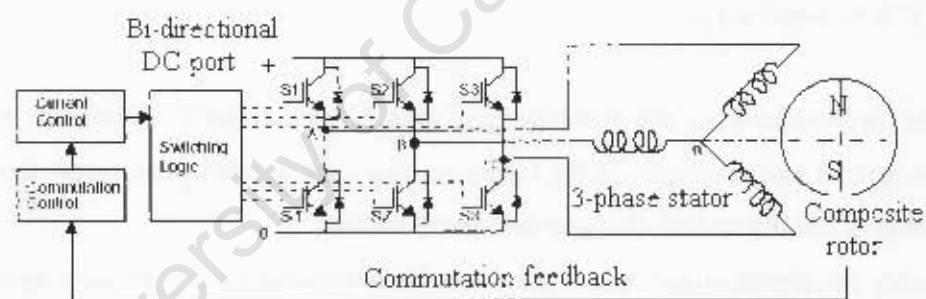


Figure 9.4. Flywheel motor/generator connected to a DC bus via a power-conditioning configuration using a 6 digit pulse topology.

The DC port is bi-directional depending on whether the battery is in generating or charging mode and could be connected directly to a DC generator and DC load or via an inverter to an AC load. In figure 9.4 the IGBTs are designated as S1, S2, etc. They are operated by micro-controllers in a 6-pulse bridge topology. Commutation is enabled by rotor position feedback obtained from Hall effect sensors built into the stator to detect the position of the rotor magnetic field.

The mounting is such that they each generate a square wave with  $120^\circ$  phase difference over one electrical cycle of the motor (figure 9.5). The amplifier drives two of the three motor

phases with DC current during each specific Hall sensor state. The technique is reputed to result in a very cost effective amplifier [21].

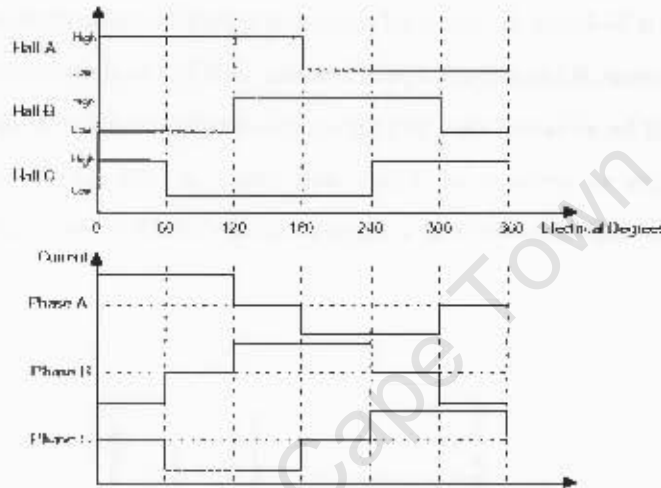


Figure 9.5. 1 Hall sensor based commutation

### 9.5 A possible flywheel battery specification for a rural application

From the above, the energy stored in a flywheel battery is proportional to the system moment of inertia,  $J$  and the square of the rotor system angular speed. (For convenience, details of the power conditioning equipment will assumed to be ideal). If the rated angular speed of the flywheel rotor is  $\omega_r$ , then maximum energy that can be stored is  $E_r$  such that

$$E_r = \frac{1}{2} J \omega_r^2 \quad (9.12)$$

If the maximum permissible depth of discharge for the battery is 90%, then there would be a balance of 10% of the energy at which point the rotor speed would be  $\omega_a$ , such that

$$\omega_a = \sqrt{\frac{\omega_r^2}{10}} = 0.316 \omega_r \quad (9.13)$$

The terminal voltage of the flywheel generator is linearly proportional to the rotor speed. Therefore, the terminal voltage at 90% depth of discharge (DOD) would be 31.6% of the full speed voltage,  $V_r$ , which is the rated voltage. Considering the internal impedance to be

negligible the open circuit voltage should be approximately equal to the output bus voltage even at full load. Let the flywheel battery be designed to deliver its continuous rated power  $P_R$  over the entire operating speed range. Then by Ohm's law, the current drawn at the minimum operating speed would be the highest permissible or rated current.

Figure 9.6 is a 24-hour electric load profile of a rural household from a database of the South African National Rationalised Specifications (NRS) Load Research Project for Garagapola village. It will be assumed that this represents a typical daily load profile. The daily peak load is 7.85A, with an average of 0.66A and hence a load factor of 8.4%. The total energy consumed by the household at a supply voltage of 230V was  $(24 \times 0.66 \times 230) = 3643.2$  Wh.

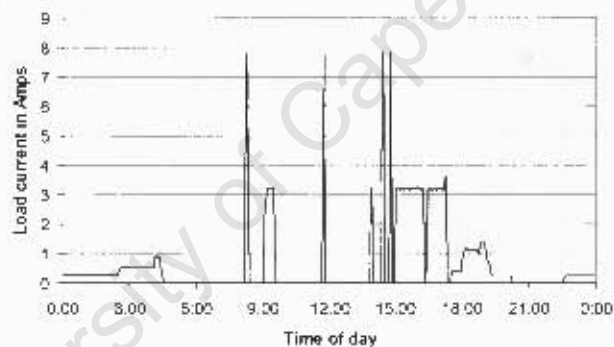


Figure 9.6. A 24-hour load profile recorded by NRS for a household in Garagapola village, South Africa

Consider the above to be an off-grid rural household operating from a stochastically distributed renewable energy source, which would require a storage battery. It is regular practice for off grid storage facilities to be specified for several autonomous days each being equivalent to the average daily requirement. So if this household were to have a storage capacity to last for 2 autonomous days (plus one normal day) then the available battery capacity would be  $(3643.2 \times 3) = 10929.6$  Wh. Since the maximum allowable depth of discharge for the flywheel battery is 90%, then the flywheel battery capacity must be  $(10929.6 \text{ Wh} \div 90\%) = 12144$  Wh. This capacity however does not take losses into account. If a battery charge-discharge efficiency of 80% is assumed [4] then final value is  $(12144 \text{ Wh} \div 0.8 = 15180 \text{ Wh})$ .

phases with DC current during each specific Hall sensor state. The technique is reputed to result in a very cost-effective amplifier [21].

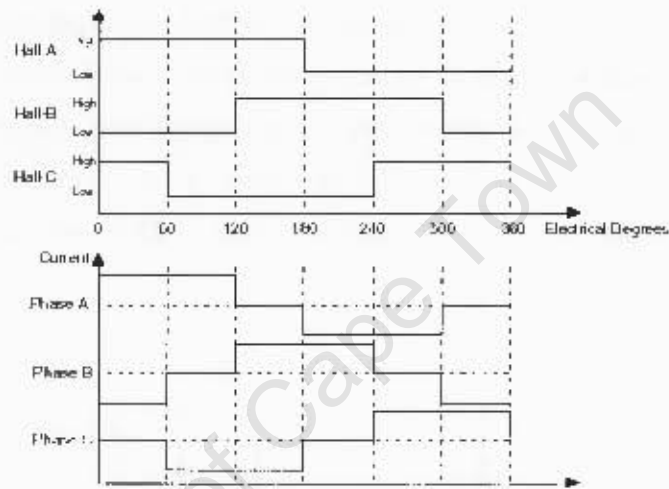


Figure 9.5. Hall sensor based commutation

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$$E_r = \frac{1}{2} J \omega_r^2 \quad (9.12)$$

If the maximum permissible depth of discharge for the battery is 90%, then there would be a balance of 10% of the energy at which point the rotor speed would be  $\omega_s$ , such that

$$\omega_s = \sqrt{\frac{\omega_r^2}{10}} = 0.316 \omega_r \quad (9.13)$$

The terminal voltage of the flywheel generator is linearly proportional to the rotor speed. Therefore, the terminal voltage at 90% depth of discharge (DOD) would be 31.6% of the full speed voltage,  $V_r$ , which is the rated voltage. Considering the internal impedance to be

Let the flywheel be designed for a rated speed  $\omega_r$  of 60,000 revolutions per minute, which is  $2000\pi$  radians per second.

$$\text{From the above, } 15180 \text{ Wh} = 3600 \times 15.18 \text{ kilo joules} = \frac{1}{2} J(2000\pi)^2$$

(where,  $J$  is the flywheel rotor system inertia)

$$\text{Therefore, } J = 2.77 \times 10^{-3} \text{ kg} - \text{m}^2$$

Household peak power demand =  $(7.85 \times 230) = 1.81 \text{ kW}$ . Allowing for a margin of error, the battery could be rated for continuous power of 2.0 kW. As stated, the validity of this specification is required for the entire operating speed range and must therefore be applicable at the minimum state of charge. In this case, when there is only 10% of storage capacity and at a rotor speed (and hence at a bus voltage) of 31.6% of the rated.

Let the full rated voltage be 100V, then at 10% state of charge (SOC) the voltage will be 31.6V.

Then the rated current,  $I_r$  must equal to the rated power divided by the minimum operating voltage

$$I_r = \frac{2000}{31.6} = 63.30 \text{ Amp}$$

The load torque exerted on the flywheel is proportional to the generator current (which is the load current) and therefore the maximum load torque will be at the rated load current.

From equation (9.11), the torque is  $T = B \frac{\sqrt{2}}{3} q I_{\text{eff}} \sin\left(\frac{\pi}{q}\right)$ . This should be true for both charging and discharging modes. But power,  $P$  is the product of torque,  $T$  and angular speed,  $\omega$ . Therefore

$$P = T\omega = K_t q I_{\text{eff}} \omega \quad (9.14)$$

Where,  $K_T = B \frac{\sqrt{2}}{3} I \sin\left(\frac{\pi}{q}\right)$  is the torque constant and  $q I_{\text{eff}} =$  total load current

From equation (9.10) the minimum flywheel speed is given by,  $\omega_s$  such that

$$\omega_s = 0.316\omega_r = 0.316 \left( \frac{2\pi \cdot 60000}{60} \right) = 632\pi \text{ radians per second.}$$

Then from equation (9.11) the machine torque constant,  $K_t$  can be calculated using rated

power at minimum speed.

$$K_v = \frac{P}{632\pi \cdot qI_{eff}} = \frac{2000}{632\pi \cdot 63.3} = 0.02 \quad (9.15)$$

Let the design be a three-phase ( $q=3$ ) machine

$$K_v = B \frac{\sqrt{2}}{3} (3 \cdot l \cdot \sin \frac{\pi}{3}) = B \frac{\sqrt{2}}{\sqrt{3}} \cdot l = 0.02 \quad (9.16)$$

From equation (9.10)

$$B = J_r \ln \left( \frac{r_o}{r_i} \right) \left( \frac{\sin \left( \frac{2\pi}{N} \right)}{\left( \frac{2\pi}{N} \right)} \right)$$

Using the dipole in figures 9.2 and 9.3 the number of magnets used is 12. Let  $N = 12$ . The remanent field of grade 32 rare earth, Nd-Fe-B (Neodymium Iron Boron) is typically  $J_r = 1.15$  tesla.

$$B = 1.15 \ln \frac{r_o}{r_i} \left( \frac{\sin \frac{\pi}{6}}{\frac{\pi}{6}} \right) = \frac{3}{\pi} \ln \frac{r_o}{r_i}$$

In [4] the value for  $\frac{r_o}{r_i}$  is assumed to be 1.5. Using this figure the value of the dipole strength,

B is

$$B = \frac{3}{\pi} \times \ln 1.5 = 0.39 \text{ tesla}$$

From (14), the expression for the axial length  $l$  can be found

$$l = \frac{0.02}{B \frac{\sqrt{2}}{\sqrt{3}}} = 0.05 \text{ meters}$$

Since the rated power of 2000W must be available at minimum angular speed of  $632\pi$  then the maximum torque T is given by

no load. Then the total amount of energy lost this way must be  $\leq 90\%$  of full storage capacity  $\leq 90\% \times 15180Wh = 13662.9Wh$ . Therefore the average self-discharge rate =  $13662.9 Wh$  in  $(24 \times 30)$  hours or  $18.98 W$ .

Assuming a total absence of air drag in the containment chamber, these losses are due to bearing friction and proportional to the rotor mass. The resulting deceleration torque  $T_d$  is therefore constant and is equal to the product of the average speed over the deceleration range and the average rate of loss of power. Speed range is  $2000\pi$  to  $632\pi$  radians per sec. So the average speed is  $1316\pi$  rad/sec.  $T_d \cdot 1316\pi = 18.98W$ . Therefore the permissible

bearing frictional torque should not exceed  $T_d = \frac{18.98}{1316\pi} = 4.6 \times 10^{-7} Nm$

$$\text{From equation (9.5), } J = \frac{1}{2} m(r_o^2 + r_i^2)$$

Let the inner radius  $r_i = 25mm$ . From [5] it is assumed that  $\frac{r_o}{r_i} = 1.5$ . Using the same assumption the outer radius  $r_o = 1.5 \times 25 = 37.5mm$

Therefore the rotor mass =

$$m = \frac{2J}{(r_o^2 + r_i^2)} = 2.73kg$$

## 9.6 The present and future of the flywheel battery [22-25]

The foregoing example has mainly focussed on the electromagnetic analysis of the battery. The assumptions made with respect to the Halbach array would hold reasonably true. However there are issues, for example, the requirement that battery self-discharge be less than 90% per month that may currently be viewed as an extreme demand. Consequently a number of values obtained, like the rotor mass could be grossly at variance with reality. Moreover, the machine was assumed to behave ideally with respect to important issues, like rotor stresses, material properties and thermal dissipation. As will be discussed in the next paragraphs these are some of the issues that are the still subject of major research efforts.

The example however has importance, in that the off-grid household load depicted is unlike

the most common terrestrial applications for flywheel batteries (like seamless power transfer during grid instability or short outages) whose purpose is mainly high power delivery for time bridging. Thus the example provides a load magnitude and duration that are significantly different and helps to highlight issues that may not arise during the aforementioned common applications.

In general, current technical concerns for the flywheel battery technologists include structural integrity of the rotor, the speed capability of the suspension bearings and the speed and power handling capability of the motor/generator and control electronics. Suspension bearings and motor/generator and drive technologies have applications in many other fields and have consequently seen relative advancement. Rotor structural integrity however, poses by far the biggest challenge in the development of the flywheel as a viable battery system. The issue is of such gravity and importance that the area of research transcends normal competition and groups of researchers have been developed to pool resources and assemble combined expertise [23].

Over the years a variety of flywheel shapes from a range of materials have been designed with the aim to maximise the stored energy. The important parameters influencing failure of a rotor disk are fabrication imperfections (misfit), mean radius, thickness, material property, load gradation and speed. These are the sub-system indices of merit, all of which must be optimised simultaneously to achieve the best and most reliable design.

Currently carbon fibres are the lightest and strongest materials available. For example, T-1000 Graphite has tensile strengths of up to 1,200,000 pounds per square inch (psi) [22]. This would in theory translate to a storage power density of 766 watts per kilogram. Fibre however is only one of the matrix constituents of a composite rotor. The epoxy with which it must be mixed has a substantially lower strength value, often of the order of 50%. The fibre constitutes only about 60% (by volume), resulting in a strength reduction of two. This then forms the design basis. Then one has to include allowances for fatigue. Fatigue is the systematic weakening of a material as a result of sustained stress over a period. This will vary depending on environmental factors like temperature and chemical corrosion due to water vapour.

The above considerations being for hoop strength alone, the designer will have to consider radial and axial strengths, which are also limited by the strength of the polymer matrix. For these forces the fibre represents a discontinuity in the matrix and the design allowable should not exceed 15% of the matrix tensile strength. Structural stress issues do impact on the electrical design as well, for example, due to the fragility of the magnets forming the Halbach array, they must be assembled close to the hub. This compromises the power density of the generator. Along with rotor failures comes the problem of designing safe containment. As a consequence of these safety concerns the PNGV later opted to defer development of the flywheel battery (as progress was deemed too slow to meet set deadlines of 2004 for concept model vehicles) but would continue to monitor progress in other programs mentioned later. In the case of a rural application however, underground containment has been found to satisfactorily address the safety concerns.

