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Technical Report #11

Alternatives to Fuel-based Lighting for Night Fishing

Field Tests of Lake and Ocean Applications in East Africa

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The Lumina Project—an initiative of the U.S. Department of Energy's Lawrence Berkeley National Laboratory—provides industry, consumers, and policymakers with timely analysis and information on off-grid lighting solutions for the developing world. Lumina Project activities combine laboratory and field-based investigations to ensure the formation of policies and uptake of products that maximize consumer acceptance and energy savings. For more information, visit http://light.lbl.gov

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Executive Summary

Many of the 12 to 18 million artisanal fishermen in the developing world fish at night using kerosene lanterns to attract fish to their nets. The lakes and ocean areas of Tanzania are a major center for this activity, involving over 100,000 lanterns used in 17,000 boats. While conducting fieldwork in these locations, we interacted with 113 individuals, including fishermen, boat captains, boat owners, traders, and local experts to determine current practices. We also conducted user-centered tests of LED-based system usability, performance and energy savings potential in the field (including 121 netting rounds over multiple nights: 73 with LED lighting and 48 with kerosene), and estimated the market sizes for today's fuel-based lighting and scenarios of transition to improved products in these waterways.

Night fishermen in the areas we studied spend 35% to 50% of their take-home pay on lighting costs (fuel plus lamp maintenance). We found that similar catches could be obtained with battery-powered LED lighting systems, while eliminating fuel costs. The simple payback time for amortizing the LED system investment would be only three to four months. Our results are far more definitive than prior studies, and provide a clearer roadmap for product manufacturers and others interested in deployment.

Due to the combination of higher intensity pressurized lanterns, and longer operating hours, Tanzanian fishermen use as much lighting fuel as would about 1 million ordinary household lanterns (equivalent to one lamp in every sixth home in Tanzania). The corresponding CO_2 emissions are on the order of 85,000 metric tons per year, or about 1.3% of the total energy-related CO_2 emissions from Tanzania.

We identified a significant market potential for the uptake of LED lighting by night fishermen, which could justify retooling and marketing investment on the part of lighting manufacturers. We estimate an existing expenditure on the order of $70 million per year for fuel and lamps by fishermen across all of Lake Victoria, Lake Tanganyika, Zanzibar, and the ocean coastline on Mainland Tanzania.[1] The retail value of LED systems that would provide the same service is $17 to 21 million, plus $6 to $7 million per year in replacement expenditures. A quarter of this market is relatively easy to reach and viewable as a medium-term target. The extent of fuel-based lighting for night fishing around the world is not known, but if even 10% of the artisanal fishermen worldwide night-fished, the global market would be 3- to 5-times larger than Tanzania's.

[1] Key assumptions based on field research: lamps in use 99,000 to 123,000; kerosene price $1.40/liter; 1.25 liters per night per pressurized lantern; 20 nights per month spent fishing; duration of fishing period 10 hours; lantern cost $40; adequate replacement LED system cost $175; service life 3 years.

Many of those we interviewed indicated a willingness to pay on the order of $250 for a system replacing a single pressurized kerosene lantern (more than the likely actual cost). That this is approximately six-times the cost of the conventional pressurized lantern provides a strong indication of user dissatisfaction with their current lights, and of how highly they value the prospect of improved lights. However, this stated price level is only a general indication; structured market tests using real products are needed to determine true willingness to pay.

While smaller in aggregate, the fishing market is in many ways easier to reach than conventional household customers. It is more concentrated geographically (around lakes and shorelines). Given that a subset of individuals (boat owners) purchase lamps and other fishing equipment, a relatively small buyer pool makes investment decisions (perhaps 20,000 individuals in the market we studied, or, a hypothetical lamp purchase of $1,000 per customer).

Solutions are available for the well-known challenges of “last-mile” distribution and financing. Existing well-established supply chains between population centers, and fishing areas and between boat owners and their crew—together with the presence of community based fishery co-management organizations with a mission to improve conditions for fishermen—provide ready-made distribution channels for LED products. Existing financing mechanisms could be readily adapted to help pay for replacement lamps.

This market is particularly ripe for LED lighting alternatives. Night fishermen have exceptionally high baseline costs both for fuel and lamp purchase and maintenance, and the cost of lighting is a much larger burden than in a household context.

The fishermen were almost universally pleased with the concept behind the prototype lights, and eager to purchase them provided the right price and performance. Given that much of the 1,000 lumens of light produced by a non-directional kerosene lantern never usefully reaches the water surface, we found that the performance could be matched with above-water replacement LED systems producing one-quarter to one-third as much light.

However none of the existing LED systems we tested were adequate for this use—although one was expressly intended as such. Essential product modifications include improved durability and performance in harsh fishing environments. Diverse fishing conditions such as calm/rough and clear/turbid water call for different designs, while varying fishing techniques pose different constraints on factors such as weight and bulkiness. Independent testing and certification would encourage product quality and support consumer confidence as they adopt these highly beneficial new technologies.

Introduction

Fuel-based lighting is pervasive in the developing world (Mills 2005), yet most efforts to understand the current conditions and potential for alternatives focus on household uses. Yet, non-household uses tend to be more energy intensive because they often use higher-power lanterns and have longer operating hours. Also of importance, by virtue of occurring in a business context, there is often more structure and available capital to invest in alternatives. One such application is night fishing, the subject of this study.

Around the world, night fishermen use lights to catch small pelagic fish, such as sardines and herring. These fish, which live near the water surface and usually move in schools, feed on zooplankton. When zooplankton are attracted to light, the fish follow, schooling—in a sense unknowingly—around the light source, and can then be harvested.

In small artisanal fisheries in developing countries, pressurized kerosene lanterns are widely used to attract fish. Typically consuming between 1 and 2 liters of fuel per night of fishing (and in rare cases up to 3 liters per night), these lanterns are expensive to operate and thus pose an obstacle to economic development. At the same time their use is associated with the emissions of a considerable amount of the greenhouse gas carbon dioxide (CO_2) to the atmosphere and a variety of health risks (Mills 2012).

