Growing energy and food security: an assessment of farm household energy requirements for the achievement of household food security in four major African farming systems

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AusAID-ACIAR Africa Agricultural Research and Development Implementation Partnership
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Introduction

African stakeholders in discussion with ACIAR have emphasised the key role of energy availability on farms for the intensification of food crop production on small holdings, especially in an era of high and increasing oil prices. Energy is often a binding constraint which limits the pumping of water, utilisation of small tractors and the local processing of food, as well as household activities such as clean cooking and household lighting. Recent advances in renewable energy technologies have opened up new possibilities for the economic provision of energy to smallholder households in remote locations, based on better utilisation of biomass and other renewable energy resources.

The research team has assessed the potential for appropriate modern renewable energy technologies to improve primary productivity to accelerate food supply security. The projects include an analysis suitable for four primary production systems:

- inland artisanal fishery systems;
- humid forest root crop-based systems;
- sub-humid savannah maize-based systems, and;
- arid/semi-arid agro-pastoral systems.

In addition to literature reviews, the projects included local producer consultation to elucidate local technical preferences, skilled service-person availability, component costs and serviceability, including agro-ecological system or social synergies for potential system integration. The research was used in the analyses of appropriate modern renewable energy technologies available to rural producers in the selected primary production system types. The proposal scope included modelled and simulated selected renewable energy technologies and biofuel precursor species with the potential to improve rural productivity using socially, technically, and agriculturally appropriate options.

The research method, where possible, included a technical and economic assessment of project suitability, including the institutional, social, environmental, and household appropriateness. The results suggest practical, cost-effective approaches for local production systems within the context of existing farming practices, and the institutional capacity available at the local level. The technical simulations (using manufacturer data and local resource assessments) were incorporated into simple economic models. Where possible, the model included capital expenditures and projected discounted operational costs and potential income, which quantified the market value of each option against the baseline of existing production systems and fuel supplies. The outputs can be used to quantify any emission abatement from the technical simulations and modelling, and were included where relevant.

Each of the projects within the four primary production systems were selected because of their potential for pilot-scale implementation to ensure that positive research outcomes could lead to real-world solutions in sub-Saharan Africa. Furthermore, the research team actively sought African collaboration and have built a strong alliance with Prof. Linus Opara at Stellenbosch University, South Africa and Mr. Ben Onyango at Community Resolve Against Hunger (CRAH) based in Homabay, Kenya.

1. Key problems that the project aims to address

Over half of the sub-Saharan population live in rural agricultural regions, which are a fundamental cornerstone of the regions economic development [1,2]. However, over the past fifty years the average sub-Saharan food crop productivity has stagnated while the rest of the world's agricultural productivity has trebled [1,3]. Yet, the sub-Saharan average productivity masks the considerable variability in productivity at the household and local level [3]. Appropriate investment is central to sub-Saharan agricultural and economic development [3,4]. The region is now viewed as a major potential new source of primary productive wealth [2,5], and is increasingly the focus of international strategic energy, water, land and food competition [6]. Despite the renewed interest, many local-scale sub-Saharan rural producers continue to subsist in extreme poverty and endure basic food, water, and other service shortages [7]. Local food insecurity continues due to a number of reasons, including poverty cycles, degraded lands, conflict, inadequate infrastructure, outdated knowledge and technology, and a poor record of attracting international investment [5,8]. In addition, sub-Saharan farmers face many challenges in relation to rural institutions, social capacity, and market development [9].

A key problem at the local scale is poor energy availability on smallholder farms, which limits the adoption of improved crop and livestock technologies. With modern technology, biomass is a local source of renewable energy to intensify farming. However, biomass has many uses, for domestic fuel, for construction, for livestock feed, for soil cover in conservation agriculture, etc. Alternative technology options such as solar photovoltaics, solar thermal, biofuels, biogas, new system adaptations, etc., provide new options for low-cost renewable energy for primary production in remote locations at the householder/smallholder level.

2. Project deliverables

(a) A literature review and analyses of each system, detailing each parameter.

(b) A technical model of each farming system, over a determined time, quantifying outputs with suitable productive ranges of uncertainty.

(c) Data on existing farming system baseline financial performance, and a simple economic model of the expected (and likely ranges) return on investments of selected production systems.

(d) An implementable demonstration energy/farming system pilot project suitable for validating and the review, analyses, simulations and modelled data leading to an extension phase of the research and development activities.

Project 1 summary

Titles: **A** - Artisanal light fishing communities on Lake Victoria, Kenya: the use of traditional kerosene lamps vs PV-battery-CFL systems.

B - Small-scale portable photovoltaic-battery-LED systems with submergible LED units to replace kerosene-based artisanal fishing lamps for sub-Saharan African lakes.

C - Post-catch *Rastrineobola argenta* artisanal fish drying on inland lakes on Lake Victoria, Kenya: markets, methods, and options for improving safety and supply security.

Project summary and recommendations

Analysis of field data and peer-research literature indicate there is a clear economic rationale for renewable energy/LED lighting technology to displace existing technology, and that implementation of efficient custom light fishing system designs deliver a substantial reduction in the opex (fuel costs) of the artisanal fishery system investigated. In addition, our research suggests that new lighting technology designs can more efficiently attract targeted fish species and potentially reduce bycatch of endangered cichlid species. Furthermore, our research findings elucidate numerous external benefits: new LED lighting systems can be locally manufactured/assembled, creating a new local service industry; cost-effective PV-battery-LED designs can be used in the household during the day/evening (in contrast to existing technology); the proposed technology reduces other major costs of fishing, such as travel to obtain existing fuels/energy; the technology is zero emissions at point of use; is healthier and safer to operate; can eliminate environmental (kerosene/lead-acid) pollution; increases local energy security, and; enables fishers to own a valuable asset with lasting value. Lastly, the project also found and explored a major opportunity to improve fish drying technologies that can drastically reduce post-harvest waste and reduce local incidence of fish-related disease burdens in people, and improve the commercial value of the artisanal fishery by simple means. The research team notes that there is tremendous scope for improving the lives of thousands of light fishing communities through cost-effective technology, and there are numerous attractive opportunities for improving energy and food security in the production system.