There is also great optimism as the carbon fibres strengths are projected to improve from the current strengths of 1,000,000 psi to 3,000,000 psi within this decade, implying a possible increase of 200% in stored kinetic energy. At this strength, the achievable material tip speeds will exceed 2 kilometers per second. Composite carbon fibre disks have an added safety advantage at failure. Unlike metallic disks, which disintegrate into dangerous solid shrapnel, in the case of a burst (which is the worst case scenario in rotor failure), fibre absorbs much of the energy by converting to cotton-like shred.

Another important factor is the cost. According to [24] the current cost of lead-acid batteries ranges between \$50-\$100 per kWh, compared to \$400-\$800 per kWh for flywheels. This disparity currently gives the chemical batteries an edge. As for efficiency, flywheels (at 80-85%) are currently equal or better than state-of-the-art chemical batteries. Operational results of 93% have been reportedly achieved [8] by NASA.

Lifespan is another major advantage of the flywheel battery, with estimates of at least 20 years as compared to between 3 and 5 years for chemical batteries. This is however compromised by their (currently) much higher self-discharge rates as compared to chemical batteries.

The biggest advantage held by flywheels however, is that being an emerging technology, their potential has barely been tapped as compared to the centuries old chemical systems which in all probability are unlikely to make major advances. This is without considering environmental issues. At the forefront of rotor integrity and safety research is the Defense Advanced Research projects Agency (DARPA). In rotor dynamics, hub rim interface, strength optimisation and fatigue life are collaborations between independent groups with funding mainly from NASA. These include, Glen Research Center (NASA GRC), Engineering Model Flywheel Energy Storage Systems, Small Business Research Contracts, Auburn Center for Space Power and University of Texas/NASA Safe Life Criteria. Existing NASA and Boeing databases, like the Gas Turbine Engine Program are reinforcing efforts by University of Texas A&M, GRC and University of Virginia on high rpm developments, among others, that constitute the National Aerospace Flywheel Program.

## 9.7 Concluding remarks

The potential of the electromechanical battery has been highlighted as well as the shortcomings of continued use of chemical batteries. This Chapter has examined the basics of kinetic energy storage as well as the machine design equations of an ironless permanent magnet synchronous motor-generator. Using these design equations a special battery supply for a rural African application has been specified. Pending research issues have been highlighted as well as the optimistic projections of the near future. With improved technologies it should therefore be possible, using machine design equations and given load requirements and availability of energy resources, to design an appropriate flywheel storage battery, that can be manufactured in Africa.

Moreover, the life cost cycle of the flywheel battery, which includes the potential for a long lifespan with virtually no maintenance as well as the positive environmental attributes are major advantages.

Currently a project is in its early stages at the University of Cape Town for the design and construction of a 300 ampere hour flywheel battery for rural application. The project will therefore bring this apparent dream closer to our reality and is awaited with much

major advantages.

Currently a project is in its early stages at the University of Cape Town for the design and construction of a 300 ampere hour flywheel battery for rural application. The project will therefore bring this apparent dream closer to our reality and is awaited with much anticipation.

## 9.8 Appendix VIII

The kinetic energy stored in a moving body is proportional to its mass and the square of its linear velocity.

$$KE = \frac{1}{2}mv^2 \quad (9.1)$$

When transformed into rotational motion one must consider the moment of inertia  $J$ . For the solid cylinder (figure 9.1) rotating about its axis the moment of inertia is defined as  $J = \sum m_i r_i^2$ , the sum of all elemental masses multiplied by the square of their distances from the rotational axis. As the sizes of these particles tend to zero they are virtually cubic with dimensions  $\delta\omega$ ,  $\delta r$  and  $h$ .

$$J = \int_{\theta=0}^{2\pi} \int_{r=0}^R \rho h \cdot d\omega \cdot dr \cdot r^2 \quad (9.2)$$

Since  $\delta\omega = r\delta\theta$  and mass = volume ( $\pi r^2 h$ ) x density ( $\rho$ ), it can be shown that

$$J = 2\pi\rho h \int_{r=0}^R r^3 \cdot dr = \frac{2}{4} \rho\pi h r^4 = \frac{1}{2} m r^2 \quad (9.3)$$

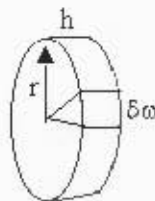


Figure 9.1. A solid cylinder with radius  $r$  and height  $h$

Likewise for a practical hollow cylinder flywheel

$$\begin{aligned} J &= 2\pi\rho h \int_{r_i}^{r_o} r^3 \cdot dr = \frac{1}{2} \rho\pi h (r_o^4 - r_i^4) = \\ &= \frac{1}{2} \rho\pi h (r_o^2 + r_i^2)(r_o^2 - r_i^2) \end{aligned} \quad (9.4)$$

where,  $r_o$  and  $r_i$  are its outer and inner radii respectively.

But the mass,  $m = \rho\pi h (r_o^2 - r_i^2)$  for a hollow cylinder

$$\text{Therefore } J = \frac{1}{2} m (r_o^2 + r_i^2) \quad (9.5)$$

For a cylindrical system, as is typical of flywheels the kinetic energy stored  $KE$  is:

$$KE = \frac{1}{2} J\omega^2 = \frac{1}{4} m (r_o^2 + r_i^2) \omega^2 \quad (9.6)$$

Where  $J$  (in kilogram square meters), is the system moment of inertia about the axis of rotation and  $\omega$  is the rate of rotation in radians per second.

## 9.9 References IX

1. Isidor Buchmann, "Can the Lead Acid battery compete in modern times?" Cardex Electronics Inc. April 2001. [http://www.batteriesdigest.com/ask\\_isidor.htm](http://www.batteriesdigest.com/ask_isidor.htm)
2. Hunt G. L., "The great battery search," IEEE Spectrum, November 1998.
3. Heibner R., Anstuous T., "Energy Storage for sustainable systems: A white paper on the benefits and challenges of kinetic energy storage," Center for Electromechanics, University of Texas at Austin. <http://www.ece.gatech.edu/research/UCEP/2000-nsf/Presentations/Heibner.pdf>
4. Post R. F., "A new look at an old idea, the electromechanical battery" Science and Technology Review, April 1996.
5. Post R. F., Fowler T. K., Post S. F., "A High Efficiency Electromechanical Battery." Proceedings of the IEEE, Volume 81, No. 3, March 1993.
6. Mukund R. Patel, "Flywheel Energy storage for spacecraft Power Systems." SAE 1999-01-2589.
7. <http://space-power.grc.nasa.gov/ppu/projects/flywheel/>

8. Bitterly J. G., "Flywheel Technology: Past, Present and 21<sup>st</sup> Century projections," IEEE AFS Systems Magazine, August 1998.
9. Herbst J. D., Manifold S. M. et al, "Design fabrication and testing of a 10MJ composite flywheel energy storage rotors." SAE 981282.
10. Hayes R. J., Kajs J. P. et al, "Design and testing of a flywheel battery for a transit bus" SAE 1999-01-1159.
11. Tsung Ying Lee, Nanming Chen, "Optimal capacity of the battery energy storage system in a power system." IEEE Transactions on Energy conversion, Vol. 8 No.4 December 1993.
12. Arnold S. M., Saleeb A. F., Al-Zoubi N. R., "Deformation and Life analysis of composite flywheel disc and multi disk systems" NASA/TM—2001-210578.
13. Baaklini G. Y., Konno K. E. et al, "NDF methodologies for composite flywheel certification." SAE 2000-01-3655.
14. Tsai S. W., Wu F. M., "A general theory of strength for anisotropic materials," Journal of Composite materials, 1971.
15. Seireg A., Surana K. S., "Optimum design rotating disk" J. Engr. For industry, Trans. of the ASME, vol 92, 1970, pp1-10.
16. Sung K. Ha, Dong-Gun Lee and Jini Kim, Optimization of hybrid composite rotor in flywheel battery." SAE 981899.
17. Halbach K., "Design of permanent multi pole magnets with oriented rare earth cobalt material." Nuclear Instruments and Methods 169, p1-10, 1980.
18. Ofori-Tenkorang J., Lang J. H., "A comparative analysis of torque production in Halbach and conventional surface-mounted permanent magnet synchronous motors." IAS '95: Conference record of the 1995 IEEE Industry Applications conference.
19. Review of the research program of the Partnership for a New Generation of Vehicles: Fifth Report (1999), (<http://www.nap.edu/openbook/0909064430/html/38.html>)
20. Sebitosi A. B., Pillay P., "Applications of Advances in Automotive Electronics to Rural Electrification: The 42V Power-net for Rural Electrification," Proceedings of the IEEE PES General Meeting, 13 - 17 July 2003, Toronto, Ontario, Canada.
21. "Brushless Amplifiers," Servo Drives and Amplifiers, Advanced Motion Controls, 3805, Calle, Tecate, Camarillo, CA 93012, USA. <http://www.a-m-c.com/download/engnotes.pdf>

22. Michael E. Bowler, "Flywheel energy systems: current status and future prospects" Trinity flywheel power, San Francisco California.
23. Pichot M. A., et al, "Flywheel Battery Containment Problem," Society of Automotive Engineers-970242, 1997.
24. Joseph B., Hebner R., Walls A., "Flywheel Batteries Come Around Again," IEEE Spectrum (April 2002), pages 46-51.
25. Khartchenko, N., "Advanced Energy Systems." Taylor and Francis, Washington, DC, 1998.

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## 10. An Analysis of Rural Off-Grid Electrical Systems

### 10.1 Introduction

An off grid electrical system may be as simple as a generator and load combination or just a rechargeable battery and a load, as is sometimes the case in Kenya. In general, there are varieties of system configurations to meet different load requirements within given budget limits. Currently, the overwhelming majority of rural off-grid electrical installations in Kenya are stand-alone PV solar home systems (SHS). These SHS installations typically consist of a single PV panel, a storage battery and a load. The other type of system that is steadily gaining popularity is pico hydro generation, where a generator is connected to a group of rural households by a mini grid but without storage batteries. PV and water pump systems also exist without storage.

As was pointed out in chapter 1, most of these systems are not optimally sized. Correct sizing of an off grid system involves the determination of an appropriate generator and/or battery capacity to cost-effectively satisfy a certain load at a given reliability level. The various methodologies to achieve this are well documented [1-11]. One shortcoming with all these methods however, is that they almost invariably discuss stand-alone systems and have no remedies for post-installation design errors.

The Kenyan national motto is *Harambee*, or “pooling together”. It advocates that unity is strength. Could this hold true for stand alone SHS and similar configurations? In the case of Kenya this question is important given the massive stand-alone SHS rural base, with many neighbourhoods in close proximity of one another. Since sizing should strictly be done prior to the purchase of equipment, any inadequacies that are realised afterwards cannot be remedied by ‘sizing’. But could it be possible to provide some reprieve for these existing installations as well? In the case of pico-hydro, what would be the effect of including energy storage on the mini-grid?

In [12] Dakkar et al have attempted to raise the issue of linking stand-alone systems but still confine their context to the same PV SHS scenario like previous authors. This chapter will

examine these issues at depth by using a generalised type of generator, storage and load and characterising the systems by the following 4 different configurations.

- Stand-alone generator and load systems without storage
- Stand-alone generator and load systems with storage
- Mini grid connected generator(s) and load systems without storage
- Mini grid connected generators (s) and load systems with storage

Using power flow equations and Matlab simulations a study, will be carried out to examine the relative performances of the above configurations in a rural power supply context. Conclusions will then be drawn on the practical usefulness of such measures.

## 10.2 Basic configuration of an off-grid power system

Consider a number,  $n$  units of stand-alone rural household installations. Let  $L_i(t)$  and  $G_i(t)$  be the load demand and generator output respectively, at the  $i$ th household at time  $t$ . Then the difference  $P_{Di}$  between the generated power and the load demand at the household is given by

$$P_{Di}(t) = G_i(t) - L_i(t) \quad (10.1)$$

At time  $t$  there are three possibilities: either  $G_i(t) = L_i(t)$  or  $G_i(t) > L_i(t)$ , or  $G_i(t) < L_i(t)$ .

- When  $G_i(t) = L_i(t)$  at time  $t$ , the generator output and the load are matched and  $P_{Di} = 0$ . All the power generated would be efficiently delivered to the load and the load requirements would be fully met. There would be no requirement for storage or other additional system support at that instant.
- When  $G_i(t) > L_i(t)$ , then the generator output exceeds the load and  $P_{Di}(t) > 0$ . In the absence of storage the surplus energy will have to be dumped to waste. For the  $n$  households the total surplus (or dumped) power at time  $t$  is  $P_{DS}(t)$  such that

$$P_{DS}(t) = \sum_{i=1}^n P_{Di}(t) \text{ for all } P_{Di}(t) > 0 \quad (10.2)$$

- c) When  $G_i(t) < I_i(t)$  then the load demand exceeds the generator output and  $P_{Di}(t) < 0$ . In the absence of a battery, either all or some of the load will be shed to protect the generator. For the  $n$  households the total deficit (or load shed) power at time  $t$  is  $P_{DD}(t)$  such that

$$P_{DD}(t) = \sum_{i=1}^n P_{Di}(t) \text{ for all } P_{Di}(t) < 0 \quad (10.3)$$

Scenario b) and c) constitute poor service delivery. Moreover, the values of  $P_{Di}(t)$  and  $P_{DD}(t)$  as shown in equations (10.2) and (10.3) only represent the minimum losses, as in practice some discrete loads may not be activated until minimum threshold power level is supplied by the generator.

### 10.3 Effect of battery storage

If a battery were in place at time  $t$  (at the  $i$ th household) when  $G_i(t) > I_i(t)$ , either all or some or none of the energy will be saved by the storage, depending on the state of charge of the storage battery. The state of charge of a storage battery in the  $i$ th household,  $B_{Ci}$  (in joules) at time  $t$  is given by

$$B_{Ci}(t) = B_{Ci}(t-1) + \eta_{Ci} P_{Di}(t) \cdot \Delta t \quad (10.4)$$

where  $B_{Ci}(t-1)$  is the previous state of charge immediately before time  $t$ ,  $\Delta t$  is an incremental time duration and  $\eta_{Ci}$  is the charging efficiency of the battery. The state of charge of a battery must satisfy the following condition:

$$B_{CiMin} \leq B_{Ci}(t) \leq B_{CiMax}$$

where the subscripts *min* and *max* denote allowable minimum and maximum states of charge respectively. If  $B_{Ci}(t-1) = B_{CiMax}$  at time  $t$  then the battery is full and can't take any more charge. The energy ( $P_{Di} \cdot \Delta t$ ) will be dumped to waste. The total system power dumped at time  $t$  is the sum of all the individual power dumps at all households where the batteries are already charged to maximum level. In addition, the presence of the term  $\eta_{Ci}$  means that energy loss will be incurred during the storage process and the generator will be required to produce more energy for storage to drive the same load than in scenario a) when the energy flows directly from generator to load.

Likewise in the case when (at the  $i$ th household)  $G_i(t) < L_i(t)$  (at time  $t$ ) but in the presence of a battery, energy will be withdrawn from the battery but conditional upon the state of charge of the battery,  $B_{Ci}(t-1)$ . If  $B_{Ci}(t-1) = B_{Ci}^{min}$  at time  $t$ , then the battery is at maximum depth of discharge and the load equivalent to  $(-P_{Di} \cdot \Delta t)$  will be shed. The total system load shed at time  $t$  is the sum of all the individual load sheds at households where the batteries are depleted to minimum level. In addition the fraction of energy recovered will depend on the discharge efficiency  $\eta_{Di}$  of the battery. Therefore the state of charge of the battery being discharged is given by

$$B_{Ci}(t) = B_{Ci}(t-1) + \frac{P_{Di}(t)}{\eta_{Di}} \cdot \Delta t \text{ for all } P_{Di}(t) < 0 \quad (10.5)$$

#### 10.4 Effect of a mini-grid

In the case of a pico-hydro system, a small rural mini grid connects all the consumers but no storage batteries are provided. Consider a case in section 10.2 when the stand-alone installations have no storage batteries. Let these units be connected by a common bus. It will be assumed that the load profiles of different households are largely independent of each other. There is therefore a possibility that the  $j$ th household could have a power deficit at time  $t$ ,  $G_j(t) < L_j(t)$ , when the  $i$ th household has a surplus  $G_i(t) > L_i(t)$ . Then either some or all the excess power in the  $i$ th generator would flow to the  $j$ th load depending on the relative quantities. In any case, the amount of load that would have to be shed or generator energy that would be dumped to waste by both the  $i$ th and  $j$ th households should be less than in the stand alone case. (For convenience let it be assumed that the load requirements are not discrete. For example, a generator output of 80 W will be accepted by a load demand of 100 W and result in a lower deficit of 20 W, instead of rejecting all the 80 W and shedding the full load). Furthermore, if this direct flow of power, (from the  $i$ th generator to the  $j$ th household,) were enabled then power would be more efficiently delivered to the load than the case if it were stored in a battery first. (The  $i$ th and  $j$ th households are assumed to be reasonably close and line losses are negligible).