The aim of the research described in this report is to investigate the technical and economic value of replacing kerosene lanterns with off-grid LED technology. We employed a user-centered process, assessing both technological and socioeconomic dimensions of existing and alternative methods of illumination. This enabled us to identify possibilities for the fledgling off-grid lighting industry to manufacture and deploy a viable commercialized product to this sizeable and previously untargeted market segment.

Our field work, conducted over a five-week period in Tanzania, focused both on freshwater fishing – Lake Victoria (Mwanza and the surrounding area) and Lake Tanganyika (Kigoma region) – and ocean fishing – Stone Town, Zanzibar and Pangani, mainland coast. In addition to testing specific technologies, we characterized the market in each location in order to obtain a deeper understanding of the socio-economic structures of the fishing communities and how lighting equipment is obtained and financed.

Interviews were conducted with the fishermen to assess needs and obtain a very specific user assessment of various LED alternatives during repeated periods of night fishing. The prototypes we tested were improved or otherwise varied and retested. To gain insight into the broader socioeconomic and market factors potentially impacting uptake of alternatives, the team conducted extensive interviews with boat owners, fish traders, local experts and institutions.

The report begins by characterizing how light behaves under water and how fish react to light in their environment, from the vantage point of designing effective systems for night fishing. We then turn to socioeconomic and market considerations, and set forth the role and opportunities of a replacement system. This is followed by a presentation of our technical results from the field trials. Drawing on these, we present some design recommendations. In the final section, we lay the challenges and most promising implementation channels and mechanisms.

With LED and solar technology at its current stage of development, a commercialized replacement product is doubtlessly feasible and demand among fishermen for a cheaper and better solution is high.

Light and Fish

While in air, the intensity of light drops off by four-fold each time the distance from the source doubles (according to the inverse-square law), and this drop-off becomes more severe once light enters water. Depending on the angle of penetration, roughly half of the light is lost by reflection at the water-surface (Ben-Yami, 1976; 31). This motivates the use of submersible fishing lights in some cases. There is no

standardized formula for the dynamics of light within water, as this depends most critically on water clarity.

Because short wavelengths tend to travel furthest under water, the green-blue end of the spectrum penetrates most effectively. As white light is a combination of different wavelengths, color can shift as it travels through water.

In water, the relation between light intensity and range of attraction for fish is not proportional. Ben-Yami (1976) cites an example from the Caspian Sea. Here, an increase in light (lumens) by a factor of 80 increased the radius of attraction only by a factor of 1.6, and the volume of water in which fish were attracted by a factor of 4.1 (Ben-Yami 1976; 36). This implies that there are decreasing marginal returns to more powerful light sources, both in physical as well as in economic terms (capital and operating costs, whether electric or fuel). It may be more sensible, then, to use an array of smaller lights rather than a single larger one so as to illuminate a greater area less intensely.

Fish will gather in schools around the source of light, allowing the fishermen to seine (net) around them. There are different interpretations[2] of and explanations for this behavior (Ben-Yami 1976). The most common one is feeding. One relevant process is that zooplankton move towards light, followed by the fish.

Ben-Yami gives an overview of typical behavior patterns of various fish species. Within East Africa, where our project took place, the main species sought by local fishermen belong to the *sardinella* and *sardina* genera. These two genera muster similar behavior patterns (Ben-Yami 1976). During the day, they move in schools relatively deep below the surface. During the night, they disperse and ascend closer to the surface. Confronted with artificial light, they again-gather into schools and move towards the light source. It seems that the fish need light to school but avoid strong light. They remain at a certain distance from the light source, which is why some fishermen dim their lanterns in the final phase of fish attraction so as to draw the fish close. When faced with a light intensity beyond their level of comfort, the fish are disoriented and react with erratic movement. The fish feed inside the illuminated zone. Other factors, such as age and gender of the fish, season, water temperature, and phase of the moon also have an effect on the attraction to light. Experiments suggest that these *sardinella*-type species react more advantageously in fishing terms to short wavelengths of light, that is, blue, green, violet.

The Global Market & Environmental Context

Night fishing using light to attract fish is practiced virtually all around the world, both in developing and in developed countries (Ben-Yami 1976). The technique is practiced on large and small scales. The sources of light range from crude flame torches to kerosene lanterns to high-intensity electrical lights in

[2] The various interpretations are investigatory reflex, feeding, disorientation, and schooling. The investigatory reflex hypothesis suggests that the fish see the light in an environment that would usually be dark and follow an instinctive reflex to investigate the source of light. The disorientation hypothesis states that fish lose their sense of orientation in the presence of a single and isolated light source at night – as opposed to the even distribution of light provided by the sun in daytime. This goes some way to explain erratic fish behavior close the fishing lanterns sometimes observed. However, Ben-Yami is critical of this hypothesis as it can serve as a partial explanation at best. Another way to explain this erratic behavior is that fish have a certain level of illumination in which they are comfortable and that strong light puts them beyond that level of comfort. The schooling hypothesis suggests that the fish have an inborn defensive reflex to school in order to ward off predators when there is light. More than one of these factors may be at work, varying by fish species.

commercial fisheries. The use of kerosene lanterns for fish attraction, prevalent in small-scale[3] artisanal fishing in developing countries—the focus of this report—is less effective than modern practices, but requires a lower initial investment. Yet it has high operation and maintenance cost in developing countries due to the low quality and energy inefficiency of the lanterns.

Figure 1. Artisanal fishing camp, Lake Victoria.

Hence, artisanal night fishermen would benefit most from a more energy- and cost-efficient lighting solution. Kerosene is not only an obstacle from a profit-maximizing point of view; it can consume a substantial portion of already very limited earnings, and thus contribute to poverty (Figure 1).

From a sustainability perspective, artisanal fisheries are often a point of focus. In comparison with commercial fisheries they can have lower ecological impact, lower energy consumption, and higher labor intensity. They provide employment opportunities, are integrated into local communities, and have lower technology and investment cost (FAO 2005). One estimate identifies more than 12 million artisanal fishermen worldwide, producing about 30 million tons of fish, and providing nutrition upon which approximately 150 million people depend (Pauly and Jacquet 2008). Another estimate places the number at about 18 million, of which 95% live in developing countries (Decoster and Garces undated). It is not known what fraction of the total is represented by artisanal *night* fishermen who use fuel-based lighting to attract fish.