Project 2 summary

Title: Rural African renewable fuels and fridges: using cassava waste for bioethanol, with stillage mixed with manure for biogas digestion for application with dual-fuel absorption refrigeration.

Project summary and recommendations

The research determined a range of opportunities to reduce post-harvest losses and reduce the burden of cassava waste product disposal. These options included a targeted focus on appropriate small-scale and simple technologies that can be used to convert non-food cassava production byproducts and waste into bioethanol through simple brewing and distillation, and biogas via biodigesters. The technology is regionally available and readily adaptable and can displace existing expensive or costly fuels and provide suitable input energy for small dual-fuel refrigeration systems operated by waste heat. Furthermore, our research findings describe several additional benefits to rural smallholders: Bioethanol can be produced by the householder from waste cassava using traditional technologies to produce a very clean cooking fuel; the bioethanol wastes are suitable to be mixed with manures in a simple biodigester to produce biogas for cooking; both the fuels are appropriate for use with conventional waste heat absorption refrigerators that do not require electricity and can run on both biofuels (and also solar) for supply security; the refrigeration has numerous benefits for rural areas, including to increase the longevity of agricultural produce, including milk – a premium product, or medication; bioethanol and biogas are clean-burning and reduce energy-related labour requirements, and; these biofuels can be produced in simple small-scale technology that is locally made, constructed by local artisans from local materials, and is within the capacity of local people to operate and maintain over time. The research team notes the adaptation of existing bioethanol, biogas, and absorptive refrigeration technology is an enormous opportunity for improving food and energy security in rural sub-Saharan regions, with numerous economic and industry development opportunities, and can avert fears of biofuels reducing food security, and improve agricultural productivity as a consequence.

Project 3 summary

Title: A PV-battery-powered 12V air compressor and N membrane for sealed PVC bag with wood desiccant for post-harvest hermetic grain storage in southern and eastern sub-Saharan Africa.

Project summary and recommendations

The research findings suggest that small, portable, and commercially available renewable energy-powered oil-less compressors are able to operate high-pressure gas membrane technology to selectively flush seed and grain storage systems with inert, non-toxic gasses (including nitrogen) that do not enable pest species to survive, eliminating the need for chemical fumigants (that are often banned in industrialised countries). Furthermore, the use of a simple dry wood desiccants are a cost-effective and widely available solution to existing options to reduce internal moisture content in sealed seed and grain storage technology to improve post-harvest productivity. The research team notes that at present, the high market cost of existing proprietary gas membrane technology is not a justifiable technology investment for sub-Saharan African rural smallholders. However, collaborative commercial arrangements that can make available gas membrane technology at lower cost (akin to generic drug provision at cost in developing countries), and derive the numerous economic and yield benefits from improved seed and grain storage technology.

Project 4 summary

Title: Improved arid/semi-arid ruminant survival for Southern and Eastern sub-Saharan pastoralists: biochar/high-tannin fodder utilisation in feed-limiting periods, with bioenergy and sequestration benefits.

Project summary and recommendations

The research team assessed the use of simple biochar (wood charcoal) feed additives to improve the health and productivity of ruminants (cattle, sheep, and goats) in pastoral production systems located in arid/semi-arid regions. The unique research approach focussed on improving the digestibility of generally the only available fodder (Acacia species) through the use of biochar to improve the survival rates and market value during the productivity limiting dry seasons and conditions of devastating drought. The research team found several benefits of this approach, including; the increased ability for pastoralists to sell livestock at seasonal market highs: the ability to increase wood-conversion efficiency via the development of new simple wood pyrolysis technologies; the co-production of both woodgas and biochar during traditional cooking methods; associated wood conversion industry development opportunities; reduced pressure on existing vegetative species and biomass fuels; potential stable carbon sequestration in soils from biochar addition from manure, and; an alternative to forestry carbon sequestration projects that is more sensitive to customary law land tenure concerns. The research team notes that this enormous potential is based on the premise that existing research on the efficacy of selected biochars for improving the protein availability of Acacia species can be reproduced in ruminants in African pastoral systems. On-site and ruminant species-specific validation work is required for quantifying the feed additive efficacy and the stability of the post-ruminant biochar as a stable form of soil organic carbon when ecologically delivered in manure.

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(Please note: projects were written as stand-alone reports for separate publication).

Title: Artisanal light fishing communities on Lake Victoria, Kenya: the use of traditional kerosene lamps vs PV-battery-CFL systems

Authors: M P McHenry, D Doepel, B O Onyango, U L Opara.

Abstract

This research investigates the use of lighting technology in use in artisanal light fishing systems on Lake Victoria in sub-Saharan Africa. Survey results suggest an increased fish catch efficacy of lighting technology can reduce the cost of existing systems, and can play a major role in increasing energy and food security in the artisanal fishing community. The research found a promising scope for the development of stand-alone renewable energy based lighting systems that improve fish catch, and enable local technical optimisation between minimising lumen production, battery storage requirements (and associated opex and capex), and maximising robustness, fisher usability, repairability, and local production content. These activities are amenable for customisation for each artisanal fishing community, and with sufficient training, more efficient technology use can create a local manufacturing, sales/supply/servicing industry, and also small-scale photovoltaic-battery recharging services. As there is likely to be more than one appropriate lighting system design for the fishery, in theory there is an opportunity to co-opt the lighting system into new productive uses during the day when there is also a need for electricity services outside of the light fishing sector. The survey findings suggest there is an enormous scope for entrepreneurial locals to apply existing efficient lighting technology to increase local fishery productivity, increase energy security, and dramatically lower the net cost of lighting technology for light fishing, and also effectively cross-subsidise lighting for the wider community.