If the total number,  $n$ , of households were connected to a common bus then the collective system surplus or deficit power at time  $t$  is  $P_{DT}(t)$  and is given by

$$P_{DT}(t) = \sum_{i=1}^n P_{is}(t) = \sum_{i=1}^n [G_i(t) - L_i(t)] \quad (10.6)$$

### 10.5 Effect of mini-grid with storage

Suppose that in the scenario in section 10.4 a storage battery were introduced. This would be analogous to either introducing a battery on the pico-hydro mini-grid or a mini-grid connection for a group of SHS households or any other analogous generator/storage/load situation.

The instantaneous power flow equation of the system without storage is given by equation (10.6).  $P_{DT}(t)$  is the total system surplus or deficit power at time  $t$ . This is the amount of power that must be handled by the collective storage battery. (In the case of SHS (or analogy) assume all individual batteries are identical and when linked form a combined capacity,  $n$  times their individual capacities). Let the collective system-battery state of charge be  $B_{CT}$  (in joules).

So at time  $t$  when  $P_{DT}(t) > 0$ , either all or some or none of the energy will be saved by the storage, depending on the state of charge of the storage battery. Then the collective system battery state of charge,  $B_{CT}$  (in joules), at time  $t$  is given by

$$B_{CT}(t) = B_{CT}(t-1) + \eta_{CT} P_{DT}(t) \cdot \Delta t \quad \text{for all } P_{DT}(t) > 0 \quad (10.7)$$

where,  $B_{CT}(t-1)$  is the previous state of charge immediately before time  $t$ ,  $\Delta t$  is an incremental time duration and  $\eta_{CT}$  is the charging efficiency of the battery. Like before, the state of charge of a battery must satisfy the following condition:

$$B_{CTmin} \leq B_{CT}(t) \leq B_{CTmax}$$

Likewise in the case when  $P_{DT}(t) < 0$  (at time  $t$ ), energy will be withdrawn from the battery but conditional upon the state of charge of the battery,  $B_{CT}(t-1)$ . In addition, the fraction

of power recovered will depend on the discharge efficiency  $\eta_{Lb}$  of the battery. Therefore, the state of charge of the battery being discharged is given by

$$B_{CT}(t) = B_{CT}(t-1) + \frac{P_{DT}(t)}{\eta_{Lb}} \cdot \Delta t \quad \text{for all } P_{CT}(t) < 0 \quad (10.8)$$

## 10.6 Simulation Results

A set of 5 random average hourly loads spanning for a 24-hour period were generated in Matlab and another set of real data from a case study in Garagapola village in South Africa. They were assigned arbitrarily small (but equal) capacities of generators and storage batteries each. It was important that the power sources (generator and/or battery) were less than adequate for the loads. This would clearly show improvements in system performance with changes in configuration without encountering saturation points (or pre-maturely running out of load). The load demand figures were average hourly values. For simplicity, the generator capacities were given as constant values but the loads were varying. The initial battery charge levels and the minimum allowable states of charge were set at 80% and 50% of the maximum allowable states of charge respectively.

Using the power flow equations developed above and the two sets of average hourly load data, Matlab code was written and simulations run. The systems were run separately and logs of the individual surplus and deficit levels for households were recorded.

In appendix X, table 10.3 gives a Matlab generated set of average hourly loads for each of the 5 households over a 24-hour period. Table 10.4 shows the load balance results for the data in table 10.3 in a stand-alone scenario with storage. Table 10.5 shows a detailed average hourly load balance sheet for the rest of the configurations namely, stand-alone without storage, mini-grid without storage and finally mini-grid with storage.

The analysed results are given in table 10.1 and 10.2, where the former uses real data from a case study of 5 households in Garagapola village while the latter uses the aforementioned Matlab randomly generated data. The first columns give the total average hourly load demand for 24 hours, which are equal for all the 4 configurations. The second columns give

the total average hourly deficit (or unserved load) for 24 hours. The third columns give total average hourly surplus (or unused generator power) for 24 hours.

Table 10.1. Results of a set of loads from six households in Garagapola village

	Total average hourly load demand for 24 hours	Total average hourly deficit for 24 hours (unserved load)	Total average hourly surplus for 24 hours (unused generator power)
Stand alone without battery storage	103530	-49907	49736
Stand alone with storage	103530	-40381	30569
Interconnected households without battery storage	103530	8048	7879
Interconnected households with battery storage	103530	-1259	2783

Table 10.2. Results of a set of 5 computer generated random hourly loads for 24 hours

	Total average hourly load demand for 24 hours	Total average hourly deficit for 24 hours (unserved load)	Total average hourly surplus for 24 hours (unused generator power)
Stand alone without battery storage	62392.8	-15068.6	11932.4
Stand alone with storage	62392.8	-6046.9	1089.4
Interconnected households without battery storage	62392.8	-7721.9	4182.6
Interconnected households with battery storage	62392.8	-1625.7	0

Figure 10.1 is a graphical result of one set of simulations. In B1 an aggregate 24-hour load profile of the households for one of the scenarios is shown. B2 gives the storage profile of

the collective battery system. B3 depicts the cumulative load balance sheet over the 24-hour period for the conditions of stand-alone without storage and finally mini grid with storage.

It is quite apparent from the results that in the case of stand-alone installations without storage, substantial amounts of energy go to waste while at the same time many of the loads remain unserved. When the systems were connected to a common bus without altering the generation or storage capacities the situation was evidently much improved.

An additional advantage of a mini-grid interconnection for power sources is the sharing of the impact of transient loads. As shown in figure 10.2 the high transient current drawn by an incandescent lamp has been shared by two power-sources with each only experiencing half the amplitude of the transient (or shock).

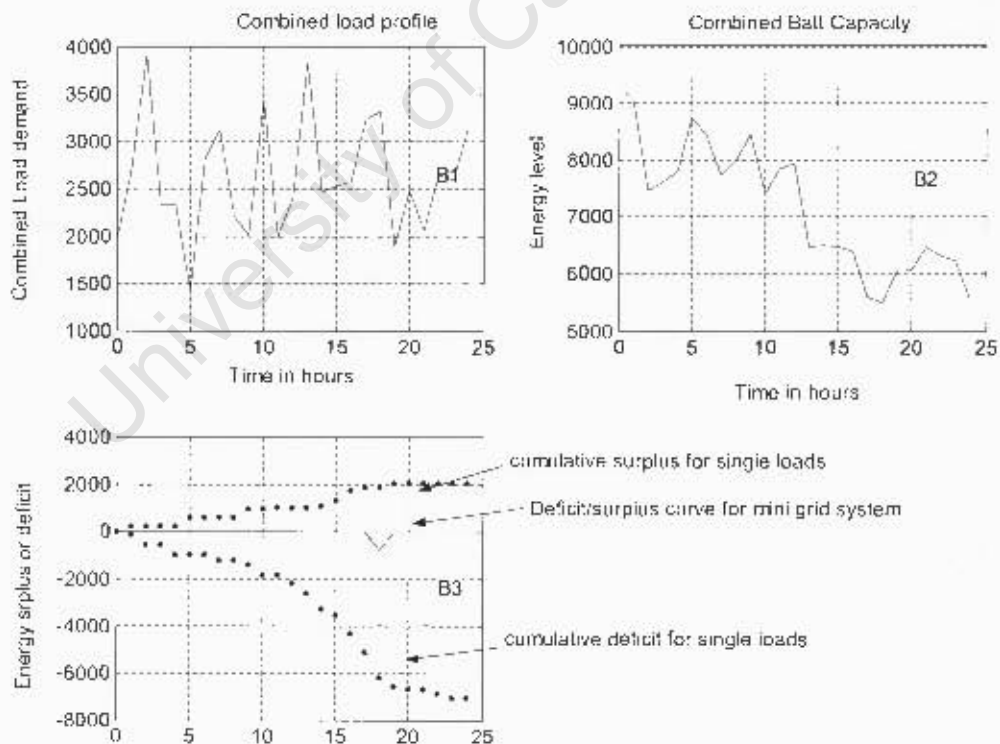


Figure 10.1. Matlab simulation results

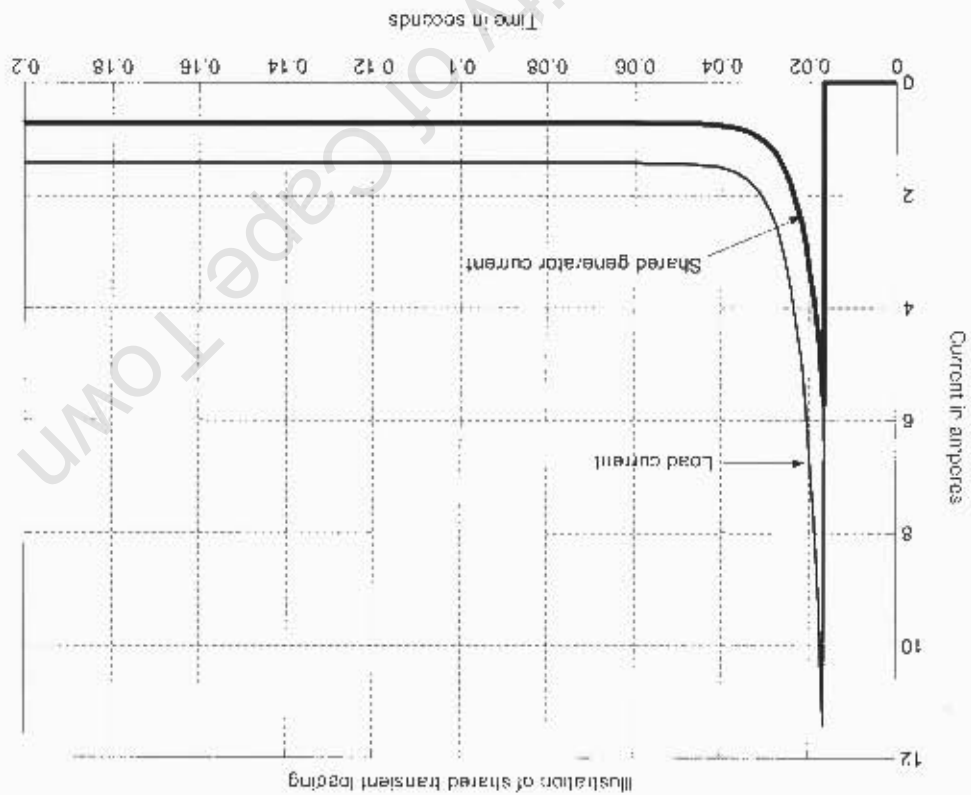
These results are important for Kenya where many rural households are in close proximity to each other. Moreover, the results mean that the performance of existing PV stand-alone systems can be improved by simple inter-linking.

system improves when battery storage is installed.

performance. It has further been shown that the performance of a mini-grid connected quite apparent that linking stand-alone systems to a common grid enhances their equations and Matlab simulations their performances were compared. From the results it's From these original configurations 4 possible types have been configured. Using power flow Three off-grid power system configurations currently found in Kenya have been described.

## 10.7 Concluding remarks

Figure 10.2. A comparison of transient loading impact on a single and two generators respectively (by an incandescent lamp)



## 10.8 Appendix X

Table 10.3. A Matlab generated set of average hourly household loads

A randomly generated set of 5 household loads at hourly averages					
Hour	House 1	House 2	House 3	House 4	House 5
1	950.13	202.77	193.43	702.74	582.79
2	231.14	198.72	682.22	546.57	423.49
3	606.84	603.79	302.76	444.88	515.51
4	485.98	272.19	541.67	694.57	333.95
5	891.29	198.81	150.87	621.31	432.91
6	762.69	15.27	697.89	794.82	225.95
7	456.46	746.79	378.37	956.84	579.81
8	18.51	445.09	860.01	522.59	760.37
9	821.41	931.81	853.66	880.14	529.82
10	444.72	465.99	593.56	172.96	640.53
11	615.43	418.65	496.55	979.75	209.07
12	791.93	846.22	899.77	271.45	379.82
13	921.81	525.15	821.63	252.33	783.33
14	738.2	202.65	644.91	875.74	680.85
15	176.26	672.14	817.97	737.31	461.09
16	405.71	838.12	660.23	136.52	567.83
17	935.46	19.64	311.97	10.757	794.21
18	916.92	681.28	789.75	893.89	59.18
19	410.27	379.48	341.19	199.14	602.87
20	893.61	831.79	534.08	298.72	50.26
21	57.89	503.81	727.11	661.44	415.37
22	352.86	709.17	309.29	284.41	304.99
23	813.16	428.89	838.51	469.22	874.37
24	9.86	304.62	568.07	64.78	15.01

Table 10.4. Power balance data for stand-alone units with storage

Hour	Surplus (+) / deficit(-) household power for stand alone units with storage				
	load 1	load 2	load 3	load 4	load 5
1	0	0	0	0	0
2	0	98.66	0	0	0
3	0	0	0	0	0
4	0	89.70	0	0	0
5	139.04	271.06	78.86	0	0
6	-291.21	436.25	0	-245.95	0
7	0	0	0	-507.60	0
8	0	0	0	-25.10	0
9	0	0	0	-422.38	0
10	0	0	0	0	0
11	0	0	0	238.71	0
12	287.45	0	348.43	0	0
13	-468.68	0	357.36	0	0
14	-264.67	0	161.01	0	0
15	0	0	-353.30	-252.56	0
16	0	-212.73	-178.03	0	0
17	-107.63	0	0	0	-4.14
18	463.22	0	0	0	0
19	0	0	0	0	0
20	356.63	29.28	0	0	0
21	0	3.12	0	0	0
22	0	-232.74	0	0	0
23	0	0	20.28	0	0
24	0	0	-75.63	114.85	0
25	0	0	0	0	0

Table 10.5. Power balance data for, stand alone without storage, Mini grid connected system with and without storage.