Other authors have identified kerosene-based light attraction techniques throughout East Africa, Indonesia (van Oostenbrugge 2002), Brazil (Martins and Alvarez Perez 2006), Sri Lanka (GNF no date), Polynesia, Micronesia, and Kiribati (Dalzell, 1992), Ghana (Bannerman and Quartey 2004), Nigeria (FAO 1984), and India (Achari *et al.,* 1998; Apte et al., 2007). Of note, fishing with electric light was recently banned[4] in Ghana (Saminu 2011), although the ban does not appear to extend to methods using fuel-based lighting.

A recent visit by the author team to Senegal found very different practices, with primary reliance on electric flashlights, with the primary purpose of ensuring safety (rather than attraction) from the larger and more dangerous fish netted there (e.g., barracuda, tuna, sting rays). Low-quality LED products and batteries are used, which are unreliable and costly to operate.

Practices clearly vary by locality. There has been no global meta-analysis the problem of fuel-based lighting for night fishing in the developing world. A small number of lighting manufacturers have

[3] The demarcation of the different types of fisheries is difficult. The FAO seems to equate small-scale with artisanal fisheries, a convention we follow for this report. However, this is not always the case. Some publications define as one distinct feature of artisanal fisheries that they are collectively owned and operated. In Tanzania, however, most of the fishermen we worked with were organized such that all equipment was owned by one fisherman, who employed a crew. Yet, these fishermen should qualify as artisanal. Market data reported in the literature may be contingent on the demarcation conventions.

[4] The fisheries Act (11) (1), which was used to impose the ban, states: "A person shall not within the fishery waters of this country (a) use any fishing method that aggravates fish by light attraction, including use of portable generator, switchboard, bulbs beyond 500 watts or bulbs whose cumulative light intensity attracts fish, and long cable to facilitate light production or any other contrivance for the purpose of aggregating fish by light." And talks about one benefit being to “bridge the gap between the canoe fisher folk, and the Inshore Boat Owners Association, in terms of income.”

promoted systems based on electrical light for replacing kerosene in fishing applications, and a handful of pilot studies have been conducted[5].

Market Structures: The Case of Tanzania

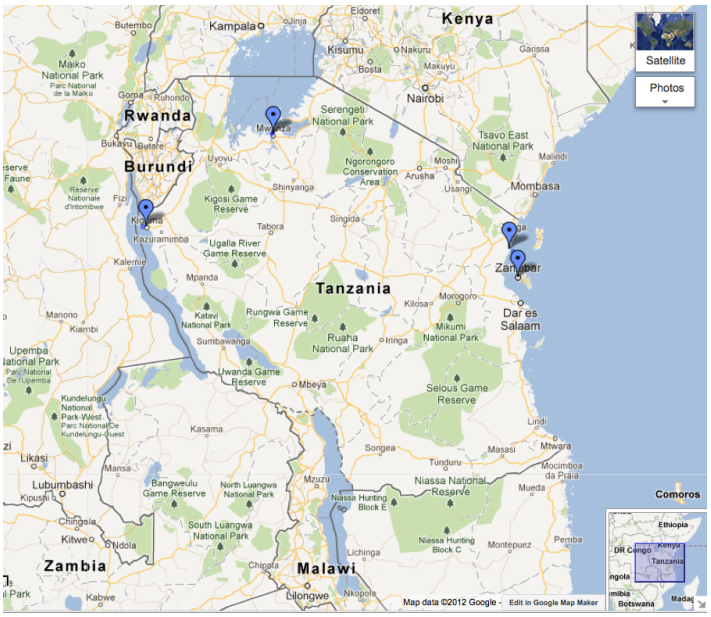
Within East Africa, night fishing has widespread application. In addition to the freshwater fishing sites the team visited in Tanzania–Lake Victoria, Lake Tanganyika, which share borders with Kenya and Uganda on the one hand and the DRC, Zambia, and Burundi on the other hand–kerosene-based fish attraction is practiced at Lake Malawi (Tanzania and Malawi), Lake Albert (Uganda and the DRC), Lake Kivu (Rwanda and the DRC), Lake Kariba (Zimbabwe and Zambia) Lake Cahora Bassa (Mozambique), and Lake Mweru-Luapula (Zambia and the DRC) (Legros and Luomba, 2011). The light-attracted fish of interest is called *Dagaa* in Tanzania, encompassing various species of *sardinellas*, *sardines* and *carp*.

The technique is also practiced at the Indian Ocean fishing sites along the coastlines of Tanzania, Kenya, and Mozambique, and perhaps other coastal states in East and South-East Africa.

The Tanzanian fishing sector has great importance for the country's economy and employment. In 2005, it contributed 2.9% to the Tanzanian GDP—with around 150,000 artisanal fishermen—and the sector is a source of income for about two million people. Fish is the third most important export commodity after mining and tourism, with a value of about $145 Million per year. Additionally, fish provide 27% of the animal protein consumed in the country (FAO 2007). The annual catch volume amounts to around 400,000 metric tons per year. Inland freshwater fishing clearly dominates in terms of catch volume. The most important species in inland fisheries are Nile Perch, Tilapia, Lates, and Dagaa (INFOSA undated). Dagaa is caught exclusively by light attraction, and in some cases Lates.

Our field research, interviews and product testing took place at four locations in Tanzania (Figure 2).

Figure 2. Field test locations (Lake Victoria, Lake Tanganyika, Dar-es Salaam, and Zanzibar Island.



Exact field-test locations can be reviewed at: http://goo.gl/maps/p4qe1

[5] For an overview of the previous efforts to that end we identified see Appendix B.

We utilized interviews and literature to study markets and practices for night fishing in Tanzania. We interviewed 113 individuals in 21 interviews during the period March 6 to March 21, 2012. These focused on fishermen who use the lamps, and other important players in the value chain (Table 1).