Introduction

Sub-Saharan Africa has the lowest intake of animal produce by far of all major regions of the world, and around half that of peoples of south Asia, and around eight times less than industrialised nations [1]. In parallel, there is an enormous unfulfilled demand for lighting services in the developing world, the key limiting factor being affordability [2]. This research investigates a unique primary production system where these two elements interrelate: the use of artisanal light fishing systems on inland lakes in sub-Saharan Africa. Lake Victoria is the largest inland Lake in Africa, and is densely populated and economically underpinned by the fishery sector [3]. The pelagic cyprinid known locally by various names as omena/dagaa/mukene (*Rastineobola argentea*) has in recent decades become a major domestic subsistence food/feed source [4]. *R. argentea* adults generally congregate at the bottom of the lake during daylight and move to the surface at night where they are fished by the use of artificial floating lights that attract the fish which are then netted [5]. The lighting technology used is commonly pressurised kerosene lamps, although several new, more efficient technologies exist, including photovoltaic-battery-compact fluorescent light (CFL) systems (etc.). These new technologies are commonly introduced by various industry, aid, and non-governmental organisations. The present study investigates by field survey-based research quantitative and qualitative methods the light fishery on Lake Victoria, and explores current light fishing technology choices, fuel usage, and associated costs. The collation and analysis of data in this research aims to provide body of knowledge sufficient to assist the development of entrepreneurial applications that can assist both the artisanal fishing industry and diverse local economy. Recent advances that have resulted in more efficient (and luminous) light fishing technologies can address several contemporary challenges, including improving profitability and fisher health, reducing environmental pollution, and assisting the development of service industries for recharging, capital expenditure sales, maintenance services, etc. Such developments will likely require numerous partnerships within the existing institutional arrangements that are present in the region, be they formal or informal [6], including the spectrum of primary researchers and end users.

The *R. argentea* fishery is crucially important for local employment, additional dietary protein, and general nutrition for both human and livestock populations, and supports several related industries [7 8]. Total annual production capacity of the current fishery stock in Lake Victoria is estimated at between 400,000-600,000 t, valued at around US$ 300-600 million [9]. In addition to the introduced Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*), the indigenous *R. argenta* is now a major species that dominates the Lake Victorian ecosystem, with catches seemingly stable or rising [5 9]. Other minor species such as *Clarias*, *Bagrus*, *Labeo*, *Synodontis*, *Schilbe*, and (rarely) *Protopterus*, are caught in small amounts seasonally, and some are used as Nile perch baitfish [9]. Modified lake fishery ecosystems that aim to maximise and sustain catches of monogastric and non-carnivorous fish such as *R. argentea* (a zooplanktivorous fish), is a trophically efficient option for enhanced overall fishery productivity with environmental benefits [1]. *R. argentea* ranks second to the Nile perch in commercial importance in Lake Victoria [5], and is often eaten in whole dried form by poor and middle-income people in eastern and southern Africa [3]. *R. argentea* and tilapia primarily serve domestic markets due to low external demand for *R. argentea*, and decreasing supply of tilapia. In Kenya, *R. argentea*, locally known as 'omena', is generally sundried, and is commonly a substitute alongside fresh, sundried, or smoked tilapia, and byproducts of Nile perch that are not exported.

The local demand of fish products is increasing in Kenya, and also has the local price of fish. Human-grade omena in Kenya is usually destined for local markets such as Gikomba in Nairobi, and Kongowea in Mombasa, with feed grade omena generally sold directly to animal feed manufacturers in Nakuru and Nairobi. As there is little market information available, omena fishers are often paid relatively little for their produce, with downstream buyers, transporters, and retailers having the competitive advantage in price negotiation. Nonetheless, it is necessary to gather information, involve local appraisals, and undertake detailed environmental and policy reviews to avoid the implementation of inappropriate strategies and misallocation of sparse resources and capacity [10]. In practice, decision makers often have little information (or control) regarding the nature of poverty, and incomplete knowledge of the processes that affect it [10]. However, there are persistent economic disparities between wealthy and poor, and the depletion of the environmental resource base for food production [1], and a great need for additional information regarding light fishing technical and economic data [11]. This includes the considerable demand for a good quality, effective, and relatively low priced fishing lighting systems [12].

Kerosene lighting technology and new alternatives

Africans represent around one-third of the global population without electricity, and lighting is generally generated by various sources of biomass, candles, and kerosene lamps [13 14]. Kerosene and non-electric lighting are often expensive, inefficient, unhealthy, hazardous, generate soot, and provide poor light [11 12 14]. A typical household kerosene lamp provides only around 10-50 lumens [2 14], whereas a 'traditional' 60 W incandescent lamp provides 15-30 times that of the kerosene lamp [2]. In addition to lumens, the value of lux, the lumens per square metre, is a fundamental consideration for lighting dependent activities [2 11]. Typical kerosene lamps deliver between 0.5-6 lux of useful light compared to the typical international standard of 300 lux for reading [11 12]. A typical wick kerosene lamp found in a archetypal Asian or African household might be yielding around 5 lux over around 1-3 m^2 , compared to 50-100 lux in a typical home located in an 'industrialised nation' [12]. Despite kerosene often being subsidised in many poor nations (as high as 50% of the cost), kerosene lighting costs can represent more than 20% of the poorest household incomes [14]. For comparison, rural developing households pay similar prices for lighting as the average American family, yet only receive around 0.2% of the lumen-hours [14]. While a typical 'Hurricane-type' kerosene lamp consumes only around 12-20 g of kerosene per hour at medium and high flame outputs, respectively [12], this can be a considerable investment for the poor, and despite the lamp being an inefficient source of lighting, source of fires/burns, and poisoning from accidental ingestion [14 15], there is often little alternative for most people in the rural communities in Africa, both for domestic and productive uses.

As light availability increases the productive hours available [14], it is more common to see higher levels of capital invested in larger, more effective lighting levels used in business operations. Pressurised kerosene lamps provide around 10-30 lux over an area 3-4 m^2, produce very little soot, exhibit a higher efficiency of combustion (around 60 g of fuel per hour for a Petromax type), and produce an intense white light [12]. However, the light distribution of most kerosene lamps are uneven (often in both the horizontal and vertical plane), and energy consumption/conversion efficiency can vary widely between pressurised lamp technology, and users remain vulnerable to the high kerosene price volatility [11]. It is common for pressurised kerosene lamps used in Lake Victoria to consume a much greater amount (~200 g) of kerosene per hour, primarily due to the higher lumens required for light fishing lamps (~1000 lm). With the increasing scrutiny on the burden of existing fuel subsidies, and a sensitivity to balances of trade, government budgetary considerations are commonly reassessing the choice between either raising additional revenue from elsewhere, or reducing spending on selected public goods and services [14] - including removing kerosene subsidies. While pressurised kerosene lamps represent an effective, yet relatively expensive technology to purchase and operate, they are also are a relatively fragile technology (particularly the mantle) [12], and new, more efficient technologies are already available and in use [11 23 25].