Hour	Surplus (+) or deficit (-) generator power in stand-alone mode w/o storage					Mini grid w/o storage	Mini grid w storage
	House 1	House 2	House 3	House 4	House 5	Balance power	Balance power
1	-450.10	297.23	306.56	-202.71	-82.79	-131.90	0
2	268.86	301.28	-182.22	-46.57	76.50	417.80	0
3	106.80	103.79	197.23	55.12	-15.51	262.00	0
4	14.018	227.81	41.674	194.60	166.01	171.60	0
5	-391.30	301.19	349.13	-121.30	67.09	204.80	0
6	-262.10	484.73	-197.90	-294.80	274.05	4.01	0
7	43.53	-246.79	121.62	-456.80	-79.80	-618.30	0
8	481.50	54.90	-360.01	-22.59	-260.37	-106.62	0
9	-321.4	-431.81	-353.66	-380.10	-29.823	-1516.83	0
10	55.29	34.006	-93.56	327.04	-140.53	182.31	0
11	-115.40	81.35	3.44	-479.70	290.93	-219.50	0
12	-291.90	-346.22	-399.77	228.55	120.18	-689.22	0
13	-421.80	-25.15	-321.63	247.67	-283.33	-804.30	-334.45
14	-238.20	297.35	-144.91	-375.70	-180.85	-642.41	-713.72
15	323.73	-172.14	-317.97	-237.30	38.90	-364.80	-405.31
16	94.29	-338.12	-160.23	363.48	-67.82	-108.44	-120.44
17	-435.51	480.36	158.02	488.24	-294.21	397.02	0
18	416.9	181.28	210.27	393.9	440.81	341.00	21.61
19	89.73	120.52	158.80	300.86	-102.87	567.01	0
20	393.60	331.80	34.07	201.28	449.73	-108.50	0
21	442.11	2,8129	-227.41	-161.40	84.62	135.41	0
22	147.13	209.47	190.71	215.59	195.01	539.00	0
23	313.02	71.11	-338.50	30.77	-374.37	-924.12	-30.16
24	490.14	195.38	-68.07	435.22	484.99	1537.70	0

- Maximum allowable battery capacity = Max\_batt = 2200 energy units
- Minimum allowable battery capacity = 1100 energy units (50% Max\_batt)
- Starting battery capacity = 1760 energy units (80% Max\_batt)
- Battery charge-discharge efficiency = 80%
- Battery charge efficiency assumed = discharge efficiency = square root (charge-discharge efficiency)

## 10.9 References X

1. Ofry E., Braunstein A., "The Loss of Power Supply Probability as a technique for Designing Stand Alone Solar Electric (Photovoltaic) systems," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS 102, No.5, pp. 1171-1175, May 1983.
2. Bratoli B., et al, "The design of Photovoltaic plants: An Optimisation Procedure," *Applied Energy*, vol. 18 no. 1, pp. 37-47, 1984.
3. Estimating Loss of Power Probability of Stand Alone Photovoltaic Solar Energy Systems," *Solar Energy* 32 (1984) 205.
4. Reddy A. K. N., Subramanian D. K., "The Design of Rural Energy Centers," *Rural Technology*, MacMillan India Press, pp., 109-130, 1980.
5. Ramakumar R., Shetty P. S., Ashenayi K., "A Linear Programming Approach to the Design of Integrated Renewable Energy Systems for Developing Countries," *IEEE Transactions on Energy Conversion*, vol. EC-1, no. 4, pp. 18-24, December 1986.
6. Gordon J. M., "Optimal Sizing of Stand Alone Photovoltaic Solar Power Systems," *Solar Cells*, vol. 20, pp. 295-313, 1987.
7. Ramakumar R., Abouzahr I., Ashenayi K., "A Knowledge-based Approach to the Design of Integrated Renewable Energy Systems," *IEEE Transactions on Energy Conversion*, vol. 7, no 4 December 1992.
8. Gavanidou E. S., Bakirtzis A. G., "Design of a Stand Alone System with Renewable Energy Sources Using Trade Off Methods," *IEEE Transactions on Energy Conversion*, vol.7, no. 1, March 1992.
9. Abouzahr I., Ramakumar R., "Loss of Power Supply Probability of Stand Alone Photovoltaic Systems: A Closed Form Approach," *IEEE Transactions on Energy Conversion*, vol. 6, March 1991.
10. Sandia National Laboratories. "Stand Alone Photovoltaic Systems," *A Handbook of Recommended Design Practices*. US Department of Energy, USA 1995.
11. Shretsa G. B., Goel I., "A Study of Optimal Sizing of Stand Alone photovoltaic Stations," *IEEE Transactions on Energy Conversion* vol. 13(4) pp. 373-378, 1998.
12. Dakkak M., Hirata A., Muhida R., Kawasaki Z., "Operational Strategy of Residential Centralised Photovoltaic System in Remote Areas," *Renewable Energy*, vol. 28, pp. 997-1012, 2003.

13. Jacobson A et al., "Field Performance Measurements of Amorphous Silicon Photovoltaic Modules in Kenya." Proc. (ASES), Madison, Wisconsin, June 16–21, 2000 (<http://socrates.berkeley.edu/~dkammen/ASES—2000—aSi—paper.pdf>)
14. Prabhu N. U., "Queues and Inventories," Wiley, New York, 1965.
15. Prabhu N. U., "Stochastic Storage Processes," Springer, New York 1980.
16. World Wide Hourly Climate Generator. Maui Solar Energy Software Corporation; Haiku, USA 2000.  
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## 11. An Approach to Rural Distribution Network Design for Sub-Saharan Africa

### 11.1 Introduction

The delivery of reliable power of sufficient quality to consumers requires, among other things, that the voltage levels at the remotest consumer from the power source satisfy the minimum appliance specifications. This is often constrained by the cost of infrastructure. It has long been recognised that distribution network designs used by utility companies are optimised for urban and industrial environments. In 1935, Morris Cooke [1], the head of a newly created Rural Electricity Administration, REA, in the USA wrote that, "since utility company ideas as to what constituted sound rural lines have been rather fancy, such costs were prohibitive for most farmers". In 1947 a New Zealander, Lloyd Mandeno [2] wrote in a paper appealing yet again for the recognition of rural power supply as, "a separate and distinct field wherein is justified a complete review of past methods and development of new ones. Such review should be untrammelled by preconceptions other than devotion to sound engineering and to the extension of power to a deserving section of our people." In a report, the World Bank [3] has recommended that, "there is need to break out from the standard mould, to review specific needs of a community, to go back to the basic principles, and to develop designs that most cost-effectively address these needs." Surprisingly, though, these calls have remained largely ignored especially in sub-Saharan Africa.

Quite often rural networks are over designed, resulting in under utilisation and therefore costly overheads. One reason often cited for the over specification is anticipation of load growth. In most sub-Sahara African rural areas however, economic growth rates are low and a designer has no justification in specifying an infrastructure capacity exceeding more than a few percent of existing consumer requirements. Additionally, the classic distribution load model depicts a uni-dimensional main feeder supplying some uniform load along it [4-10]. The only losses of concern are those along the main feeder with little or no regard being paid to the loading in the lateral directions. On the contrary it will be shown in this chapter that, especially for mini distribution networks, paying attention to the full geometry of a network makes a big difference. Such an approach provides opportunities in cost saving.

In section 11.2 a method for constructing a minimised distribution network from an external source to a given number of consumers using constructal theory and idealised networks will be illustrated. In section 11.3 a method for the evaluation of power delivery losses in an idealised network will be illustrated. The effect on losses, by managing a conductor cross sectional area in different topologies, will be investigated in section 11.4 using algebraic equations. Using Matlab simulations and a rectangular idealised consumer area in section 11.5, consumer configurations are derived to dissipate minimum network losses to a given number of consumers. Conclusions will then be drawn as to the usefulness of paying detailed attention to consumer area geometry.

## 11.2 Design of a minimised network infrastructure

The impedance of a distribution network is proportional to its total length. So by Ohm's law, line voltage drops and network losses should increase with network length. It would therefore be reasonable to anticipate that by designing a distribution network topology that minimises path length from a power source to a given number of consumers, one would minimise the losses. Moreover, a more compact network would require less material and hence be less expensive to construct.

A novel concept in the minimisation of flow paths called *constructal theory* has been articulated in [11-17]. Initially a method was developed for heat flow, with application to cooling of heat generating volumes like electronics packages. A finite-sized volume of low conductivity material in which heat is being generated at every point was used. A small heat sink to cool it was located on its boundaries. By applying small amounts of high-conductivity material, to enhance the transfer of heat to the sink, it was observed that the resulting conductivity paths were tree shapes of the high conductivity material. The spaces in between, were filled by the non-conducting material. It was then deduced that these tree structures were a result of (heat transfer) optimisation. It was concluded that this had to be what unified a whole range of engineered and natural flows that include vascular tissue [18-20], river basins and lightning (see figure 11.1).

It has further been shown that the geometric details of a lightning bolt path, for example, are

not due to natural chance but can be deterministically predicted. In [12] this principle was used to demonstrate the construction of a minimum path linking an external point source to points on a straight line. The same technique could be used for the design of a minimised power distribution network.

Real rural consumer areas range from planned, like community service structures, to amorphous and scattered structures and therefore difficult to model mathematically. In order to establish some rationality, idealised networks have historically [4-7] been used in distribution system designs. These are sometimes referred to as elemental networks or models. Their variations may include the location of the source, the way in which consumers are connected to the source, allowed routing and available distribution nodes. The shape of the elemental areas can be one of a square, equilateral triangle or regular hexagon. Rectangles will be used here for illustrations.

Using this method it is assumed that consumers (nodes of consumption) are uniformly distributed over the area served by the network (see figure 11.2). Their consumption rate is assumed to be uniform and constant. The system structure is fixed in time. The requirement is that power be connected from an external source point to all the consumers.



Figure 11.1. A lightning bolt as an example of path optimisation by nature

Like all models, the idealised networks described may differ with respect to a number of details from a real situation. However, the purpose of such an exercise is to identify an optimisation opportunity that can serve as a basis for adapting specific decisions in real life situations. In this case, it has been hypothesised that a minimised distribution infrastructure would result in minimised voltage drops and network losses. Comparisons can be made using different topologies to distribute power to the same consumer area. Finally this result can be used for more generalised situations.

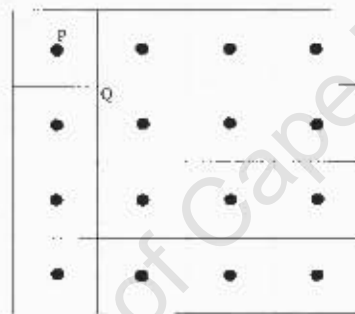


Figure 11.2. An idealized consumer area

In a 1965 manual, Westinghouse [8] depicted the function of power distribution as one of gathering from the consumer. The argument is that rather than originating from the power source, a network load actually originates from the consumer when a switch is flipped. This concept has been exploited in [12] to compute the pressure drops inside a uniform cross-section pipe in a fluid distribution network. They used an analogy of a river basin, where rainwater is collected at a uniform rate per unit area. The first rivulet then forms and begins to collect water out of the territory (similar to linking P to Q). Several rivulets form a tributary systematically channelling the collected water into a single stream. The same analogy can be used to analyse a rural power mini-grid, as will be demonstrated. Figure 11.3 is a Matlab generated profile of pressure or voltage drop from a source located at the origin (marked  $(0,0,0)$ ) of a distribution network into a rectangular consumer area with a uniformly distributed load. The voltage drop at every point in the network is shown. The figure was generated using the gathering concept.

### 11.3 Parameters of merit for idealised networks

A method to construct a minimised path length from a source point to several sink points on a line was demonstrated in [12]. When the same method was applied to an idealised rectangular consumer area in figure 11.2 the network in figure 11.4 was generated. Using the method, this network topology offers the minimum path length from the source to the consumers. The performance of this topology can then be compared with several other possible distribution topologies for the same area.

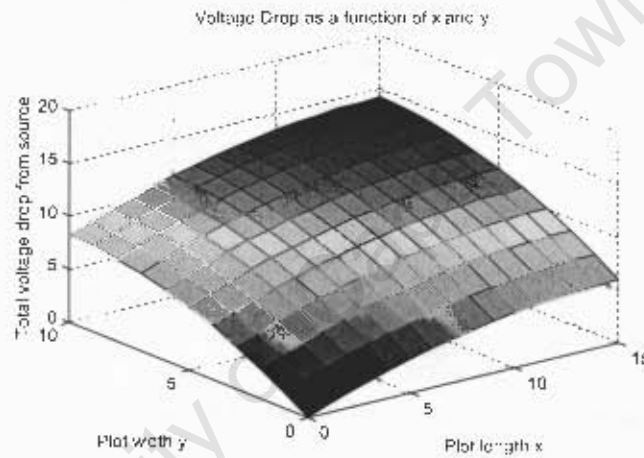


Figure 11.3. A plot showing a typical voltage drop profile of a rectangular consumer area

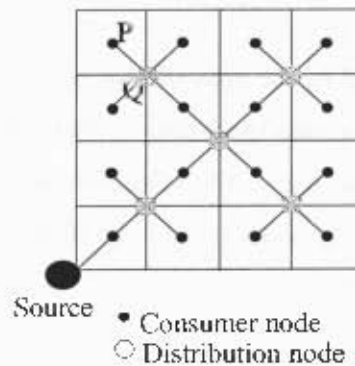


Figure 11.4. Minimized distribution network

Let each consumer node in figure 11.4 draw a load of 1 unit current and let the elemental conductor link between nodes be of unit length and unit resistance. Gathering starts at P, the furthest consumer node and proceeds with the link to distribution node Q. At Q it is joined by currents from two other consumer nodes. The next link therefore has three unit currents flowing in it. Figure 11.5 shows the various currents flowing in the respective network links. Since the elemental links have unit resistance, the summation of currents in these links from P to the source represents the total voltage drop between them.

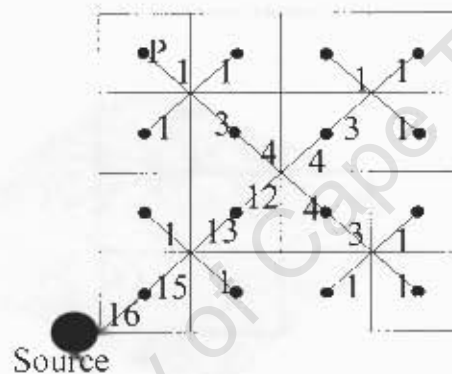


Figure 11.5. Evaluation of branch currents by a gathering method

From figure 11.5 the following evaluation results can be obtained for the network. The total infrastructure length is equal to the number of elemental links = 21.

The total voltage drop between point P and the source is

$$1 + 3 + 4 + 12 + 13 + 15 + 16 = 64.$$

The total power dissipated in the network can be evaluated by summing up the squares of the currents in each of the elemental links = 880. All these figures are relative values that assume that each consumer load is the reference unit current. The topologies in figure 11.6 were subjected to the same conditions and had their performances compared to figure 11.5. The results are tabulated in table 11.1.

The earlier definition for a unit length referred to the (half) diagonal link PQ. Using this standard the relative length of a horizontal or vertical link is  $\sqrt{2}$ . So all parameters for such

links are bigger by the same factor. The results were however disappointing in that while the topology in figure 11.4 remained the shortest of the lot (and hence the cheapest to construct), its performance with respect to losses and voltage drops ranked poorly.

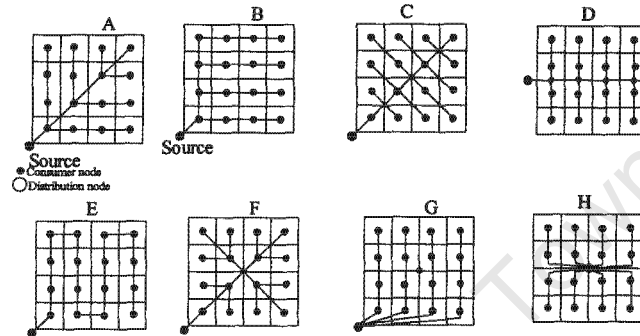


Figure 11.6. A variety of possible distribution topologies

Table 11.1. A variety of possible Distribution Topologies

Topology	Relative total cable length	Max relative voltage drop	Total relative power loss
A	23.97	44.0	508.6
B	22.21	58.6	651.0
C	25.0	64.0	820.0
D	22.6	59.4	711.9
E	22.21	185.7	1769.6
F	24.31	64.0	858.8
G	31.0	28.3	305.5
H	28.3	4.24	79.2
Fig. 11.4	21.0	64.0	880.0

It would appear, though, that while minimisation of network size for a given consumer area may not necessarily result in minimum losses the choice of a distribution network topology certainly affects its performance. Topology H performs best with respect to losses but since each lateral feeder draws a separate line from the source, the cost of infrastructure would be very expensive and counter to the purpose of this exercise. Moreover, its source is located in an advantaged and most unlikely position, much closer to the consumers. In this case topologies A and B appear to perform fairly well with regard to infrastructure size and network losses. To the author, topology B appeared more practical and esthetically more appealing and will be used for further demonstrations

#### 11.4 The effect of aspect on network losses

Aspect refers to the variation of conductor cross-sections to achieve optimum network resistance. This, according to [9] is an art that has been perfected by human blood vessels. Consider topology B in figure 11.6. Let the segment from the source to the node connecting the last lateral feeder be designated as the main feeder (MF1). The length of MF1  $= 1 + \sqrt{2} \times 3 = 5.24$  units. If the cross sectional area of MF1 is doubled, then the power dissipation in the section will reduce by 50%. Change in network dissipation  $\Delta H_{n1}$  is given by

$$\begin{aligned}\Delta H_{n1} &= \left[ 16^2 + \sqrt{2}(12^2 + 8^2 + 4^2) \right] \times \left[ 1 - \frac{1}{2} \right] \\ &= 572.8 \times \left[ 1 - \frac{1}{2} \right] = 286.4\end{aligned}$$

From table 11.1 the whole network originally dissipated 651 units. Therefore, the resulting total network dissipation after doubling MF1 is  $(651 - 286.4) = 364.6$  units.