Table 1. Summary of interviews.

Location	Fishermen	Captains*	Boat owners	Traders	Local experts	**Total**
Lake Victoria	35	0	5	4	1	**45**
Lake Tanganyika	22	0	0	0	3	**25**
Ocean-Zanzibar	16	2	1	0	1	**20**
Ocean-Mainland	21	1	0	0	1	**23**
Total	**94**	**3**	**6**	**4**	**6**	**113**

* At Lake Victoria and Lake Tanganyika some of the interviewed fishermen were also Captian's. We only made the distinction at the Ocean were the hierarchy is more important and we were explicity told to speek to the captian about certain matters.

At Tanzania's main night fishing sites, market structures are influenced by external factors such as the species caught, fish stock abundance, climate, trade, political circumstances and so on. It is imperative to adjust for local constraints when considering alternatives. However, some characteristics apply for all locations.

Ownership and Organization

There is usually a single individual who owns, maintains, and coordinates the fishing equipment: nets, lanterns, and boats. This individual does not normally go fishing, but employs a crew of fishermen. These relationships typically persist over long periods of time.

During a typical fishing night, the crew spends 8 to 12 hours fishing. Upon return, the catch is sold directly at the beach, the operating expenses are deducted from the gross proceeds, and the remaining profit is divided in two parts of equal size – one for the owner, one for the crew. Fuel costs thus tend to be divided equally between the owner of the lamps and the crew.

Boat owners vary with respect to status and income. Some own just one boat, others run an enterprise with several boats. At freshwater locations, the boat owner is often a former crewmember, still living in the fishing camp. However, at the Indian Ocean, boat-owners sometimes live in the cities, far from their boats and crew. In that case, a senior crewmember organizes the fishing trips, payment, and gear supply. This structural difference is reflected in the degree and scale of organization at the different locations, which, as we experienced, is highest at the Indian Ocean, and more rudimentary at Lake Victoria. Collective ownership of vessels and gear also occurs, but the boat-owner-crew structure seems to prevail (Jiddawi *et al.,* 2007).

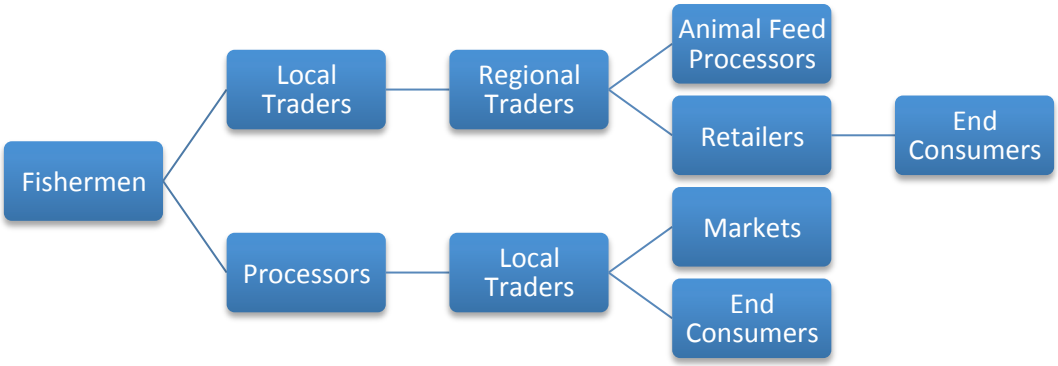
There are important differences between the freshwater and saltwater fishing areas. At Lake Victoria and Lake Tanganyika the night fishermen have their own fishing camps. Although these are often near or within city or town limits, they tend to be secluded and self-contained. These camps vary in size from beaches with just a few boats on islands to large camps on the mainland with about 200 boats (Nsinda 2005). Many of these camps are registered as *Beach Managing Units* (BMUs), both at Lake Victoria and at Lake Tanganyika. BMUs are a form of fishery co-management institution, and as such community-based organizations. While different types of communal organization have long existed in the fisheries sector, BMUs have recently been legally defined, with the aim of including and empowering all stakeholders present at a fishing camp—boat-owners, crew members, fish traders, carriers, processors,

and builders—in the process of managing, regulating, and monitoring fishing activities and socioeconomic developments. In each BMU, there is a representative committee and assemblies are held on a regular basis. BMUs are organized on different levels, from fishing camps up to regional, national and lake-wide networks (LVFO 2012b).

At the Indian Ocean fishing sites, we witnessed fishermen living individually in town rather than in isolated fishing camps. Before departing on fishing trips, the fishing crews meet at designated beaches where they leave their vessels during the day.

Though the specific markets for varying fish species caught at different venues have their unique characteristics, the trading structure, which involves many different parties, seems to be somewhat similar at all locations, especially in the initial steps of the value chain. Upon return to land, the fishermen sell their catch directly at the beach to processors, mostly women, who resell the fish either wet or dried. The fish are then sold at local and national markets, or exported for human consumption (Legros and Lumba 2011). Part of the Lake Victoria Dagaa landing is also processed for animal feed. Figure 3 shows an illustrative value chain for Lake Victoria Dagaa, drawing on Legros and Luomba's analysis (2011).

Figure 3. Illustrative value chain for Lake Victoria Dagga.



Source: Legros and Luomba

Among the main export destinations are DRC, Burundi, Zambia, South Sudan, Kenya, Rwanda, Malawi, Zimbabwe and South Africa (Legros and Luomba 2011). The marine fishery venues, Zanzibar in particular, possess a rich diversity of fish species caught by light attraction, and export also to countries off the African continent. Most fish traders operate within a union or business cooperative.

Lake Victoria

With an area of 68,800 square kilometers, Lake Victoria is the world's third largest—and Africa's largest—lake, stretching 337 by 250 kilometers. Yet, its depth averages only 40 meters. Its shorelines are shared by Tanzania (49%), Uganda (45%), and Kenya (6%). Night fishing was first introduced in the late 1960s (Gibbon 1997), and the fishing technique differs significantly from other locations in the region.