Alternative lighting demand and technology

A key challenge in sustainable economic development is to realign government expenditure patterns towards investments with longer-term benefits [16]. Sector-based intervention project approaches have largely replaced small-scale stand-alone investment projects, often due to the small and unsustained benefits of such approaches, which were commonly, yet not always implemented inefficiently [10]. Furthermore, special interests within poverty reduction interventions may have shifted focus away from the basic development processes of achieving incremental progress in major existing sectors. Such progress underpins the tax base to which other useful investments can be financed [16]. The often small economies of scale and associated higher prices limit existing new lighting technology dissemination to the wealthy [14]. A focus on market demand for productive uses of new lighting systems can both expand the market for greater economies of scale, and generate wider benefits over time. Nonetheless, there are numerous assumptions that can compromise a seemingly balanced analysis between lighting technologies [11]. Particularly, as ‘aid-based’ interventions can introduce ‘perverse incentives’ generating proscribed development activities, often politically motivated [17]. In terms of lighting-related development activities, in addition to the reduction of domestic kerosene consumption, there are options that mitigate several negative consequences of liquid fuel-based lighting (including preventing deaths and economic losses from simply reducing house fire frequencies) [14]. Yet, the ability of people to meet, read, and work after dark has an enormous impact on physical, social, and economic lifestyles [14 18]. As such, there is a strong market demand for cheap rural lighting technology in developing countries which indirectly foster an associated supply industry [19], with numerous, although differentiated value chain opportunities and challenges [20].

There are several reasons to explore distributed renewable energy systems, both from a government and private citizen perspective. As examples, the increasing price of oil imports and the avoidance of electricity utility rationing has driven much interest in renewable energy systems in sub-Saharan Africa [21]. Furthermore, rural community-based renewable energy services for small-scale and mobile phones, satellite phones, radios, internet, and other accessory charging services are in high demand [19]. Despite the general interest, there is a great need for a rigorous analysis of various lighting technical and economic data on lighting, both for systems and technology transfer approaches [11]. For example, technical and economic analyses between kerosene lighting and alternative lighting under taken by Mills (2003) [11] at the Lawrence Berkeley National Laboratory, USA, found that light emitting diodes (LEDs) provided the most cost effective light technology available for homeowners from a total cost perspective. The results suggested the total cost was half that of CFL technology, and many times less than common kerosene options [11]. (For economics and CO_2 calculations for lamps, see Mills (2003) [11]). LEDs are often contrasted against fluorescent lighting, usually the 'next best' technical alternative to LEDs. Both linear and CFLs are less efficient than LEDs [14], are relatively fragile, have low lifetimes, and are difficult to design for task lighting [12 14]. In contrast LEDs have superior energy efficiency, ruggedness, low weight, generally longer service life, low voltage, relatively smaller battery storage requirements, and also higher optical controllability [11].

Decreasing capital cost of photovoltaic (PV) technology cost has expanded the interest in use as a generation component in efficient lighting, communication, and refrigeration systems in developing regions of Africa [18 21]. However, in stark contrast to the considerable interest, there is a very small number of existing small-scale stand-alone renewable energy systems still operating in these regions, most of which were PV-battery-lighting systems [22], (although the numbers of operational PV-based lighting systems have increased in recent years). While LED technical performance shows economic and environmental benefits when compared to kerosene and all other electric light technology [11], the lighting system component with the shortest life often receives the least attention: the battery [2]. Smaller batteries (12 V and <10 Ah) and small PV modules are preferred basic system components for reasons of low cost and low load demand [14]. Yet there are also wider considerations for technology-based interventions, both positive and negative. For example, mobile phone charging services generally cost around US$1-2 per week, and travel times to charging stations are often long and expensive, and the spontaneous development of small-scale PV-battery system phone charging entrepreneurs is yet another effective unplanned activity in developing countries [14]. However, unplanned renewable energy-based activities can also lead to negative consequences, including the improper disposal of lead-acid batteries or PV panels, as it is uncommon for recyclers to be willing and/or able to accept the many non-conventional smaller sealed batteries and components [13]. Despite the need for energy and lighting, new renewable energy-based systems bring the most benefit to rural off-grid areas over time when they are economically underpinned by a major productive use [19]. This research explores the case for light fishing.

Light fishing expansion and resource management

The *R. argentea* fishery makes a major contributor to food security by the provision of a locally produced, affordable, highly available, and divisible source of nutritious protein with a relatively high shelf life [7]. Artisanal fishing on Lake Victoria yields over 100,000 t each year (roughly one-fifth of the entire fishery production), which provides a major local source of protein and nutrition [7 8]. The indigenous *R. argentea* has increased in number and total biomass since the introduction of the Nile perch and the Nile tilapia [5], as it's contemporary zooplanktovorus competitors (mostly haplochromine cichlids) seemingly shared more of the water strata and were selectively preferred by the predatory Nile perch, while the *R. argentea* swam at lower depths during daylight hours [3 5]. The Nile perch was introduced to Lake Victoria in the 1950's, and began to dominate the lake's top predatory fish biomass by the early 1980s, underpinning a European 'table fish' industry supporting several large-scale processing plants [3]. In parallel, the artisanal fishers small catamarans and trimarans of artisanal fishers for *R. argentea* fishing were introduced around the 1980, and in combination with artisanal processing methods provides an economic industry to supply the local market [3 7]. *R. argentea* light fishing occurs primarily in the dark phases of the moon, and is more common in deeper lake waters [3 5 7]. It's market has expanded due to the rising prices of high-protein domesticated animal feeds, increasing urbanisation, and also structural adjustment, with higher profitability due primarily to increased industrial animal feed demand [3]. However, the sharply growing demand from both the animal feed sector and local communities is exposing the light fishing industry to collapse by overfishing, sharply lowering food security in the region [7]. In 1979 there was an estimated 20 canoes per km of the 1,300 km shoreline [8]. Now Lake Victoria has an unknown, yet significantly larger number of canoes, in addition to larger more modern boating vessels, processing factories and an export industry. At present, *R. argentea* fishing does not often operate under the guidance of fisheries institutions [7], and thus may be under threat from resource depletion without appropriate fishery management [17]. The sustainability of common fish resources in the Lake Victorian system is becoming an increasingly contentious issue, particularly with the growth of fish export industries [9], notably as the lake falls under the jurisdiction of three countries; Tanzania, Uganda, and Kenya [8 9]. Furthermore, it is common practice that fishing communities are excluded in local, national, and international decision-making regarding fishing industry policy and technology [9].