In general, if  $a$  were the new relative cross-sectional area, then the change in network dissipation  $\Delta H_{na}$  would be given by

$\Delta H_{na} = 572.8 \times \left[ 1 - \frac{1}{a} \right]$ . Likewise the total network dissipation would become  $(651 - \Delta H_{na})$ . Thus, the maximum theoretical value for  $\Delta H_{na}$  (as  $a \rightarrow \infty$ ) is 572.8 and the minimum possible amount of network loss with the largest MF1 cross section would be  $651 - 572.8 = 78.2$  units.

Let figure 11.4 be subjected to the similar conditions. Consider the first 5 segments from the source. Let this length be designated as the main feeder MF2. Its total length is 5, which is slightly shorter than MF1. When the relative cross-sectional area is 1, the power dissipated in MF2 is  $(16^2 + 15^2 + 13^2 + 12^2 + 4^2) = 810$  units. Total network dissipation = 880.

In general, if the relative cross-sectional area of MF2 is  $b$  then the total change in network dissipation is given by  $\Delta H_{nb}$  such that

$$\Delta H_{nb} = 810 \times \left[ 1 - \frac{1}{b} \right]$$

Total network dissipation =  $880 - 810 \times \left[ 1 - \frac{1}{b} \right]$ . Therefore, the minimum theoretical network dissipation with the largest cross section of MF2 is  $880 - 810 = 70$  units.

Since this is less than the value of 78.2 obtained above and given that MF1 was longer than MF2, it is reasonable to conclude that the network in figure 11.4 will subsequently out-perform topology B with the right choice of main feeder diameter. Or put differently, figure 11.4 would appear to be more suited for high power delivery than topology B. There also exists a cross-sectional area of the two main feeders such that the losses of both networks will be equal for the same loading.

## 11.5 Maximising the consumer area for a given allowable standard

### 11.5.1 Maximum allowable voltage drop

This section discusses how one can maximise the number of consumers for a given voltage drop constraint. This issue has also been discussed in part in [22], however, the methodology used here and the results were originated by this author. Figure 11.7 represents an idealised rectangular consumer area of a uniformly distributed load. It is supplied by a main and lateral feeders (using topology B in figure 11.6) from a single power source. For a uniformly distributed consumer load the maximum voltage drop from the source will occur at point C, the end of the last lateral feeder. This is equal to the sum of the drops across the main feeder and the furthest lateral. But resistance is proportional to conductor length. So for a given conductor the maximum allowable voltage drop determines diameter, the length of the main feeder and the laterals. This condition can be satisfied at one extreme by a very long main

feeder and short laterals or by a short main feeder and long laterals. However, since it's preferable to maximise the number of consumers for a given constraint, neither of the above options will necessarily satisfy that requirement.

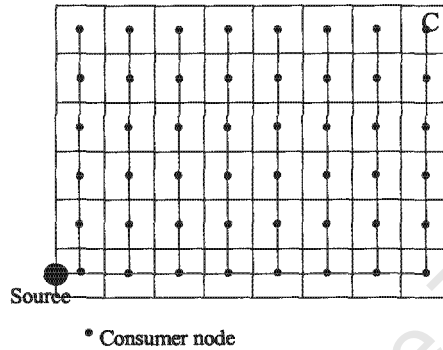


Figure 11.7. A rectangular consumer area

Assume (as before) that the consumer nodes are each consuming one unit of current and spaced one unit length,  $dx$ , from one another. Let the number of equally spaced laterals be  $L$  and one unit length apart and hence the length of the main feeder be  $L-1$ . Let each lateral feeder have  $w$  equally spaced consumer nodes and also inter-spaced by a distance of one unit and hence be of length  $w-1$ . The distance between the power source and the first node is assumed to be negligible.

Total number of lateral feeders =  $L$

Total number of main feeder segments = length of main feeder =  $L-1$

Total number of consumer nodes per lateral feeder =  $w$

Total length of each lateral feeder = total number of lateral segments =  $w-1$

Segment length from one node to the next = 1

Using the aforementioned gathering method, the voltage drop across each feeder can be worked out. The current in the last segment is 1 and equal to the voltage (for a segment of unit resistance). Segment 2 has 2 voltage units across it and so on.

The total voltage drop ( $\Delta V_f$ ) across a lateral feeder with  $w$  segments from a main feeder is

given by using the identity  $(1 + 2 + 3 + \dots + n) = n \frac{(n+1)}{2}$

$$\Delta V_F = (w-1) + (w-2) + \dots + 2 + 1 = (w-1) \frac{w}{2} \quad (11.1)$$

The total voltage drop along the main feeder  $\Delta V_M$  can be worked out by adding up the individual contributions from the lateral feeders (each contributing  $w$  amps) into  $L-1$  segments of the main feeder

$$\begin{aligned} \Delta V_M &= w + 2w + 3w + \dots + (L-1)(w) \\ &= wL \frac{(L-1)}{2} = \frac{w}{2}(L^2 - L) \end{aligned} \quad (11.2)$$

Maximum voltage-drop from source to the furthest consumer  $\Delta V_T = \Delta V_F + \Delta V_M$

$$\Delta V_T = \frac{1}{2} [w(w-1) + wL(L-1)] \quad (11.3)$$

The total number of consumers  $N = wL$ . If  $w$  and  $L$  were varied as factors of  $N$  each pair would yield a different value of  $\Delta V_T$ . Therefore there exists a pair of factors of  $N$  such that  $\Delta V_T$  is a minimum. This is the combination that would achieve the maximum number of consumers for a given permissible maximum voltage drop.

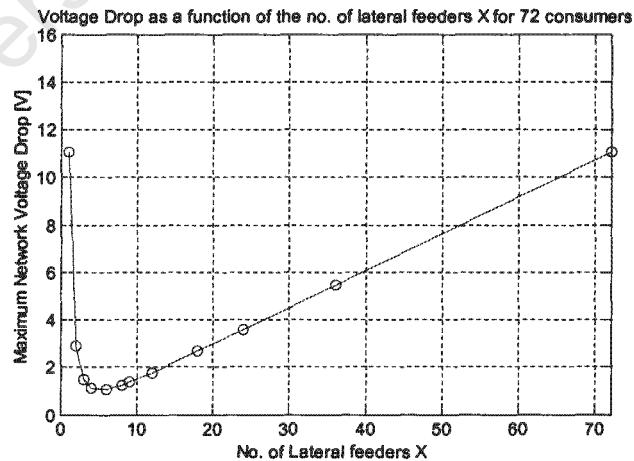


Figure 11.8. Plot of maximum network voltage drop as a function of consumer area shape for 72 consumers

This is illustrated by a result of a Matlab simulation in figure 11.8 where a group of 72 consumers are arranged in 12 different (rectangular) configurations corresponding to the factors of 72. These factors are (1, 2, 3, 4, 6, 8, 9, 12, 18, 24, 36, 72) and are used as the X variables. X variable refers to the number of laterals in a configuration (or number of distribution nodes from main feeder). For example X = 8 refers to a rectangular consumer area with 8 distribution nodes on the main feeder (or 8 laterals) and 9 consumer nodes per lateral feeder, giving a total of 72 consumers. For each of these configurations the maximum network voltage drop is plotted. The inter-consumer spacing and load current per consumer are kept constant. From the results the configuration with 6 laterals each with 12 consumer nodes would realise the lowest maximum network voltage drop for the same consumer load and would be the most suitable choice, provided no other conflicting factor is encountered.

### 11.5.2 Maximum allowable network power losses

Under the same conditions the losses in the network in figure 11.8 can be computed.

Using the idealised 1 unit current per consumer and a unit link resistance of 1 unit the losses in one lateral feeder (with w consumer nodes) are as follows (using the

identity  $(1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n}{3}(n+1)(n+\frac{1}{2})$

$$\begin{aligned}\Delta P_L &= ((w-1)^2 + \dots + 1^2) \\ &= \frac{1}{3}w(w-1)(w-\frac{1}{2})\end{aligned}\quad (11.6)$$

The total number of laterals is L

So the total power dissipated in the L laterals along the main feeder is

$$\Delta P_{Lr} = \frac{L}{3}w(w-1)(w-\frac{1}{2})\quad (11.7)$$

Power lost in the feeder main

$$\begin{aligned}\Delta P_M &= (w^2 + (2w)^2 + \dots + (w(L-1))^2) \\ &= w^2(1^2 + 2^2 + \dots + (L-1)^2) = \frac{w^2L}{3}(L-1)(L-\frac{1}{2})\end{aligned}\quad (11.8)$$

Total network loss is  $\Delta P_M + \Delta P_{LT}$

$$\text{In general the total network loss} = I_C^2 R_{km} dx [\Delta P_M + \Delta P_{LT}], \quad (11.9)$$

Where  $I_C$  is the current demand per consumer,

$R_{km}$  is the conductor resistance per kilometer,

$dx$  is the inter-consumer spacing in kilometers.

Figure 11.9 shows the results, in network loss performance for a group of 72 consumers, as a result of considering a number of lateral feeders. The conditions are similar to figure 11.8. When compared with figure 11.9 the general shape of figure 11.8 is deceptively similar but the fine details actually differ!

In figure 11.8 lowest maximum network voltage drop is obtainable using (the 5<sup>th</sup> factor) 6 laterals with 12 consumers each. In figure 11.9 minimum network losses are obtained using (the 4<sup>th</sup> factor) 4 laterals with 18 consumers each. This scenario leaves discretion to the design engineer for a specific situation. It can also be shown that each number of consumers has unique results. However since for a given situation  $I_C^2 R_{km} dx$  is assumed to be a constant the relative performance of these rectangular shapes will remain the same as that constant is varied.

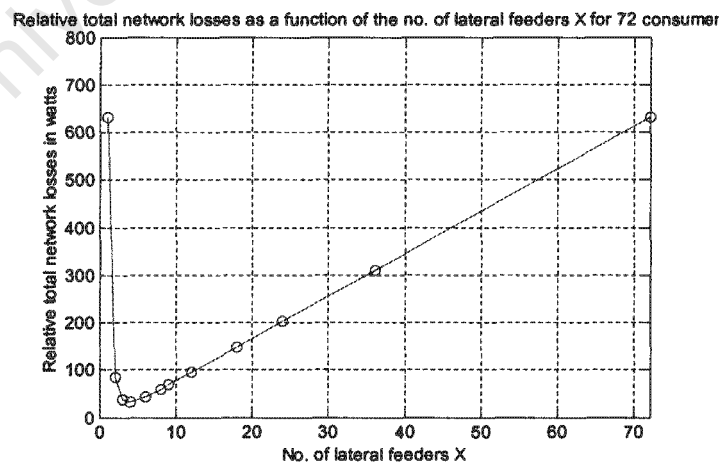


Figure 11.9. Plot of total relative network losses as a function of consumer area shape for 72 consumers

## 11.6 Concluding remarks

The use of idealised networks in distribution network design has been illustrated. A minimised distribution network to a group of consumers in a given consumer area that had previously been realised using idealised networks and an aspect of the constructal theory method has been illustrated. It has been shown that with the appropriate aspect ratio of the distribution conductors the minimised network has superior properties. It has further been demonstrated from Matlab results that a minimal loss network to a group of consumers in a rectangular consumer area can be achieved with the right combination of main feeder length and the number of lateral feeders.

Therefore, it is important to pay detailed attention to network geometry when designing a mini rural power distribution network.

## 11.7 References XI

1. Cooke M. L., "Electrifying the countryside." Survey Graphic. Survey Associates Inc. 1935.
2. Mandeno L., "Rural Power Supply, Especially in Back Country Areas," Proceedings of the New Zeland Institution of Engineers, Vol. 33, 1947.
3. Mini grid design manual, April, 2000  
[http://www.worldbank.org/html/fpd/energy/off\\_grid/mini-grid.htm](http://www.worldbank.org/html/fpd/energy/off_grid/mini-grid.htm)
4. Willis H. L., "Power distribution planning reference book," New York: Marcel Dekker; 1997.
5. Lakervi E., Holmes E. J., "Electricity distribution network design, 2<sup>nd</sup> Edition," London: Peter Peregrinus; 1995.
6. Gonen T., "Electric power distribution system engineering," New York: McGraw-Hill; 1986.
7. Kersting W. H., "Distribution System Modeling and Analysis," CRC Press LLC, 2002.
8. Westinghouse Electric Corp: "Electrical Utility Engineering Reference Book - Distribution Systems, Vol. 3," East Pittsburgh, Pa., 1965.
9. Denton W. J., Reys D. N., "Distribution Substation and Primary Feeder Planning," AIEE Transactions, June 1955, pp. 484 –499.

10. Arion V., Cojocari A., Bejan A., "Integral measures of electric power distribution networks: load-length curves and line network multipliers," *Energy conversion and management* vol. 44, Issue 7 (2003) pp. 1039 –1051.
11. Bejan A., "Shape and structure, from engineering to nature," Cambridge, UK: Cambridge University Press; 2000.
12. Lorente S., Wechsato W., Bejan A., "Tree-shaped flow structures designed by minimizing path lengths," *International journal of heat and mass transfer* 45 (2002) 3299 –3312.
13. Arion V., Cojocari A., Bejan A., "Constructal tree-shaped networks for the distribution of electrical power," *Energy conversion and management* 44 (2003) 867-891.
14. Wechasato W., Lorente S., Bejan A., "Optimal tree-shaped networks for fluid flow in a disc-shaped body," *international Journal of heat and mass transfer* 45 (2002) 4911 – 4924.
15. Bejan A., "Constructal tree network for fluid flow between a finite-size volume and one source or sink," *Rev Gén Therm* (1991) 36, 592-604.
16. Bejan A., Rocha L. A. O., Lorente S., "Thermodynamic optimization of geometry: T- and Y-shaped constructs of fluid streams.
17. Almogbel M., Bejan A., "Constructal optimization of non-uniformly distributed tree-shaped flow structures for conduction," *International Journal of heat and mass transfer* vol. 44 (2001) pp. 4185 - 4194.
18. MacDonald N., "Trees and networks in biological models," Wiley, New York, 2000.
19. Zamir M., "The arterial bifurcations in the cardiovascular system of a rat," *Journal of general physiology*, 81 (1993) 325 –335.
20. Murray C. D., "The physiological principle of minimum work applied to the angle of branching arteries," *Journal of general physiology*, vol. 9 (1926) pp. 835-841.
21. Morrison, C., "A linear approach to the problem of planning new feed points into a distribution system," *AIEE Transactions*, pt. III (PAS), December 1963, pp. 819 – 832.
22. Van Wormer, F. C., "Some Aspects of Local Area Geometry," *AIEE Transactions*, December 1954, pp. 1343 – 1349.



## 12. A Case for the Automotive 42 V PowerNet as a Power Distribution System in Rural sub-Saharan Africa

### 12.1 Background

In “Making a case for a next generation automotive electrical system”, Miller et al [1], like a host of other authors [2, 3], expressed concerns about the escalating electrical functionality of the automobile, and the ability of the existing harness to continue handling the load. This was especially so in the luxury class. They pointed out that a similar juncture had been encountered in the history of the automobile and the solution was to shift from 6 V to 12 V. Therefore, they suggested a similar remedy. The choice of the new voltage would be informed by, among other factors, the safety of users as well as the operating conditions of affordable semi-conductor switches.