Fishing Techniques

At Lake Victoria, the fishermen use rather small boats (*Canoe-style*) – about 4 meters long and 1.5 meters wide – usually in crews of four. Most boats are rowed. The kerosene lanterns are tied to small

wooden floats (60cm by 60cm), where each float carries one light. There are usually four floats and thus four lanterns per boat. The floats are lined up on the water in 100 meters to 200 meters intervals, and anchored to the ground using rocks.

When the fish have gathered around the lights, the fishermen row around one float at a time, releasing the net such that it forms a circle with a diameter of about 30 meters, with the float and the light in its center. They then begin pulling in the net, thus closing the circle, and use a wooden stick to keep the float and its kerosene lantern in the center of the net. The fish are taken onboard and the lantern and float are again released on the water for another cycle of netting (Figure 4). The fishermen usually stay within sight of land; the outer waters of Lake Victoria can be too rough for the small fishing vessels, and work between 14 and 21 nights per month for eight to twelve hours each night. In addition to the fishing camps mentioned earlier, there are small remote fishing communities on the many islands of Lake Victoria. These are supplied with all necessary equipment and fuel by fish traders, who visit the islands to buy fish.

Figure 4. Fishing technique at Lake Victoria.

Socioeconomic Conditions

Lake Victoria hosts Africa's largest inland fishery, with about 175,000 fishermen working full-time around the lake. Of these, 31,891 fishermen with 8,272 vessels are employed in night fishing (Legros and Luomba 2011) for Dagaa (in this case *Rastrineobola Argentea*, or silver cyprinid, a small fish of the *Cyprinidae* family). The importance of Dagaa for local food supply and economic development is increasingly recognized (Legros and Luomba 2011). Dagaa has become the dominant species by yield, with a total landing of around 500,000 tons in 2006 (LVFO 2012a).

Of note, there occurs some seasonal migration of fishermen to different fishing sites mainly in search for better fishing conditions and prices. Almost half of the fishermen interviewed in a survey in 2007 stated to have moved fishing sites at some point in their career (Odongkara and Ntambi 2007).

Income Structures

Given that catch, turnover, profit, and income tend to vary greatly, many of our interviewees did not articulate a specific amount of monthly income, but told us that in some months they have surplus income while in other months they are left with nothing. Demand and supply and thus prices for Dagaa also vary. According to a survey conducted by the Lake Victoria Fisheries Organization (LVFO) in 2007, the average income of a crew member is around $4 per night, and for a boat owner it is around $16 per night of fishing. Given that the fishermen go out around 17 nights per month, a crewmember earns around $70 per month and a boat owner around $270 per month (LVFO, 2007).

Lake Tanganyika

Lake Tanganyika is the second largest lake in Africa and one of the world's deepest. It stretches 676 km in a north-south direction, with an average width of 50 km. The lake has a surface area of 32,900 km^2 and a shoreline of 1,828 km. Its greatest depth is 1,470m.

Lake Tanganyika is a traditional stronghold of night fishing within East Africa, which focuses mainly on two species: Mgebuka *(Lates stappasaii)* and Dagaa *(Stolothrissa tanganicae)*. Both are sold in the same lot size (a wooden box of about 60kg) and at the same price. Four countries share coastlines at Lake Tanganyika. Tanzania (41%) on the East side, Democratic Republic of the Congo (DRC) (45%) on the West side, Burundi (8%) in the North, and Zambia (6%) in the Southwest.

Kigoma, where our team conducted its fieldwork, is in a difficult position in terms of immigration, with refugees from the turmoil-stricken Democratic Republic of the Congo and Burundi trying to make their way across the border into Tanzania. This sensitive situation complicated the team's fieldwork, with people tending to be reluctant to share information.

Fishing Technique

At Lake Tanganyika, lift-net fishing using a catamaran of two slim vessels is the technique most frequently employed. The fishermen go out in boating pairs, that is, two vessels cooperate with six to eight crewmembers per boat. One boat has an engine and tows the other one, which has the net onboard. Each boat has between 6 and 10 kerosene lanterns onboard. Sometimes a special kind of kerosene lantern, a downward facing *down lighter* – called *Standard* by the fishermen – is used so as to avoid shading caused by a lantern's base when in an upright position. These down lighters are more powerful but also more fuel consuming (about 3 liters per night) than the usual pressurized kerosene lanterns. A number of fishermen asserted that the additional light output does not compensate for the higher fuel consumption in terms of catch volume, which is consistent with the fact that light intensity drops off particularly rapidly with distance under water.

Of the kerosene lanterns on board, two are affixed on the outward-facing flank of either boat. Six to eight are on the inward facing side of either boat. The two boats – each about 10m long – wait for about three hours about 50 to 100 meters apart before they approach to 20 meters and connect with two long wooden sticks.

They then let a net down to about 100 meters. The net itself measures 300 meters by 50 meters. They then begin switching off the outer lights. Only one lantern per boat, covered with an ordinary metal bucket to dim the light is left on so as to draw the fish to the center of the boating pair. The fishermen then pull up the net. Before they have the fish onboard, they relight the outer lamps so as to attract another group of fish. This process is repeated several times each night.

The fishermen go out around 22 nights per month, for around 11 hours per night.

We were told that when the catch is bad, such that the fishermen and the vessel owner experience a net loss and may not be able to afford kerosene and fuel for the next day, a third party steps in, sometimes a trader, to carry these costs. This way the trader can dispose of the catch of the following night, dictating prices or agreements that all fish are to be sold to him only.

Socioeconomic Conditions

Estimates suggest that there are 304 vessels in the Kigoma urban area and 4,100 vessels, with perhaps 25,000 fishermen in the wider Kigoma rural area (personal communication, Kazumbe 2012). Night fishing is also practiced in the Tanzanian part of Lake Tanganyika south of the Kigoma region as well as on the Western side in Zambia. However, from informal reports we gathered that the Zambian fishermen use more sophisticated techniques and gear. The greatest concentration of fishing seems to be in the Kigoma region. In the DRC, apparently fishing was not sustained during the conflicts of the last decade. In recent times, it seems that it may have been resumed. We were told by various fishermen and authorities that from time to time there occur robberies of Tanzanian fishing boats by Congolese and sometimes Burundian bandits. Fishing in Burundi, though conflict stricken itself, seems to flourish.