It is well known that not all fishing or processing methods used on Lake Victoria are legal [7 23], or benign for the fishery as a whole. Selectively catching some species on the lake requires the use of gear that is illegal in some areas, particularly as fishing laws along the Lake Victoria are not homogenous [9]. The elimination of post independence (1961-63) fishing regulations relating to Lake Victoria in the three bordering nations of Kenya, Tanzania, and Uganda resulted in the removal of fishing net prohibitions of small nets below 13 cm, except for Kenya's restrictions on medium range gillnets (6.4 – 9.5 cm), and beach seines during tilapia peak spawning period [8]. The use of beach seines to fish for *R. argentea* in Kenya is the oldest fishing method in the region, and are undertaken by groups of 6-8 men and one lamp [3], with the most common seine net size of 0.5 cm [5]. Artisans undertake beach seining on dark nights from around midnight to close to dawn (15-18 nights per lunar month) [3]. The beach seine is cast in a semi-circle around 100 m off the beach, and a floating lamp is positioned for an hour or more and slowly moved towards the beach, with the net pulled in slowly to enclose the fish around the lamp. Artisanal light fishing with canoes is similar to beach seining, although it occurs more often and on open water with the lamps and nets being towed behind and hauled back onto the canoe/boat [5]. Those who cannot afford the beach or canoe/boat seines use simple scoop nets operated by two men on a canoe/boat in shallow water, although they are rarely used [3 5]. The canoe/boat seine is the preferred light fishing method as less time is needed to tow the lamps to shore and the nets catch economic quantities of fish [5]. There are an estimated 100,000 lamps in use (the vast majority are pressurised kerosene) for light fishing on Lake Victoria, primarily catching *R. argentea* [23].

Fishers are well aware that certain fishing gear is destructive to the fishery which remain in use (such as beach seines, joint double/triple, nets, undersized gillnets), and they believe this is the primary cause of the recent decline in fish catches [9]. Even as early as 1979, research by Marten [8] noted that Lake Victoria has symptoms of severe overfishing, primarily due to the use of small gillnets and beach seines to catch smaller fish, which also catch juvenile larger species as bycatch [8]. Bays (<4km width) and shallow near shore waters (<2 km) are generally breeding and nursery grounds, and fishing should be minimised in such areas to ensure good recruitment [7]. Fishers also attribute the decline of high-value Nile Perch catches to destructive fishing gear, and also fishing in near shore breeding and spawning grounds [9]. Yet, the small size of artisanal canoes often restrict fishing gear and fishing locations that are suited to smaller fish, including shallower areas near the coastline [5]. The bycatch of *R. argentea* light fishing is mainly haplochromine cichlids caught in shallow bay areas [7]. The cichlid bycatch exacerbates what has been described as one of the worst vertebrate extinction events in recent decades, with the loss of 200 species in Lake Victoria alone, which was due to the local fishing industry directly and indirectly [24]. Artisanal fisher catches demonstrate that with current net sizes *R. argentea* enters the fishery when predominantly immature, yet peak catches occur when most of the cohort reaches maturity [5]. It has long been known that smaller mesh nets (5 mm) commonly in use catch a high proportion of immature fish [7]. Research by Manyala (1992) [4] showed that 5 mm seine mesh nets caught around half of the 38 mm *R. argentea*, which is around 6 mm below maturity length [4]. Yet it is also known that all mesh net sizes in use (10, 8, 6, 5, and 3 mm) catch immature *R. argentea* fish when fishing in nursery grounds [7 4]. While nets between 10 mm and 5 mm are commonly used, larger mesh nets (between 8 and 10 mm) catch a higher proportion of mature *R. argentea*, and the total weight of catches do not differ significantly between mesh sizes [7]. The use of an 8 mm mesh net is believed to be a compromised optimal net size, although more research is required on the biological impact of various fish nets and mesh sizes in Lake Victoria [7 9]. There has been a recent affordability of hooked 'long line' fishing relative to nets due to their cost, their ability to catch larger fish, greater resilience to theft, and ability to be moved to follow migrating Nile perch [9]. However, long lines raise issues regarding reduced fishery productivity available for human consumption through metabolic losses of catching primarily carnivorous fish [8], and also the indiscriminate use of small fish as bait for long lines. Furthermore, long lines do not yield the same consistent catches as in the past when fishing stocks were under considerably less pressure [9].

It is general belief among fishing communities that less fish should be caught on Lake Victoria; however, there is a predictable difference of opinion of who owns the resource, and who should be able to fish, with each response consistently favouring the rights of the respondent [9]. While most fishing should be undertaken in offshore (>2 km) open waters outside of bays where mostly mature *R. argentea* are caught [7], artisanal fishers do not commonly possess the motorised boating vessels that can reach the primarily mature *R. argentea* stocks. Poorer fishers are also at a technical disadvantage with larger commercial operations when attempting to follow the high-value, seasonally migrating Nile perch [9]. (For a detailed description of boats and fishing in practice, see research by Gibbon (1997) [3]). IT is the objective of this research is to quantify and qualify current light fishing technology choice, fuel use, and associated costs of both traditional kerosene and new photovoltaic-battery-CFL systems, and to identify end-user preferences to inform new technology development of a portable light fishing system for inland lake fishing communities.