Additionally, there would be need to limit the cost of the power distribution harness. It is generally agreed that dc voltage at around 60 V peak is unlikely to generate a major safety hazard, hence special protection beyond existing materials should not be required. Such a condition would be achievable by a nominal dc bus of 40 V. The value of 42 V was borne of the fact that it's a convenient multiple of the nominal 14 V, which is the bus voltage of a running automobile using the existing 12 V battery. Line voltage drops would be divided by 3 and network losses by 9 for the same load. These savings on their own however, would not be adequate to achieve a revolutionary energy conservation goal. Despite that, it had been recognised, especially in the face of globalisation, that there was need for a new automotive standard. After some hitches, international acceptance of the 42 V idea began to pick up and the drafting of an informal standard [4, 5] got underway.

In the meantime the US government moved to advance three public policy objectives: environmental protection, energy security, and economic competitiveness. The automobile was targetted as it was deemed a major player on all three fronts. With an estimated 200 million vehicles countrywide, fuel consumption by the automotive industry along with its accompanying environmental degradation, easily dwarfed the US national power grid. A target was set to achieve a fuel economy of up to 80 miles per gallon (33.4 km per liter) for a family sedan carrying 5 passengers and 200 pound (90 kg) of luggage. With the 42 V

standard in the making, it became the logical choice as the centerpiece of this massive emerging energy conservation drive [6-9].

A new power distribution standard, the 42V-dc PowerNet thus began to take root and is destined to be the standard for the next generation of automobiles. Could it be adopted as a rural power distribution standard in sub-Saharan Africa? As pointed out, the actual value of 42 V alone does not contain an energy saving attribute. It is, however, the collective attributes of the technologies highlighted in this thesis that constitute a major attraction. Hence the distinguishing acronym, PowerNet. In this case the rural 42 V PowerNet would take a step further by including all the additional non-automotive attributes covered in this thesis.

The most fundamental feature of the energy conservation design is load factor management using the hybrid electric vehicle (HEV) strategy. This minimises the required generator size whose power capability is complemented by a storage battery. Moreover, because the emerging support technologies that include appliances, energy storage and generators are designed and tested on 42 V, they are bound to perform optimally on the same system. Additional features include a draft specification [4, 5] that requires components and appliances to operate over a very wide supply voltage range of +12% and -28% of the nominal 42 V dc bus. This allows, among others, the potential for enhanced available battery storage without necessarily resorting to use of electronic converters, while ensuring that maximum peak voltages are well below levels that are dangerous to humans.

## **12.2 Cause for change**

A state-of-the-art rural power distribution system in Kenya uses 230 V ac single-phase [10-12]. The most problematic feature of rural loads is poor load factors. In such a system the generator must supply the peak load demands. The generator must therefore be sized to meet the peak demand, which makes it much bigger and more costly than necessary. Additionally, it is generally not practical to switch generators on and off, as and when they are required. For example, in the case of a pico-hydro, the river flow must not be unduly interfered with. Thus the generator must continue to run and the unusable power must be dumped to maintain stability.

The classic rationale that has been used since the dawn of the 20<sup>th</sup> century to justify the systematic adoption of ac power supply systems and the subsequent relegation of dc in mainstream power delivery was the exclusive attribute of ac (at the time) to transform to higher voltages. This would result in lower line voltage drops and network losses: a fact that cannot be disputed. Voltage transformation has, however, long ceased to be an exclusively attribute of ac. But even if dc voltage transformation were not possible and 42 V dc were compared to 230 V ac, the assumption that the latter would automatically have lower network losses would be flawed.

The main flaw with the argument would be an implicit assumption that loads are always at long distances from the generators. In the context of this thesis, the energy sources are basically local with fairly short delivery distances. In addition, wind and insolation resources are stochastic with hardly any coincidence with load demand and therefore nearly all the energy must be stored. Energy storage plays a pivotal role in load factor management. With current technologies, the only electrical form that can be cost-effectively stored in rural areas is dc. In addition, ac loads are riddled with power factor, phase and frequency issues that particularly affect power stability, power delivery losses as well as the required infrastructure and generator sizes. Moreover, the allowable appliance operating voltage range at 230 V ac of  $\pm 6\%$  is much narrower and is at potentially lethal levels. The latter is an issue of particular importance in the rural areas.

In the above cases, where dc storage is virtually inevitable, the operation of ac rated equipment requires an inverter: occasioning additional cost in energy and capital. Furthermore, since most of the domestic equipment is intrinsically dc, transformers and rectifiers are required and result in further energy conversion losses. Losses of up to 15 W have been reported in an appliance step-down transformer of just 50 VA [13]. When a dc supply must be inverted to ac in order to operate such an intrinsically dc appliance, an escalation of energy conversion losses is inevitable. In the case of motorised loads for the low range of power requirements (in rural areas) it is an established fact that small dc motors operate at higher efficiencies than their ac counterparts.

This chapter looks at the new 42-V PowerNet distribution system and using the 230 V ac single-phase as the benchmark, examines its comparative attributes, in the context of a rural application. The new distribution system will be assumed to enjoy the aforementioned new automotive technological attributes. The 230 V ac will use standard commercial ac appliances. Their performances will be examined under current and projected appliance technologies, variable conditions of power factor, load factor and use of an inverter. Conclusions will then be drawn as to the comparative performance of the new system and hence its suitability as a rural power distribution standard in sub-Saharan Africa.

### 12.3 Examples of Rural application of the 42 V PowerNet

#### 12.3.1 Effect of appliance technologies

The following critical rural loads namely water pumping and lighting are specified in terms of social requirements according to specifications by relevant South African authorities. The requirement for refrigeration is not as easily quantifiable and so the values used here are from a South African case study. The aim is to compare the electric power consumed to achieve the same social requirement under the different power supply standards.

**Rural water supplies:** The South African department of Water Affairs [14] has specified 6000 liters of water as the minimum monthly requirement for a household of 8 people or 200 liters a day. In reference [15] is a typical (230 V ac) driven domestic pump with a capacity of 10 liters per minute for a head of 24 meters and consuming 350VA. In order to deliver 200 liters, the pump would be required to run for 20 minutes. Assuming an ac power factor of 0.8, then the equivalent dc power at the same efficiency would be  $0.8 \times 350 = 280\text{W}$  and a daily energy consumption of  $\frac{280 \times 20}{60} = 93 \text{ Wh}$ . If this load were spread round

the clock, the required 42 V dc pump power rating would be  $93.3 \div 24 = 4 \text{ W}$ . As mentioned in chapter 4 the slow pumping rate results in efficiency improvement and much less wear and tear. But even without considering any increase in efficiency this equipment would be much smaller, less costly as would be the required power source. A case study [15] put the energy savings of similar equipment at 30%. The continuous pump rating would then become  $4 \times 70\% = 2.8 \text{ W}$ . However, there is bound to be a battery to guarantee this supply.

Assume a storage efficiency of 80%. The required continuous power to operate the pump becomes  $2.8 \div 80\% = 3.5$  W. Total energy required per day would be  $3.5 \times 24 = 84$  Wh.

**Rural lighting:** Assume a typical daily rural domestic lighting requirement to be for a 4 hour period in the evening. In [17] it was estimated that during such an evening the same 8-member family (as above) would require some 10800 lumen hours of illumination energy. The estimated load factor for the lighting load during the said four-hour evening was 80%.

So the peak illumination power rating would be  $\frac{10800}{4} \div 80\% = 3375$  lumens. If the assumed lamp for ac voltage were an incandescent (with efficacy of 15 l/w) then the peak power consumption of  $3375 \div 15 = 225$ W and a daily electric energy requirement of  $10800 \div 15 = 720$  Wh. If the 42V system were to be assumed to use a white LED (in year 2012) at an efficacy of 120 l/w [17], the resulting peak power consumption would be  $3375 \div 120 = 28$  W. Total electric energy consumed per day =  $10800 \div 120 = 90$  Wh. If this were battery supported (assuming a storage efficiency of 80%) then the required daily energy supply would be 113 Wh.

**Rural refrigeration for food preservation:** In reference [18] a South African consumer study rated the capacity of typical domestic refrigerator at 180VA with an operating duty cycle of 15hr/day. This is quite comparable to the capacities typically found in Kenya. It will be assumed to be the 230 V ac mains operated induction motor driven compressor controlling the temperature by cyclic on/off routines. The consumption of a dc version will be assumed to use new automotive air-conditioning technology [19, 20] with estimated 50% energy saving under the same thermal loading. At a typical power factor of 0.8, the wattage consumption of the ac refrigerator is  $180 \times 0.8 = 144$ W. An equivalent dc system running for 15 hrs would consume  $144 \times 15 = 2160$ Wh/day. At the estimated 50% saving, the energy consumed by the equivalent 42 V dc system would be 1080Wh. At continuous operation this would require a power rating of  $(1080 \div 24) = 45$ W. Assume that a battery supports the continuous dc operation. If one assumes the battery efficiency factor of 80% then the actual power rating becomes  $45 \div 80\% = 56$  W (or 1344 Wh per day).

Table 12.1. A comparison of power requirements for appliances on 230 V ac and 42 V dc.

Rural load	Daily Requirement	Power demand and/or load current at 230 V ac	Power demand and/or load current at 42 V dc
Water	200 liters	350VA (power factor 0.8),1.5A	3.5 W
Light normal demand	10800 lumen hrs	225 W (incandescent)	28 W WLED (2012)
Refrigeration	180VA (230V) for 15h 2700 VAh @ 230 V ac	180 VA	56 W

From the above, the peak non-coincident power per household would be 755 W and 89 W for the 230 V ac and 42 V systems respectively. The total amount of energy used per day would be

Table 12.2. A comparison of the daily energy requirement per household

Rural load	Total energy consumed per day at 230 V ac	Total energy consumed per day at 42 V dc
Lighting	720 Wh	113 Wh
Water	117 VAh	84 Wh
Refrigeration	2700 VAh	1344 Wh
<b>Total load per day</b>	<b>3537 VAh</b>	<b>1541 Wh</b>

### 12.3.2 Effect of inter-linking

From the above the peak non-coincident demand per household is 755 VA and 87.5 W for 230 V ac and 42 V dc respectively. These are equivalent to the minimum generator capacities per household. If the neighbourhood were 41 households the collective peak generating capacities would therefore be (41 times) 30955 VA and 3588 W for 230 V and 42 V respectively.

If the households were supplied from a common generator the peak load would be determined by the group load profile. In chapter 5, figures 5.16 and 5.17 are graphs of a case study from a South African village and depict the load profiles for an individual household and a group of 41 households over several days. The average daily peak currents are 8.5 A and 85 A for the individual and group households respectively. If each individual household were to own a generator, the collective capacity would be  $(41 \times 8.5) = 348.9$  A. But in fact the group only requires a peak capacity of 85 A.

If the profiles in figures 5.16 and 5.17 were valid for the above cases then the group peak demand would only be about 10 times the individual household peak demand. Thus, a much smaller generating capacity and capital costs would result from linking all households to a common source.

### 12.3.3 Effect of load factor

If equal average loads were connected to each of the 230 and 42 voltage systems, the currents drawn would be in the ratio 2:11 respectively, if the network infrastructures were identical. As pointed out however, the loads are not always level or average and are dependent on load profiles. The instantaneous currents drawn determine the network losses and generator size. Extreme (but not uncommon) load factors of 6% in households have been reported [21] when the resulting peak currents were 17 times as high as the average demand. Therefore, the required generator size would rise by the same factor to meet the load. With the 42 V dc operated in the aforementioned HEV mode and assuming a battery efficiency of 100%, the ratio of line currents for the 230 V ac and 42 V dc would be 17 : 5.5. If the battery efficiency were assumed to be 80% and all the energy were stored first before delivery to the load, then the average line current for the 42V system rises

$(\frac{1}{80\%} \times 5.5 = 6.9)$ . At peak demand the load current ratios would then be 17 : 6.9 for 230V and 42V respectively. Therefore using the model in figure 11.7 the maximum network voltage drop during peak demand for the 230V would be  $(17/6.9) = 2.5$  times that of the 42V system.

However as a percentage of supply voltage, the voltage drops would depend on actual load.

On the other hand, network power losses for the 230V system would be  $(2.5)^2 = 6.2$  times those of the 42V regardless of load current.

In general, load factor as well as the required generator capacity rises with the load current by a factor of  $\frac{1}{loadfactor}$ .

Likewise the network losses as a result of load factor are given by  $\frac{1}{(loadfactor)^2}$

Figure 12.1 illustrates a comparison of peak line currents (or voltage drops) between 230V ac and 42V dc as functions of load factor at varying power factors and storage efficiencies.

Figure 12.2 illustrates relative network losses as a function of the load factor.

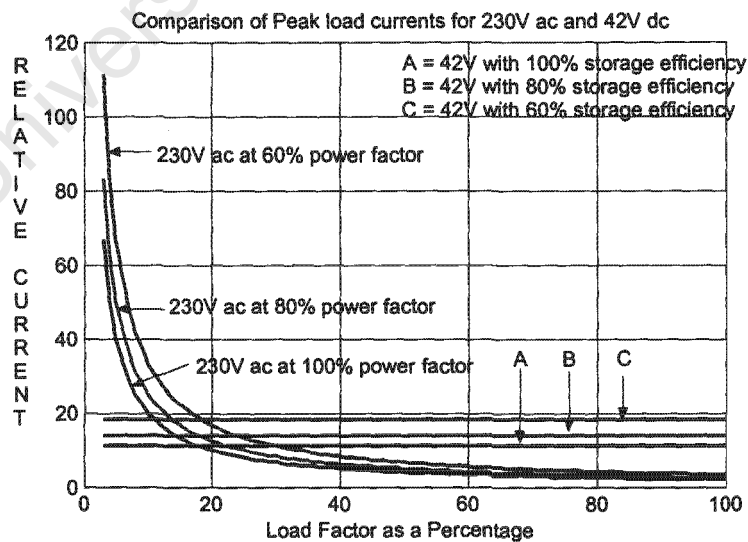


Figure 12.1. A comparison of peak line currents (or voltage drops) dc, as functions of load factor at varying power factors and storage efficiencies

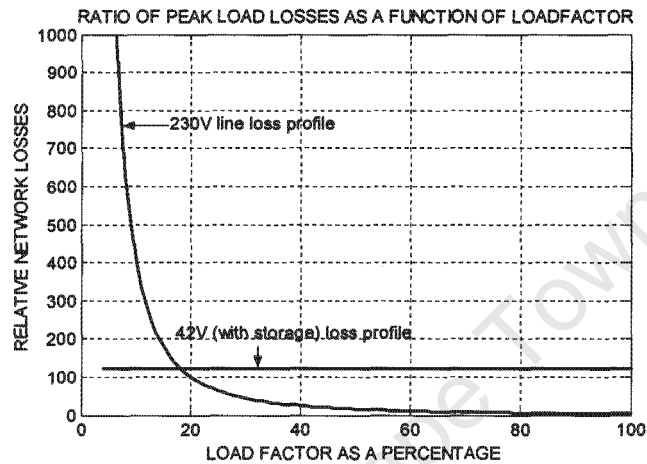


Figure 12.2. Relative network losses between 230V and 42V (with storage) as functions of load factor

#### 12.3.4 Effect of power factor

Like the load factor, power factor affects the line currents, voltage drops and the required generator size by a factor equal to  $\left(\frac{1}{\text{Powerfactor}}\right)$ . Delivery network losses are also

increased to a factor of  $\left(\frac{1}{\text{Powerfactor}}\right)^2$ . Figure 12.3 is the variation of generator size as a function of power factor at various load factors. These are compared to the sizes of the 42 V generators supported by batteries with different efficiencies.

#### 12.3.5 Effect of using an inverter

In the more likely event that the available energy in a rural situation is in dc form, one may be faced with a choice of using ac or dc appliances. In this context the issue then becomes a choice between 230 V ac and the 42-V powerNet. When the choice is 230 V ac an inverter will be required.