A local expert (personal communication, Kazumbe, 2012) suggested that the total number of vessels on the lake is roughly 8,000.

Apart from local consumption, we were told that traders with DRC purchase especially large quantities of fish at high prices. Reselling in DRC is lucrative since with ongoing turmoil, food supply for mining workers, just across the Lake from Kigoma, is not ensured, which spurs demand. In the year 2000, one 60kg box of fish was priced at TZS 20,000 to 30,000 ($13 - 19); current prices range between TZS 150,000 and 300,000 ($90 - 190).

Income Structures

As at Lake Victoria, there is a great deal of uncertainty and volatility in the fishing business. The fishermen and boat owners we interviewed stated that their average turnover per night ranges between TZS 100,000 (about $60) and TZS 2,000,000 (about $1,200), implying 1 to 20 box units of 60kg of fish. A boat owner told us that in the course of a given month he often experiences a net loss. It seems reasonable to assume a monthly income ranging between zero and $800 for a boat owner, and between zero $200 for a crewmember.

Indian Ocean

The team visited Stone Town, Zanzibar and Pangani on the Tanzania mainland coast. Zanzibar comprises numerous small and two large islands, Uguja and Pemba.

The Tanzania mainland fishing zone is 1,450 kilometers long and the Exclusive Economic Zone has an area of 223,000 square kilometers. Fish diversity, especially in Zanzibar, is great. Among the fish species caught in night fishing, a local expert from Zanzibar (personal communication, Jiddawi, 2012) told us, are Indian Mackerels (*Rastrelliger kanagurta*), Goldstripe Sardinella (*Sardinella gibbosa*) and Spotted Sardinella (*Amblygaster sirm*). Given frequent tourism to Zanzibar, fish prices at the larger local markets are high.

Fishing Techniques

We encountered a variety of techniques at different ocean fishing sites. The most common seems to be to use a fairly large boat (8m), called simply *Boat* or *Boti* by the fishermen, equipped with two small *Dinghies*. The large boat has an engine and carries a large net, a purse seine, about 120 meters wide, and 26 meters deep. About 15-17 fishermen work on the large boat, which is usually owned by a small- to medium-scale entrepreneur who does not work onboard, or by a collective of fishermen. The two dinghies are equipped with four kerosene lanterns each. In the fishing process, the dinghies set their anchor and turn on the lanterns to attract fish. The boat then travels around one dinghy at a time with the net.

Figure 5. Fishing technique at Indian Ocean)

Another method, which we also observed several times, is the use of a medium size boat, equipped with three to six kerosene lanterns, which attracts fish. The large boat goes around it (much like with the dinghies) (Figure 5). The catch is split equally between the two boats, unlike the case of the dinghy technique.

The use of a scoop net is also common. It is used either to augment the large purse seine, when there is a big catch or as a proper fishing technique. During waiting periods, the fishermen also use fishing lines to catch bigger fish. At the ocean, where the main catch is a small sardine-like fish they also use buckets to dim (and color) the kerosene lanterns (Figure 6). In this way, they draw the fish particularly close, just before laying out the net.

At the ocean, we encountered several boats, which used 400W or 1000W Metal Halide spotlights to attract fish. The fishermen stated that they use these electrical lights to land a greater catch volume (we did not determine how much greater). These lights are powered by on-board generators (the noise does not seem to be a problem at the ocean, while we were told it would be at Lake Tanganyika).

Figure 6. Dimming kerosene lanterns with colored buckets.

One boat owner reported that, depending on the wattage, they either use a diesel generator consuming 5 liters of fuel per night (for 4 lamps at a 1000W each), or a gasoline generator consuming 3 liters per night (for 4 lamps at 400W each). We only observed the 400W lamps, which were powered by a 10HP gasoline generator. With these lights, the fishermen attract fish from a greater area than accommodated with kerosene lanterns. Part way through the night, the fishermen switch off the electrical lights and ignite their kerosene lanterns on a dinghy that they pull behind the boat. All the fish then move towards the (weaker) kerosene lights. The rest of the process is equivalent to the standard

kerosene lights-only technique mentioned above. At any rate, one could interpret the use of electrical lights for fishing as a proxy for their general willingness and ability to invest in a new technology.

The fishermen asserted that they usually go out very far with their boats: between 10 and 45 kilometers. The fish are usually attracted from a depth of 25 to 50 meters.

Socioeconomic Conditions

Fishing conditions at the Indian Ocean sites appeared to be superior to those at most freshwater sites. This may be due to the fact that the marine fishing grounds of Tanzania are vast and, since the fishery is almost exclusively artisanal and small-scale, not over-exploited.

Oftentimes, it seems, boat owners do not live in the same place as their crew. They hire a captain who is in charge of assembling a crew and organizing fishing trips.

We estimate that there should be around 600 night fishing vessels in Zanzibar and another 600 at the Tanzanian mainland coast (Jiddawi *et al.,* 2007; Sobo 2001). The number of fishermen and fishing vessels employed in the marine fishery sector seems to have increased rapidly over the last ten years, and the figures given above may be conservative (Jiddawi et al., 2007).

Income Structures

We were told by an owner of two boats that he usually earns between TZS 1 and 1.5 million, equivalent to $625 to $ 930. This implies an income of $300 to $450 per boat. A local expert (personal communication, Jiddawi, 2012) confirmed this, suggesting that in Zanzibar a boat-owner would on average earn around $600 per month and a hired crewmember $200. The estimate of $200 seems to be on the upper end of the usual amount. At the mainland coast, incomes appeared to be well below those of Zanzibar.