Method

Two survey instruments were developed to assess the use and associated costs of two light technologies (kerosene and solar lamp) among fishers, including, fish catch, and capex and opex data, market prices, and challenges. The surveys were administered by twelve employed and trained local enumerators who undertook the fisher interviews in July 2012. Ten local beaches were randomly selected for the 'kerosene survey' with 195 respondents, and five beaches were selected for the 'solar survey' with 105 respondents. The surveys took place on Mfangano Island and Sindo mainland, in the Suba District of Homabay County in Kenya. The descriptive data was translated and reproduced to accurately represent the full meaning of the response in context of the question asked. The survey included the use of open-ended questions which cross-referenced many subjective questions with quantitative data, and also gave respondents an opportunity to comment on various aspect included in the survey. Peer-review literature was used to add additional information and compare between existing data and data found from the surveys.

Results and Discussion

The survey interviewees collated the responses of 300 light fishers operating at different beaches on demography, fishing technology use, lamp economics, and fish catch data for both solar PV-battery lamp and kerosene lamp users. The results obtained on gender and age (Tables 1 and 2) shows that the majority of omena (*R. argentea*) fishes are male. Table 1 shows that around 89% of fishers using kerosene lamps are male, while the percentage using solar PV-battery lamps are 99%. The interviewees recorded that female fishers are less likely to use solar PV-battery lamps due to the lower awareness of solar PV-battery lamps, and also logistical and economic challenges associated with accessing areas for recharging of the solar PV-battery lamp on a daily basis. Yet, this does not, in the authors opinion at least, sufficiently explain the difference and further research would be necessary to uncover the apparent disparity. In terms of fisher age, the most common age bracket is the category above 33 years of age. While around 49% of males using kerosene lamps were over 33 years of age, 64% of females using kerosene were between the ages of 26 to 33.

Table 1: Kerosene lamp user respondent by gender and age.

Beach	Respondents			Age (Male)			Age (Female)			Age (All)		
	M	F	Total	18-25	26-33	>33	18-25	26-33	>33	18-25	26-33	>33
1	8	1	9	2	0	6	0	0	1	2	0	7
2	9	0	9	2	5	2	0	0	0	2	5	2
3	8	1	9	0	2	6	0	1	0	0	3	6
4	9	0	9	0	2	7	0	0	0	0	2	7
5	9	0	9	3	4	2	0	0	0	3	4	2
6	30	0	30	0	13	17	0	0	0	0	13	17
7	11	19	30	1	2	8	4	13	2	5	15	10
8	30	0	30	7	15	8	0	0	0	7	15	8
9	29	1	30	6	9	14	0	0	1	6	9	15
10	30	0	30	4	12	14	0	0	0	4	12	14
Totals	**173**	**22**	**195**	**25**	**64**	**84**	**4**	**14**	**4**	**29**	**78**	**88**

Table 2: Solar PV-battery lamp user respondents by gender and age.

Beach	Respondents			Age (Male)			Age (Female)			Age (All)		
	M	F	Total	18-25	26-33	>33	18-25	26-33	>33	18-25	26-33	>33
1	21	0	21	2	7	12	0	0	1	2	7	12
2	21	0	21	5	6	10	0	0	0	5	6	10
3	20	1	21	0	12	8	0	0	1	0	11	9
4	21	0	21	5	6	10	0	0	0	5	6	10
5	21	0	21	3	9	9	0	0	0	3	9	9
Totals	**104**	**1**	**105**	**15**	**40**	**49**	**0**	**0**	**1**	**15**	**40**	**50**

Table 3 shows the reported economics of kerosene lamp fishing. The respondents used an average of 4 kerosene lamps per boat per night, consuming 1.59 L kerosene per lamp per night operating for around 10 hours on average. This is equal to 0.159 L per hour, or with a density of 0.790 kg per L, equivalent to around 0.2 kg per hour. This result is consistent with research by Hormann (2005) that found the use of pressurised kerosene lamps for light fishing among fisherfolks on Lake Victoria consumed around 1.5L per night when used [25]. The average capital cost of purchased pressurised kerosene lamps on all beaches were KSh 4,420 (AUD 51.45), yet the cost varied considerably between the average for a beach (between KSh 5,111 (AUD 59.50) and KSh 2,688 (AUD 31.30), although is likely due to lamp quality and efficiency. Respondents were asked how long the working life of each lamp was, with 46% of respondents stating the lamp lasts for more than one year. Respondent data show the average cost of kerosene for all beaches was KSh 113 (AUD 1.315) per L, with the lowest cost beach averaging KSh 100.56 (AUD 1.17) per L, and the highest cost beach averaging KSh 125.86 (AUD 1.46) per L. The variation of the cost of kerosene was primarily determined by the distance between the fishing beach and the nearest kerosene outlet. While the average distance travelled to a kerosene outlet was 8.22 km, the lowest was zero km, and the highest 25 km, which is a large distance to travel in areas with very little transport infrastructure and high cost of transport services. In addition to the kerosene operating cost, respondents indicated that the mantles of the pressurised kerosene lamps required replacing each day of fishing on average at a cost of KSh 20 (AUD 0.23) per mantle. Other annual costs indicated by the respondents included the average of KSh 249.05 (AUD 2.90), which included the cost of lamp glass, lamp washers, pumping, and needle costs.

The number of fishing days in the Suba District per month during the peak period was reported to be 20 days, with off-peak days representing around 6 days per month. In the peak period, the average "trough" catch (a trough is a local measure that is approximately 24 kg of wet fish) for all kerosene fishers was reported to be 15.76 "troughs", while the off-peak catch was reported to total 2.90 "troughs", all per night. Therefore, the average cost in the Suba District of Kenya of acquiring and using a pressure kerosene lamp for one year can be estimated in KSh: 4,420 + [(113*1.59*26*12) + 249.05 + (20*26*12) = 66,966.00 (AUD 779.484)]. As each boat uses an average of 4 lamps, one boat requires KSh 267,864.00 (AUD 3,117.937) per year for kerosene-based lighting. Note that the lamp might last for more than one year, yet the capital cost of purchasing the lamp is only around 7% of the total annual cost, a minor consideration. Kerosene lamp users stated that in addition to kerosene fuel being expensive and not readily available, there were several practical issues with using pressurised kerosene lamps. These included the high frequency of kerosene lamps failure, requiring high additional costs to amend. The mantle and glass shield commonly broken due to either to accidents, but also rough weather conditions. Furthermore, it was stated that it was common for the lamps to be extinguished or overturned by strong winds and rain, leading to fishers inhaling nauseating fumes, in addition to kerosene spilling into the lake.