To begin with, the introduction of an extra piece of equipment reduces the reliability, not to mention cost, time to repair or possibility of inability to repair. Inverters are also affected by natural phenomena like weather and geographical location. In circumstances where critical loads like vaccines are involved, system reliability becomes very critical. This is exacerbated by statistics that show general lack of service back-up in the African rural environment. Overwhelming evidence including a recent Sandia field study back these fears [22, 23].

The use of multiple inverter units whose total capacity equals or marginally exceeds the required load instead of a single unit, have been suggested in certain critical circumstances as a measure to enhance reliability. This can however escalate the cost of capital.

In the case of transient loading, which occurs for example with induction motor-driven water pumps and refrigerators, the unit will have to provide the necessary peak transient currents. From a data sheet of an American inverter [24] the longest permissible duration for 150 – 220% of rated output load capacity is 24 cycles (or 480 milli-Seconds at 50 Hz). An output of 300% of rated capacity can only be sustained for up to 4 cycles (or 80 ms at 50 Hz). Figure 12.4 shows the current waveform drawn from an inverter by a starting induction motor-driven refrigerator. The transient peak current is 850% of the operating current for a duration of 120 ms. Therefore, the minimum size of the inverter to run this load (assuming a 200% overload) would be 425% of the rated refrigerator capacity. But inverter efficiency is load dependent and therefore the unit with the right capacity will not operate optimally. The input dc operating range of this inverter is +10% and -18%. This is inferior when compared to the 42-V PowerNet rated appliance range of +12% and -28%.

It can be shown that the voltage of a floating dc bus under constant load is almost linearly proportional to state of charge (SOC) of the battery. Therefore, a specification of -18% means that the minimum supply dc voltage for an inverter rated for 42-V PowerNet is 34.44V, as compared to (-28%) or 30.24V that can be used by a 42-V rated appliance. Therefore, the amount of extra charge available to the dc equipment after the inverter has

shut down (on under voltage) is  $\frac{34.44 - 30.24}{42} \times 100\% = 10\%$ .

If the inverter average efficiency is assumed to be 85% then the extra storage capacity that will be required to operate an appliance of equal capacity but running directly from the 42-V PowerNet is  $\frac{1}{85\% \times 90\%} - 100\% = 30.7\%$ . This is without considering that the equipment may require to internally convert the ac back to dc.

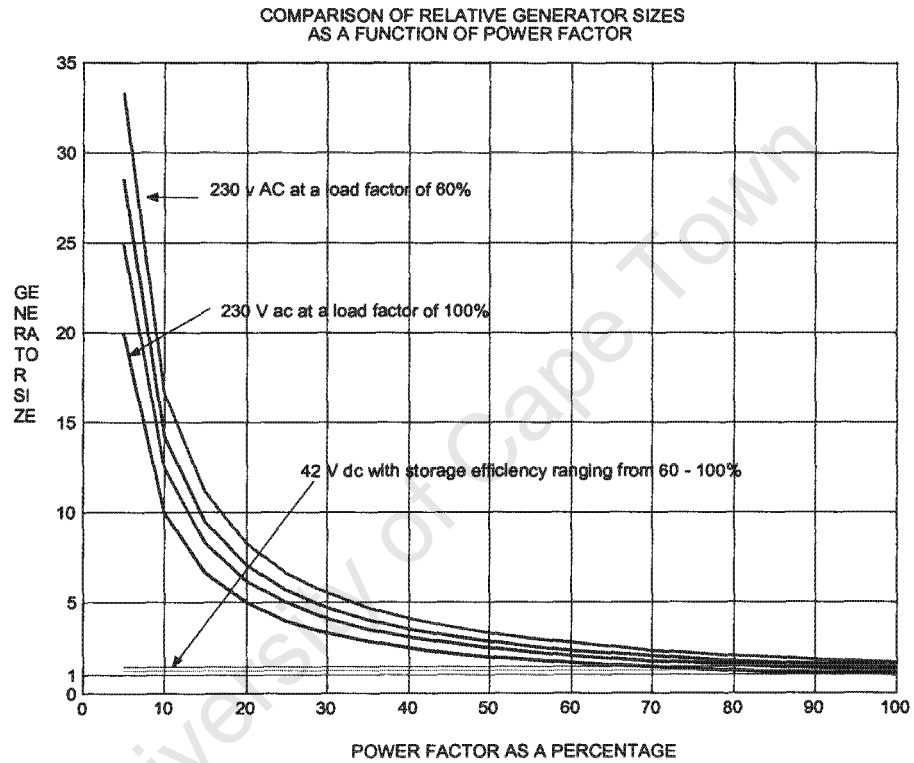


Figure 12.3. Generator size as a function of power factor at varying load factors and storage

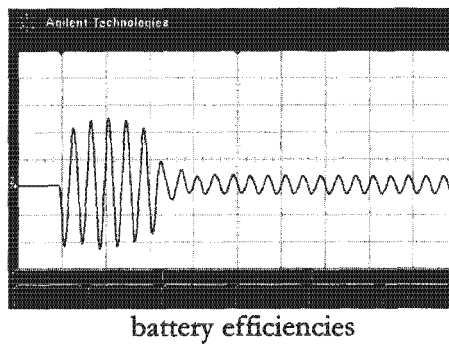


Figure 12.4. The starting current of an induction motor-driven refrigerator

## 12.4 Concluding remarks

In this chapter a background as to the origin of the 42 V PowerNet has been given. The shortcomings associated with the use of the traditional 230 V ac system in the rural areas have been cited. Then using 230 V ac as the benchmark, the performance of the 42-V PowerNet as a rural power distribution standard, has been analysed under different appliance technologies, varying load factors, power factors and using an inverter. Subsequently, using Matlab simulations and graphs it has been shown that when combined with the attributes of new automotive technologies and appliances, the 42-V PowerNet would be the preferred distribution system under typical African rural conditions.

It could be argued, in the case of relatively distant generators, like pico-hydro and some cases of wind, that the use of 42 V could result in unacceptably high voltage drops. This would perhaps call for a combined system where power delivery from the stream to a central point in the village would be 230 V ac and then distribution by 42 V dc thereafter. However, it must be pointed out (as also illustrated in figure 12.1 and 12.2) that with the technique of load leveling, line currents can be very low. This is especially so with low load demands and efficient appliances as well as the absence of frequency and power factor encumbrances. There is still the issue of availability of appliances and indeterminate pricing of the transitional automotive technologies and appliances. However, if the story of the cellular phone in rural Africa, which has dropped in price to one tenth in ten years, is anything to go by, these are only but very temporary hitches.

Current dc appliances used in rural areas are largely designed as recreational appliances for camping and thus run on the current 12 V automotive system. Since the system is gradually being phased out, supplies of such appliances will likewise cease.

## 12.5 References XII

1. Miller J. M., Goel D., Kaminski D., Schoner H. P., Jahns T.M. "Making a case for a next generation automotive electrical system." MIT Consortium. ([http://www.infineon.com/cgi/ecrm.dll/ecrm/scripts/sol\\_cat.jsp?oid=-8259](http://www.infineon.com/cgi/ecrm.dll/ecrm/scripts/sol_cat.jsp?oid=-8259))

2. Hans-Dieter Hartmann, "Standardization of the 42v PowerNet- history, Current Status, Future Action." SISCAN GmbH, Hanover. (<http://www.sci-worx.com/internet/bordnetzforum/bn42vnorep0701.pdf>)
3. Miller J. M., Emadi A., Fahimi B., Ehsai M., "On the suitability of low voltage (42 V) electrical power system for traction applications in the parallel hybrid electric vehicles." Society of automotive engineers, 2000.
4. "Road vehicles – Conditions for electrical and electronic equipment for a 42V powernet," Ref WGS/WD 03/2001-1. Work Group "Standardization" April 2000.
5. "Road vehicles – Conditions for electrical and electronic equipment for a 42V powernet," Ref WGS/WD 03/2001-2. Work Group "Standardization" April 2000.
6. Review of the research program of the Partnership for a New Generation of Vehicles: 5th Report (1999). National Academy Project (04/01/1999). ISBN: 0309064430
7. Sebitosi A. B., Pillay P., "Applications of Advances in Automotive Electronics to Rural Electrification: The 42V Power-net for Rural Electrification," Proceedings of the IEEE PES General Meeting, 13 – 17 July 2003, Toronto, Ontario, Canada.
8. Heitner K. L. et al "Advanced Automotive Technologies Energy Storage R&D Programs at the US Department of Energy-Recent Achievements and Current Status." Society of Automotive Engineers, 2000.
9. Langenwalter J., "42 V Design Process" Society of Automotive Engineers, 2000
10. Gitonga S, Balla P., "Poverty impacts of Pico hydro power schemes in Kenya." Post Installation Socioeconomic Report for European Commission, March 2002.
11. Maher P., Smith N.P.A., Williams A. A., "Assessment of Pico hydro as an option for off-grid electrification in Kenya," *Renewable Energy* 28 (2003) 1357–1369 <http://www.eee.ntu.ac.uk/research/microhydro/picosite/>
12. "Affecting Electricity Policy through a Community Micro Hydro Project in Kenya," *Global Village Energy Partnership Newsletter*, Issue #59. January 23, 2004
13. "Strategic studies of household energy and greenhouse issues" June 1998. <http://www.greenhouse.gov.au/coolcommunities/strategic/refer.html>
14. White Paper on Water Policy, Republic of South Africa, 30 April 1997. [http://www.cmc.gov.za/peh/soe/legal.htm#WATER\\_QUALITY](http://www.cmc.gov.za/peh/soe/legal.htm#WATER_QUALITY)
15. B S Pumps Pvt. Ltd. <http://www.bspumps.com/product.htm>

16. "Drives cut cost of compressed air," Case study/Application note from Control Techniques, Stafford Park 4, TF3 3BA United Kingdom. May 2004.  
<http://www.engineeringtalk.com/news/cod/cod154.html>
17. Sebitosi A. B., Pillay P., "White LEDs for rural lighting," Proceedings of the IEEE PES General Meeting, July 2003.
18. Thorne, S., "Financial costs of household energy services in four South African cities." Energy & Development Research Centre, University of Cape Town. Cape Town, 1996.
19. Nadamoto H., Kubota A., "Power saving with the use of variable displacement compressors", Society of automotive engineers, 1999.
20. Bhatti M. S., "Enhancement of R-134a Automotive air conditioning system" Society of automotive engineers, 1999.
21. Newborough M., Augood P., "Demand side management opportunities for the UK domestic sector," IEE Proceedings, Generation, Transmission and Distribution Vol. 146, No.3 May 1999.
22. Maish A. B., Atcitty C., Hester S., Greenberg D., Osborn D., Collier D., Brine M., "Photovoltaic System Reliability," Presented at the 26th IEEE Photovoltaic Specialists Conference, September 29 - October 3, 1997, Anaheim, California Sandia National Laboratories.
23. King D. L., Kratochvil J. A., Boyson W. E., "Photovoltaic System Performance Characterization Methodologies," Sandia National Laboratories Albuquerque, New Mexico 87185-0752 (NCPV and Solar Program Review Meeting 2003).
24. "Topaz S3 DC to AC inverters."  
<http://www.mgeups.com/products/pdt230/invert/s3/pdf/s3uk.pdf>

## 13. Conclusions

### 13.1 What has been done?

This work has, firstly, explored technological advances that have resulted in energy conservation. Moreover, by aiming to combine fuel conservation, production cost minimisation and environmental friendliness, the PNGV embraced the hallmarks of sustainability. It has further been argued that the problems of an automobile and a remote rural village are analogous in many respects and therefore solutions could be shared. “Application of advances in automotive technologies to electrification in rural sub-Saharan Africa” has thus demonstrated that the potential of leading edge automotive technologies could be exploited to unravel rural African electric supply issues. From the above, it would also be reasonable to infer that the rural solutions so derived, would similarly conserve energy cost-effectively, while not compromising the environment.

In addition, the author has made contributions to rural load modelling, rural mini-distribution network and system configuration designs as well as identifying a variety of socio-political issues that could contribute to failure in the provision of energy services in rural sub-Saharan Africa. Subsequently, the issues that would appear to influence the collective sustainability of a rural energy supply system have been identified as, accuracy of energy resource assessment, prudence and efficiency of resource-to-need conversion technology, human factors, load factors, appliance efficiency, energy storage efficiency, power delivery network efficiency and system configuration. In the final chapter, in an attempt to harness these attributes, the new automotive power distribution standard, the 42-V PowerNet has been proposed as the next power distribution standard for rural sub-Saharan Africa.

The primary automotive energy source is gasoline. The ultimate aim is to maximise the distance travelled per liter of fuel consumed (with a clean environment in mind). With the concept of the hybrid electric vehicle (HEV) design, the PNGV achieved a fundamental breakthrough in automotive energy conservation. A small primary power plant (PPP) converts the fuel and has a maximum capacity of about average load demand. Any excess energy is stored in a battery, which complements the power capability of the PPP when

accelerating or climbing a hill. In addition, a start-stop control system ensures that the engine stops running when the car is at standstill. So the automotive PPP is only required to generate enough energy (over the driving period) rather than meet the peak power demand. In the above strategy the PPP experiences a near level load and minimal parasitic losses. No generator can be designed to operate optimally over its entire power range. Thus, by narrowing the operating power range, the high load factor offers an opportunity for a generator design that operates close to its optimum efficiency point, which results in further minimisation of the required PPP capacity.

By contrast a state-of-the-art pico-hydro PPP at the Kathamba village, for example, must supply all the power required at every instant in time, on its own. The generator capacity must therefore be at least as big as the peak load demand. A rural lighting load for example is typically 4 hours per evening and yields a load factor of about  $\frac{1}{6}$ . It therefore requires a generator capacity, which is at least six times as big as should be necessary. In addition, as the river flow must not be unduly interfered with, the generator continues to run during the 20 hours of no load. The unused power must be squandered by dumping into a dummy load to maintain stability. This can be likened to a water tap left running round the clock without being attended and then suddenly at some point in time everyone shows up with buckets to collect their day's ration. It exacerbates an already meager supply rate even further.

If however the HEV concept were applied to the Kathamba situation, practically all the unused generated energy (less battery inefficiency) would be stored. The capacity of the battery would then be appropriately sized. Thus the efficacy of the original 10 W per household would be multiplied several fold. Or put differently, the 1.1 kW generator at Kathamba could have in fact supplied a similar load to nearly (390) six times as many households as are currently connected. The apparent additional cost imposed by the necessary battery in the HEV version would therefore be very easily defrayed by the additional consumers or by the reduction in generator size. It would therefore appear to be prudent to adopt an HEV-like system for such a pico-hydro power distribution network.

It was further shown in chapter 10, using Matlab simulations, that this strategy could be further improved on if a common bus linked several autonomous HEV systems: a feat that couldn't easily be achieved by the automobile. This conclusion was arrived at when 4 different configurations of systems of the size typically found in Kenyan rural areas were analysed. Because of the diversity of loads, the common bus enabled a load to utilise power from a generator in a different system at the instants when its own generator was insufficient and thus cut down on system storage losses. The technique was shown to have an added advantage for transient loading. Ultimately, the necessary system generator and battery capacities and hence capital costs would be reduced. This would be especially important for Kenya, where the performance of hundreds of thousands of stand-alone PV systems already installed could still be improved by simply being inter-linked. Moreover, individual households would have an added reliability factor, as failure at one household would enjoy interim back-up from the rest of the community before being attended.

The next issue was the energy resource-to-need conversion efficiency. From the PNGV selection of primary power plants the author opted for the fuel cell as discussed in chapters 6 and 7. The biggest attraction of the fuel cell in the rural areas was its ability to use biogas, a fuel that could be inexpensively produced by the rural agricultural communities through anaerobic decomposition of plant and/or animal waste and has zero emission rated energy conversion. Moreover, harmful underground water polluting pathogens, problematic weed seeds and offensive odours would be controlled and mitigation of landfill green house gases would be achieved, while producing valuable fertilisers as by-products.