Baseline Energy Use and the Potential for LED Lighting Systems

Our field measurements (described in greater detail below) indicated that most night fishermen utilize between 1 and 2 liters of kerosene each night, per lantern, with a likely average value of 1.25 liters.[6] We observed a range of 14 to 24 nights per month of fishing, with a likely average value of 20 nights. There are also variations in the number of lanterns per boat. The ~110,000 lanterns used on the ~17,000 boats[7] in the lakes and coastal areas that we studied thus utilize about ~33 million liters of kerosene each year, or a ~$47 million annual expenditure assuming local fuel prices (Table 2), and another ~$20 million for lantern maintenance and replacement.[8] Thus, there is a substantial lighting market already in place, spending on the order of $70 million per year for equipment and fuel.

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[6] According to Mair (2009) the degree of pressurization results in fuel use rates between about 100 and 300 milliliters per hour, at the upper end of which a lantern would use 3 liters of fuel in a 10-hour work shift. Observations in Kenya suggested 1.5 liters per night (Mair 2009).

[7] An obstacle to estimating the macroeconomic dimensions of current practices is that there is fairly little statistical reporting on the numbers of fishermen and boats engaged in night fishing. However, considerable advances have been made by the installation and coordination of supranational institutions such as the Lake Victoria Fisheries Organisation (LVFO), the Lake Tanganyika Authority (LTA), or the Indian Ocean Commission (IOC).

[8] In this report, we assume a 2012 average energy price for kerosene of $1.40 per liter (2250 TSH). At Lake Victoria we observed kerosene prices of TZS 2200 ≈ $1.40. However, further from the cities the prices rise to about TZS 2500 ≈ $1.60. At Lake Tanganyika TZS 2300 ≈ $1.40; In Zanzibar TZS 1700 ≈ $1.10; On the Indian Ocean mainland shore TZS 2100 ≈ $1.30. As concerns the other riparian countries of Lake Victoria: the prices in Kenya and Uganda are similar to those in TZ.

The energy use associated with night fishing in these areas corresponds to greenhouse gas emissions of ~85,000 metric tons each year. Due to the combination of higher intensity and longer operating hours per day, this is the energy use of perhaps 1 million ordinary household lanterns (equivalent to one lamp in every sixth home in Tanzania). It is clear that more energy-efficient substitutes for pressurized kerosene lanterns could significantly improve the fishermen's economic situation, lower health risks, and drastically reduce CO_2 emissions. We developed a rough cost-benefit analysis of LED alternatives to the kerosene lanterns, along with macro-level estimates of how much energy could be saved regionally.[9]

Table 2. Numbers of fishing boats, energy use, and CO_2 emissions estimates for the areas studied.

Location	Number of Nght-fishing Vessels	Min Lanterns per Vessel	Max Lanterns per Vessel	Min Lanterns	Max Lanterns	Sources	Quality of the sources and other comments
Lake Victoria - All shores, all bordering countries	8,272	4	4	33,088	33,088	LVFO Fisheries Frame Survey from 2010.	Some uncertanty is introduced by the assumption that each vessel carries four lanterns. Some may carry more (as reported from some parts of Kenya).
Lake Tanganyika - Kigoma Region (Urban + Rural)	4,400	7	10	30,800	44,000	Interview with a local expert	These data were difficult to independently verify. Older studies (all of them about 15-20 years old) report lower and conflicting numbers. For example a 1995 survey conducted by LTR estimated the number of lamps at 20,000 for the whole lake. Fishing activities have dramatically increased since then, particularly in the Kigoma region.
Lake Tanganyika - Other areas (Tanzania Rest + Zambia + DRC + Burundi)	3,600	7	10	25,200	36,000	Local estimates and extrapolation	Uncertain reports from various sources indicate that the southern Tanzanian shorelines are less active, whereas Zambia and Burundi have very active fisheries. Activity on the DRC fisheries is highly volatile due to ongoing unrest. A local expert estimated that the number of boats around the rest of the Lake is at least as high as in the Kigoma region. We thus estimate that there are 8000 boats around the entire lake.
Ocean Zanzibar	600	8	8	4,800	4,800	2007 Zanzibar Fisheries Frame Surevey	Uncertanty is introduced by the assumption of 8 lamps per boat and (1) that these types of boats are always used for night fishing and (2) no other types of boats are used for night fishing. Our own observation was that the fishing boats of this type were regularly used for night fishing and that there is a small number of other types of boats also used for night fishing. Moreover, the data are 5 years old. The 2010 Frame Survey is not yet available. In the 4-year period of 2003-2007, there was a dramatic increase in fishing activity in Zanzibar, for instance the number of fishermen increased by 43% and the number of vessels of all types increased by 73%. We consider our estimates to be on the low end of the spectrum.
Ocean Mainland (Tanzania coast only)	600	8	8	4,800	4,800	2001 Marine Fisheries Frame Survey Report 2001 + modest extrapolation	We could not obtain any recent data for the Tanzanian mainland marine waters. We regard this 2001 estimate similarly to the Zanzibar data. Also, we observed strong growth in the number of boats at the landing sites considered in the 2001 report. For example the number of boats at the Pangani site grew from 0 to 6. Hence, we made a modest extrapolation, and consider our estimates to be at the lower end of the spectrum.
TOTAL						Average	
Count	17,472			98,688	122,688	110,688	
Fuel use (M liters/year)				30	37	33	
Fuel cost ($M/year)				41	52	46	
Maintenance cost ($M/year)				18	22	20	
Total lamp operating costs ($M/year)				59	74	66	
CO2 emissions (metric tonnes/y)				75,496	93,856	84,676	

Notes: Includes shorelines of the *entire* lakes and the Tanzania ocean coast plus Zanzibar. Assumes 20 nights per month of night fishing, 1.25 liters kerosene per lantern per night, $1.40 per liter fuel price, and 2.55kgCO_2/liter kerosene emissions factor. Does not include the uses of lanterns at home, for net handling within the boats, or for work on shore.

[9] If not otherwise stated we based our calculations on an estimated retail price of $175 for an LED system sufficient to replace one pressurized kerosene lantern.