Table 3: Kerosene lamp user lamps, fuel consumption and related travel, and fish catches. *Note: at the time of the survey, 1 KSh was equal to 0.1164 AUD. A 'trough' of wet omena weighs 24 kg.

Beach	Lamp/ boat	Lamp (KSh)	Kerosene (KSh/L)	Travel to outlet (km)	Trough catch (peak)	Trough catch (off-peak)
1	5	2,688.90	100.56	0.94	10.00	1.89
2	5	4,400.00	110.00	0	16.44	3.33
3	4	3,966.70	111.11	3	9.44	1.89
4	5	4,322.20	115.89	3.11	15.33	1.39
5	5	5,111.10	100.63	0	20.00	2.78
6	4	4,836.90	113.27	0	-	-
7	4	4,756.70	120.00	22.8	17.20	1.07
8	4	4,337.90	111.64	19.1	23.48	9.07
9	4	4,950.00	121.03	-	14.20	1.76
10	4	4,833.30	125.86	25	-	-
Av.	**4.4**	**4,420.37**	**113.00**	**8.22**	**15.76**	**2.90**

In contrast to the majority of fishers with kerosene lamps that were purchased outright, the fishers using solar PV-battery lamps rented the lamps for KSh 1,000 per year (AUD 11.64). The rented systems are 11W CFLs connected to a 12V 100 Ah lead-acid battery charged for a fee at a PV-powered charging station operated by the company (Osram) that rents the lamps. (See Fig. 1 and Fig. 2). Each boat used a total of 5 solar PV-battery lamps that were designed to last around 10 hours when fully charged. The average cost of charging a lamp each day was KSh 82.00 (AUD 0.95), and a further average cost of KSh 92.00 (AUD 1.07) was incurred when travelling to a charging point with the lamps. Respondents indicated that lamp charging was a very expensive element of using the solar PV-battery lamps. The respondents also stated that there were no 'other' costs associated with the PV-battery lamp. The same number of peak and off-peak fishing days, 20 and 6, respectively, were observed by the solar PV-battery fishers and the kerosene fishers. Solar PV-battery lamp respondents commented that the light from the solar PV-battery lamps seems weaker than the equivalent kerosene lamps, and that the light does not penetrate as far into the water. Furthermore, the respondents indicated that it is common for the lamp to be totally discharged before a nights fishing would be concluded. The respondents did not indicate whether this was because some systems were not properly charged, or if some solar PV-battery lamps had lower battery capacity than others, or that a higher average battery capacity was required for a full nights fishing. The respondents further stated that they believed the lamp must be expensive to purchase, as the lamp is only available to rent. As the lighting technology is rented, the fishers are unable to utilise artisanal repairers for the lamps when they fail, which was stated as inconvenient when out fishing on the lake. Crucially, the respondents believed that the limiting factor for the uptake of solar PV-battery lamps was the low number of lamp recharging points, not any technical issue with the lamp itself, or the low annual rental price.

Table 4 shows a snapshot of the troughs of fish caught per night for both light fishing technologies based on data from all 105 PV-battery lamp users, and 195 kerosene lamp users. The average number of troughs caught by solar PV-battery lamp users per night in the peak period was 24, ranging from 10.81 on beach 1 to a very high 47.62 on beach 5. In comparison, the average numbers of troughs caught by using the kerosene lamp technology in the peak period was 16, ranging from 9.44 on beach 3, to 23.48 on beach 8. Simply from these basic catch numbers, even when removing the excellent average peak catch from beach 5 with the solar PV-battery lamp fishers, it seems that the use of the 5 solar-based lamps is clearly no less effective than the use of the 4 kerosene lamps per boat. Further research would be required to determine if, and by how much, the solar PV-battery lamp technology increases fish catches relative to kerosene lamps on Lake Victoria. The associated cost of using one solar PV-battery lamp for one year can be estimated by the calculation: KSh 1,000 + (82*26*12) + (92*26*12)/5 = KSh 3,324.80 (AUD 38.70). As 5 lamps are used per boat, the total annual lighting cost for a boat using solar PV-battery lamps is KSh 16,624 (AUD 193.50). This contrasts sharply with the high costs using kerosene lamp technology in the same region. Even when using only an average of 4 kerosene lamps, the fishers require on average KSh 267,864.00 (AUD 3,117.937) per year to pay for the lighting costs of a boat. This is over 16 times the cost of the solar PV-battery technology.

Fig. 1: The battery in use on Lake Victoria in the Suba District of Homabay County in Kenya.

Fig. 2: The CFL lamp in use with the CFL in the Suba District.

Table 4: Omena caught in troughs and crew cost (All costs are KSh).

Beach	Troughs caught using the Solar lamp		Troughs caught using the Kerosene lamp		Crew/ boat	'Solar' crew cost	'Kerosene' crew cost
	Peak	Off peak	Peak	Off peak			
1	10.81	1.72	10.00	1.89	4	307.14	366.67
2	27.43	3.70	16.44	3.33	4	452.50	411.11
3	11.30	2.16	9.44	1.89	4	329.41	222.22
4	25.33	3.76	15.33	1.39	4	652.00	400.00
5	47.62	2.06	20.00	2.78	4	614.29	788.89
6	-	-	-	-	4	-	-
7	-	-	17.20	1.07	4	-	345.50
8	-	-	23.48	9.07	4	-	217.96
9	-	-	14.20	1.76	4	-	308.83
10	-	-	-	-	4	-	-
Av.	**24**	**3**	**16**	**3**	**4**	**471.00**	**382.65**