The technology was shown, in a worked out example, to have a potential for generation of both electricity and heat in CHP application. This strongly supports it as a prudent technology choice. In the example, a rural community load was met at a constant FC power output, while the load power peaks and troughs were buffered by a storage battery. The recent exponential growth trends in investments in automotive and general power fuel cell technologies and projected technological advances, as well as anticipated reductions in material costs, were highlighted. It would therefore appear that the adoption of fuel cells as rural PPPs would be both prudent and inevitable.

The next issue was energy storage efficiency. The excess energy that had to be stored could only be recovered at a percentage depending on the efficiency of the storage battery. There were also concerns raised about charge/discharge rate limitations, maintenance and lifespan of traditional chemical batteries as well as environmental issues due to disposal. From the PNGV shortlist of storage technologies, the flywheel battery was shown in chapter 9 to have the potential to address those concerns. In a worked out example a battery specification for a South African rural load requirement was designed. The current and projected statuses of the flywheel battery were highlighted. It was therefore suggested that the flywheel battery has great potential as a future rural electric energy battery, once the pending shortcomings are addressed. Moreover, the current flywheel project underway at UCT brings that possibility even closer.

From the above, a basic HEV working framework was established at this juncture. The next step was to establish the load requirements. It was shown that the best energy conservation strategy could be frustrated if the designer ignored human factors. Toyota, a corporation at the leading edge of automotive technology only realised this when American drivers could not replicate the fuel economy results achieved previously by Japanese drivers using the same car design. The oversight consequently cost them a whole year in sales revenue. Chapter 2 took cognisance of this fact and identified a detailed range of human issues that must be considered before realising sustainable rural energisation. Since energy is required to enable human endeavour, the choices made by humans could be as important as the ingenuity put into the mechanical design of systems. In the words of the chapter title, “How conducive to electrification is the African rural environment?”

In chapter 3, a detailed discussion showed how the use of advanced illumination technologies minimises the electrical power consumed by lighting loads while maximising the lighting quality. Further electric energy savings would be realised by the use of efficient electric-to-light conversion systems. The inroads made by LEDs into the automotive and signal markets and the resulting massive energy savings were highlighted. It was subsequently shown by worked out examples that the white LED (for general lighting), even in its present semi-developed form, would result in substantially higher electric lighting energy savings than state-of-the-art rural electric lights. These savings would even rise to record levels when

the projected white LED efficacies were achieved. There was therefore ample reason to suggest that the white LED would be the right rural lighting choice for now and the future.

In chapter 4, the critical appliances in rural refrigeration and water pumping were shown to improve their efficiencies by exploiting leading edge automotive air-conditioning and motor drive technologies. In addition, (chapter 5) models of transient and steady state load currents were derived for an incandescent light source, a fluorescent light source, light emitting diodes, a water pump and induction motor driven refrigeration compressor. LED transient loading was the least severe among the lighting loads thus vindicating earlier recommendations for white LEDs. Then finally by using a new technique devised by this author, a mathematical model of an average daily load profile for a group of households from a South African rural village was derived. The technique involved the summing up of fragmented sections of the profile using Matlab.

At this juncture, the requirements of individual appliances as well as the aggregate and daily load profile, would be known. These would constitute the total amount of energy that should be supplied by the PPP. However, as mentioned, the load demands do not always coincide with generation, which makes the inclusion of storage losses inevitable. In a worked out example for specifying a fuel cell for a rural village load, chapter 7 illustrates the computation of the final capacity of a PPP after taking the storage losses into account.

The above illustration however assumed that power delivery losses were negligible. In chapter 11 a methodology for the design of a minimal loss distribution network was illustrated. This was not an automotive technology but a derivation by the author using idealised networks and a new network minimisation concept, so-called the constructal theory. Matlab simulation results showed that by manipulation of the main feeder length and the number of lateral feeders in a rectangular field of consumers, one could minimise line voltage drops and power distribution losses. It was then concluded that paying attention to geometric detail is beneficial to the design of energy efficient rural mini distribution networks.

From the above, therefore, the required output of the PPP was the total daily load plus all the aforementioned losses. The amount of fuel required for the task could then be derived using the resource-to-need efficiency of the PPP.

During normal operation of an automotive PPP, a fuel gauge monitors the amount of available fuel. It ensures that the energy density of the resource is constant and hence the PPP output continues to be predictable. This is also possible for a rural fuel cell using biogas, as well as a pico-hydro generator. The difference however, is that while an automobile driver could replenish his tank at a refueling station, a rural fuel cell user must look for sources of raw materials to generate the required gas. This issue was discussed in chapters 6 and 7 where graphs showed estimates of the number of various types of animals and/or weight of crop residue that would be required to sustain the operation of a fuel cell PPP, to satisfy various village sizes. These results strongly suggest that biogas production is viable since adequate quantities of raw materials for its production could be found in many parts of sub-Saharan Africa. In the case of pico-hydro, the energy resource is natural and must be assessed to determine the average flow of the river or stream as well as seasonal variations. Methods for this evaluation were described in chapter 8.

The resource energy density available to a wind turbine or a solar PV panel is variable due to the stochastic nature of the resources. A suitable generator size could only be designed when large amounts of hourly climatic data extending for years are available. But as pointed out in chapter 8, these are largely unavailable in sub-Saharan Africa. The chapter addressed this issue, by discussing various probabilistic models and commercially available software that could be used to synthesise the required hourly data from monthly averages. It was also pointed out that leading international weather laboratories have validated the accuracy of such data. The conclusion drawn therefore, was that it was possible to design wind and insolation based generators with acceptable accuracy (and hence cost-effectively) for virtually any rural African location.

The final chapter highlights the PNGV new power distribution system, the 42-V PowerNet. The question posed was how well it would perform as a rural power distribution standard. The familiar traditional 230 V ac was used as the benchmark. Performance comparisons

were made using the results and network evaluation methodologies developed in chapters 10 and 11. It was shown that under typical rural mini-grid load conditions the 42 V dc has a potential to incur lower network losses despite its apparent numerical disadvantage. Additionally, graph plots showed the rapid increase in the 230 V ac generator size with decreasing load factor and power factor. Given therefore that this standard epitomises all the attributes developed for the successful fuel-efficient HEV design along with the futuristic appliance technologies, it has promise as a future rural electrification standard.

### **13.2 What should be done next?**

This work has sought to compile a comprehensive list of social and technical components that are responsible for system energy conservation, in an attempt to redefine the art of electrification in rural sub-Saharan Africa. While the aforementioned components may not individually appear as profoundly novel, it's the author's contention that, the concept of deliberately compiling and presenting them as interactive and interdependent (socio-technical) constituents of a functioning and optimisable 'entity' is a precedent. There are system models for purposes other than this. For example, a computer model, HOMER, developed by the National Renewable Energy Laboratories (NREL) is also referred to as a system optimisation model [Visit, <http://www.nrel.gov/homer/>]. The model however is a methodology for the evaluation of energy resource-to-need options under varying energy resource and economic conditions. In other words, how many (generators) of what type and size should one use and under what conditions? In addition, the availability of any of the aforementioned modern appliances need not be a necessary condition for the function of the entity but a bonus whenever available.

The first issue one should then address is to what extent a percentage change in each of the aforementioned components affects the performance of the entity. This is sometimes also referred to as a sensitivity test. In order to pre-empt disproportionate apportionment of resources therefore, future work should seek, first, to establish the comparative efficacy of the individual components in the system and hence identify those that require more attention. It would also provide an opportunity for the identification of possible omissions from the presented list and possibly result in an even more refined product.

The importance of this point was most aptly illustrated in reference [15] of chapter 4, where Bhatti presented a thorough system analysis of the vapour compression cycle. He concluded in part, "...an increase in compressor isentropic efficiency (IE) has a strong influence on the COP (overall coefficient of performance of the air-conditioner). For example, a 10% increase (in IE) results in a 26% increase in COP." In such a case one would infer that Bhatti regarded improvements in IE to be more discerning.

In the field of resource-to-need conversion more fronts should be opened up. Wind has been cited as a grossly under-explored field in sub-Saharan Africa. But in this case it could premier with a difference: for example, as pico-wind. A household could be assigned a small turbine with an output capacity of the order of 10–50 W. With drastically improved appliance efficiencies such power levels could become a rural norm. This should naturally be preceded by resource assessment. This way rural artisans would be encouraged to complement existing imported renewable energy technologies with local alternatives.

The notion of manually generated electric power was only briefly mentioned at the end of chapter 8 but clearly presents life-saving possibilities like cell phone charging and is worth pursuing further.

The use of stepper motors as generators has been suggested in the literature for small generator applications. For this author, stepper motors present particularly interesting possibilities. While this technology may perhaps not yield ground-breaking energy conversion efficiencies, their multiple poles should equip them to operate like small off-the-shelf wind generators and make them suitable candidates for the aforementioned pico-wind and human pedalling, among other possibilities. Even if the efficiency of the motors were as low as 20% they should still be considered; after all, PV cells which are on average half as efficient still continue to do a commendable job. Moreover, there is a good prospect that these motors exist by the millions in discarded computer dumpsites worldwide and as such would provide an inexpensive source of energy conversion.

From the author's anecdotal experiences, the practice of parts recycling is not alien to sub-Saharan Africa. Large percentages of stocks of automotive spare parts used in Kenya,

Uganda, Tanzania and Zambia, for example, are recovered from (mainly) Japanese automobile dumpsites and they have provided affordable backup to those struggling rural transport industries for many years. (See also, "Meeting the rising demand for spare parts," African Business Pages. <http://www.africa-business.com/features/spares.html>). The aforementioned cellular communications industry in Africa is booming; thanks to fashion trend driven first-world consumers, whose discarded old sets have found ready markets in Uganda, Kenya and elsewhere. By adding local technical value, the above suggestion would therefore be not only in conformity with trend but also a leap further.

There is the issue of thermal energy for ironing for example. If pico-power technologies are to attain a respectable and unchallenged status, more attention ought to be paid to the provision of reasonably decent thermal energy conversion for those necessary but often ignored chores like ironing of clothes. The disseminator should be able to anticipate 'normal' expectations that cannot (sensibly) be met by say, PV generators and adequately educate the consumer. It cannot be over-emphasised that Africans ought to discard the notion that the ultimate solution to all energy needs is electricity. For at least two decades, natural gas has been the *de facto* official source of thermal energy for much of Europe and resulted in major savings. There is therefore need to look at options, like biogas, more seriously. This author has in fact been informally researching into methods used in early 20<sup>th</sup> century, to design kerosene and gas (pressing) irons: an idea, which many colleagues from rural South African townships confirm, would be appreciated.

There is also the issue of carbon trading which is still evolving and could provide a breakthrough in future finance and capital for rural energisation in sub-Saharan Africa. The benefits of the aforementioned UN Forum Convention for Climate Change financial mechanisms are yet to be fully understood and exploited by consumer communities. More clarity and education is needed for a whole range of environmental terminology [see references 64-66 in chapter 1]. For example, what, in fact, is 'sustainability'? How does one identify which fuels are zero emission rated? What is 'carbon sequestration'? What everyday activities contribute positively or negatively to it? How can one financially (or otherwise) benefit from all these?

African governments classify much of the economic activities by their people as informal. Ironically the incomes from some of these 'informal' transactions often rival and sometimes exceed official activity. For example banks in Dakar, Senegal estimate that Senegalese traders and workers abroad send back \$40 million a month, equivalent to 60 per cent of the country's economy. [See "African governments reach out to diasporas", Economic and Social Research council (ESRC) <http://www.transcomm.ox.ac.uk/traces/iss12pg2.htm>]. Similar figures could be quoted for Zambia, Uganda or Kenya. Going back, for example to the proposal of scavenging of spare parts from dumpsites, one could argue that such activities do in fact mitigate carbon dioxide emissions and should therefore earn some 'carbon credits'. However recipient communities would stand to benefit from the relevant UNFCCC provisions only if their governments had the insight to argue for such cases in New York, as the UN only recognises sovereign states as legitimate entities.

However, there appears to be other emerging options, as some international non-governmental organisations seem to be exploring alternative routes. For example, as of the writing of this paragraph, the online *Global Village Energy Partnership (GVEP)* Newsletter: Issue #61 (18<sup>th</sup> March 2004) has just reported that the Mayan villagers in the Guatemalan highlands have just received funds in connection with greenhouse gas mitigation achieved through their community-owned micro-hydro power system. This is believed to be the first time that an indigenous people's organisation has benefitted from the nascent global greenhouse gas emissions market. The benefactors are a Canadian foundation (*The EnerGreen Foundation*), who will be entitled to any accruing "carbon credits". According to EnerGreen's chairman, Jeff Arsenych, "This partnership with the Chel community is a new approach to renewable energy development that will be a model for future initiatives."

With regard to marketing and networking, of all networks, except for food, the automotive service and parts retail industry is the most widely established in rural Africa. In Kenya for example, this very network has for many years been operating an 'informal' link between the automotive industry and rural electrification. One example, is the aforementioned dependence by numerous families on used car batteries to power basic home infotainment appliances. The next generation of automotive technologies should therefore find a friendly and virtually 'familiar' environment in rural Africa.

Finally, in an article, “Top 10 Tech Cars,” John Voelcker [See, *IEEE Spectrum*, March 2004, pp. 27] confirms that the 2005 version of Toyota’s ‘Crown Royal’ model will be the world’s first mass production car, fully standardised on the 42-V PowerNet. This follows the display of its concept version as well as those by the competition, at the 2003 Tokyo Motor Show, [See also, [http://www.autoweek.com/specials/2003\\_tokyo/](http://www.autoweek.com/specials/2003_tokyo/)]. It would therefore appear that there is no going back on the 42 V system and preparing to exploit its advantages would be most prudent for rural Africa. Without an existing infrastructure to discard or retrofit, rural sub-Saharan Africa is most suited for new technology.

### 13.3 An anecdotal note

This work has been a great learning experience for the author. During a 20 year long career as an industrial engineer, the thought of ever getting so passionate about energy conservation never occurred. Even with such technical background the author remained complacent in a shielded urban environment where a flip of a switch was all that was needed to get the necessary function; with a few occasional hitches notwithstanding. The origin of the power did not seem to concern anyone.

This changed dramatically when a prolonged drought took its toll on the major Kenyan rivers that provided the bulk of power for the national grid. The hydro dams were at rock bottom levels and the rivers had to be slowed down. Consequently a nationwide power-rationing regime was initiated after the grid capacity was de-rated by over 30%. Power was on average available for 3 days, of eight hours each, per week. Independent power producers were subcontracted to thermally produce the deficit but were not in place until nearly a year later. The consequent economic damage was substantial, to use mild language. [See also, Peter Munaita, “Power Crisis Deepens as Kenya Hires ‘Mobiles’,” *The East African*, May 15, 2000. <http://www.nationaudio.com/News/EastAfrican/15052000/Regional/Regional12.html>]

In the meantime all means of rudimentary storage technologies and inverters on the market were scrambled but only the most basic office and domestic functions could be sustainably run. An inverter alarm to indicate an ailing battery bank, followed by a blackout, in the middle of an important transaction became the order. It is a most agonising experience that

is not easily forgettable. It is then that the author had a first 'hands-on' experience and comprehension of energy conservation and resolved to start a new career.

The master's dissertation focussed on the design and construction of a three-phase load compensator. It was shown that the three-phase passive network could simultaneously compensate for reactive and unbalance, load currents and reduce the required generator and power delivery infrastructure. This was specifically directed at informal urban settlements (prevalent in Uganda and Kenya) whose unplanned activities impose massive problems on the utilities.

Looking back at the Kenyan power crisis, one cannot help but wonder if the fundamental flaw was not inherent in the concept of focussing on supplying power rather than energy. Considering that the rivers continued to flow during the drought, albeit at much slower rates, what in fact was the utilisation efficiency of this meager energy resource by the utility? Granted that the utility could not possibly determine the consumer load, but isn't this perhaps one reason why their planning team should include consumers? Kenya, Uganda and Tanzania continue to search for international investors in power generation, while their industrial outputs remain far below their existing generating capacities in giga-watt hours per year. These are issues that underscore the author's core concerns.

It's hoped that someone will find this work equally enriching.