In terms of the economics of light fishing in the Suba District of Lake Victoria, the results obtained show that light fishing is an attractive business in terms of the lighting and wage costs relative to fish catches and prices. The survey respondents reported that the average value of trough of omena was KSh 500.00 (AUD 5.82). From Table 3, the total average catch per year using solar PV-battery lamps was estimated at 7,704 troughs [(24*26)+(3*6) = 642*12 = 7,704)], with a total approximate value of KSh 3,852,000 (AUD 44,837), assuming zero wastage and 100% sales at the average price. Respondents stated that the average annual wages a crew of four were KSh 587,808 (AUD 6,842), [(KSh 471*4*26*12)]. Adding this to the total annual cost of the solar PV-battery lamps gives the total annual reported cost of crewing and lighting a boat of KSh 744,432 (AUD 8,665). (Note that OV-battery lamp boat crews are paid more because the fish catch is higher and is able to pay the crew more). Based on reported costs associated with crewing and lighting a boat, against the average value and catches of the solar PV-battery fishers, the undiscounted average annual net revenue per boat (excluding all other costs such as the boat, nets, etc.) is approximately KSh 3,107,568 (AUD 36,172). Similarly, calculating the undiscounted average annual net revenue per boat using kerosene light is also an economically attractive business. From Table 3, the total average catch per year using kerosene lamps was estimated at 5,208 troughs [(16*26)+(3*6) = 434*12 = 5,208)], with a total approximate value of KSh 2,604,000 (AUD 30,311), also assuming zero wastage and 100% sold at the average price. Respondents stated that the average annual wages for four crew using the kerosene lamps were KSh 477,547 (AUD 5,559), [(KSh 382.65*4*26*12)]. Adding this to the total annual cost of the kerosene lamps gives the total annual reported cost of crewing and lighting a boat of KSh 745,411 (AUD 8,677). Based on reported costs associated with crewing and lighting a boat with solar PV-battery technology, against the average value and catches of the fishers using kerosene, the undiscounted average annual net revenue per boat (again, excluding all other costs) is approximately KSh 1,858,588.8 (AUD 21,634). Based on respondent survey data, the net value of fishing with a crew using solar PV-battery lamps is around one-third more cost-effective than fishing with a crew using kerosene. These results must be used cautiously. For example, recalculating the same undiscounted average annual net revenue per boat using kerosene using the higher reported average fish catch (and associated value) of the solar PV-battery lamps, the annual net revenue per boat becomes KSh 3,106,589 (AUD 36,161) (KSh 3,852,000 - 745,411). This recalculated value is not significantly different from the solar PV-battery option net annual revenue figure of KSh 3,107,568 (AUD 36,172).

The survey findings demonstrate that the fish catch variable is very sensitive in the calculation of the net value of the omena fishery, and that the primary objective of any lighting technology will be the effective catching of fish rather than cost or efficiency. Thus, the lighting technology must ensure fishery productivity is at least higher, or the same as any existing lighting technology. If an increased fish catch efficacy of lighting technology can be attained while reducing the associated costs relative to existing methods (and also not increasing the wage cost component), the new technology likely will play a dominant role in the artisanal omena fishery, and similar industries worldwide. Furthermore, the significantly high value of the fishery relative to the relatively low cost of the lighting technology, particularly the current cost of the solar PV-battery lighting technology, suggests that fishing would likely continue to be profitable even with very high lighting costs. This also suggests that a more expensive, yet more effective lighting technology can be absorbed into the fishery operating costs without too much difficulty. However, the capital costs of such a technology would need to be relatively low, and a model such as the existing solar PV-battery rental, might be a familiar and effective means of such an introduction.

Conclusion

The survey findings demonstrate that artisanal light fishing is an economically attractive business in the Suba District, and the introduction of solar PV-battery technology has led to a reduction in fisher lighting costs relative to the traditional kerosene lamps. This research suggests that based on average catch reported, the number (5) of solar PV-battery lamps used per boat are at least equivalent and may be slightly superior to the number (4) of kerosene lamps used per boat. This is despite a reported lower level of lumen production from the solar PV-battery lamps. Yet the majority of fishers reported that existing rented solar PV-battery lamps required additional storage capacity, or correspondingly more efficient lumen production per watt-hours of storage. This suggests that there is a promising scope for the development of a lighting technology that improves the fish catch, while optimising the balance between minimal lumen production and battery storage (and associated opex and capex), and maximising higher levels of robustness, fisher usability, repairability, and local content in terms of artisanal manufacture, supply, servicing, and also recharging services (with sufficient training). The role of new LEDs with superior energy efficiency, ruggedness, are commonly waterproof, have low weight, generally longer service life, low voltage requirements, alongside a flexible optical controllability [11], requires greater attention for inclusion in such developments.

Survey results presented in this research provide an indication of the economic margins that are available in several small-scale entrepreneurial opportunities related to the fishery. A simple example is the expansion of solar PV-battery charging stations, in addition to local iterative development, manufacture, and sales of more effective light fishing technologies and configurations that improve the local light fishing productivity. Higher fishery productivity may be achieved by either increasing catches, or also reducing input costs, such as reduced need for travel to either kerosene suppliers, or solar PV-battery lamp charging stations. There is a clear economic incentive for locals to capture of some of the profitable light fishing service industry market, and at the same time also find complimentary innovative economic activities that are effectively cross-subsidised by the light fishing industry. As there is likely to be more than one lighting system technical design that will fit the light fishing niche, each design in theory presents an opportunity to co-opt lighting technology into new productive uses during the day when there is also a need for electricity services. This would maximise the utility of the technology at all times, improving total value of the investment, and generating new economic opportunities outside of the fishery industry with creative entrepreneurship. Such innovation is likely to be enhanced with the availability of cheaper, more efficient LED technology.

There remain several issues associated with increasing the pressure on the fishery, and environmental considerations regarding net sizes. However, expanding the availability and market size for the zooplanktivorous omena to supply the human demand for protein can increase the overall lake productivity in terms of total catch supplying the growing human demand, in stark contrast to the lower trophic efficiency of exporting carnivorous Nile perch to Europe. The replacement of carnivorous fish, or the fishmeal industry with direct consumption of non-carnivorous fish would reduce the net pressure on fishery systems to an extent [1]. However, the Nile perch remains the backbone of the economy in the region at present fishing levels. Furthermore, there are several constraints to primary production in sub-Saharan Africa that have led to underprivileged populations that are unrelated to the primary resource [26] [27], including legal restrictions, regulatory frameworks, labour laws, commercial laws, transport legislation, market access, lack of public goods, poor environmental management, etc. [17] [27] [28]. Nonetheless, there remains an enormous and unprecedented scope for entrepreneurial locals to apply existing efficient lighting technology to lift at least some out of poverty [14] and to dramatically improve local food security.

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