The operational cost of a single kerosene lantern is about $50 per month (divided equally between the boat owner and crew). Of this about 30% is spent on lantern maintenance and periodic replacements, and 70% on fuel. The pressurized lanterns initial cost is approximately $35-$55 (average probably $40), and each is incrementally replaced—sometimes part-by-part—once or twice a year. Depending on how many lights a boat is using, and other local conditions, the fishermen spend an amount on the kerosene systems that is equivalent to about 35-50% of the crewmembers' and boat owner's take-home pay after lighting-related expenses are deducted.[10] (A report where kerosene is heavily subsidized found rates in range of 20-30% of household income (GNF no date).) An LED-based electric fishing light could decrease the monthly lighting costs to about $7.30 and thus increase the fishermen's profit by 30-40%. This equates to a simple payback time of only 3 months.

Considering the efficiency of kerosene alone we estimate the average catch volume per liter of kerosene to be about 50kg of (wet) Dagaa resulting in gross revenue (before lighting costs) of $12. Net profit must take into account operational costs such as lantern maintenance, kerosene, nets, boat and all other equipment and supply as well as labor.

The true market potential of such a change depends on the overall economics, conditioned by the dynamics between fishermen and boat owners together with their willingness and ability to carry the investment. Fishing takes vary widely (which directly influences cost recovery for new technologies), and the user population exhibits high variation in income and education.

We observed a wide range of fishermen's reactions to the idea of a replacement system that requires a higher initial investment but is economically sound in the longer run. Nonetheless, our overall impression is that the demand is very strong. At least 20 individuals, spanning all fieldwork locations, fishermen immediately wanted to buy the gear we were using for field tests, undaunted by the high prices, even at a hypothetical price point of $ 250 that we tested in our interviews. This price level can only be taken as a very general indication, and for the particular individuals we interviewed. The only way to determine true willingness to pay is with structured market tests using real products. That said, a price of $250 represents less than half the annual operating cost of a typical pressure lantern when used for night fishing.

We estimate that between 100,000 and 120,000 pressurized kerosene lanterns are used on a regular basis throughout the areas we studied, namely all shores of Lake Victoria and Lake Tanganyika, plus the Mainland Coast of the Indian Ocean and the Zanzibar Coast of the Indian Ocean (Table 3). The total costs to this fishing population of running their kerosene lanterns are thus between $59 and 74 million per year. For our market volume estimations, we use an estimated retail price of $175 for LED systems to replace each kerosene lantern, including the charging/storage infrastructure supporting it, which seems by far more realistic than the $250 used to test the limits of willingness to pay in the interviews. At this price, we estimate the potential overnight-replacement sales volume to be $17 to 21 million and an annual replacement sales volume[11] of $6 to 7 million. A considerable number of additional more conventional lighting systems could no doubt be sold to this market for use in net handling within the boats, use on shore, and use at home by the fishermen. The baseline energy use, potential savings, and additional revenue potential for these additional applications are not estimated here.

[10] Using the range of actual average conditions (days spent fishing, fuel costs, lantern costs, catch value, etc.) at Lake Victoria and the ocean areas at Zanzibar, respectively.

[11] After initial saturation, the recurring replacement rate that would be a function of system lifetime. Current battery technologies would be unlikely to last more than two or three years. Lamps and solar panels (if any) may last longer, but this is speculative given the harsh conditions and varying qualities of construction prevalent in the marketplace.

The question remains as to how many kerosene lanterns can feasibly be replaced by an innovative lighting system in the medium term. Considering the differences in accessibility and circumstances in the particular submarkets, a segment of pressurized kerosene lanterns will be hard to replace, at least in the medium term. Market penetration will depend to a large degree on the products actually offered, their price and quality and on the marketing and distributions strategy. Assuming a system that meets the users needs at a price point of $175, and with limitations to the existing distribution infrastructure, we very roughly estimate that about one-quarter of the potential market could be captured in the medium term, or ~26,000 lanterns.

Table 3. Rough estimate of medium-term market potential for LED replacement systems.

	Lake Victoria	Lake Tanganyika	Mainland Ocean	Ocean Zanzibar	Total
Number of kerosene lanterns	33,088	68,000	4,800	4,800	110,688
Feasible percentage	30%	15%	50%	80%	24%
Feasibly replaceable	9,926	10,200	2,400	3,840	26,366

The medium-term feasible sales volume we thus estimate to be about $4 to 5 million for initial market penetration, and $1 to 2 million per year for replacements.

There is no solid basis for estimating the global market size for off-grid night-fishing products. As noted above, it is estimated that there are 12 to 18 million artisanal fishermen in the developing world (Pauly and Jacquet 2008; Decoster and Garces no date). Assuming, for illustration purposes only, that 10% conduct night fishing using one lantern per four fishermen, there would be 300-450,000 lanterns with an overnight replacement value of ~$50 to $80 million.

Field Tests and User Needs

By deploying an array of LED lighting system types and configurations on the boats and floats, we investigated the adequacy of light output; diffusion, dispersion and angle; submerged vs. above-water design; and color. We further assessed the design constraints put on a new system by bulkiness and weight requirements.

Each configuration was used in multiple trials, and the volume of each catch was logged and then benchmarked against baseline reference catch levels using kerosene lanterns. In all, 73 netting rounds with LED systems were conducted over multiple nights, accompanied by 48 rounds with kerosene lanterns (for the purposes of establishing baselines for comparison).

Prototypes and Methodology

In collaboration with working fishermen over a period of several weeks, we field-tested six commercially available off-grid lighting devices, arranged in 15 lighting configurations (Table 4).[12] Several of the initial designs were improved according to the fishermen's suggestions and preferences. In particular, we used of-the-shelf products Barefoot PowaPack 5W, with a total of 190 lumens and the Trony Sundial with a total of 261 lumens per system, both of which come with their own matched battery. We further used Lumitronix waterproof Superflux LED strips in white, producing 170 lumens, and in green, producing 180 lumens each (peak wavelength 523 nm), and the Fishing Lights Etc. Aqua Star Super Brite 192, producing 1000 lumens of white light. These latter two systems were powered with a 12V lead acid dry battery. We also built a prototype relying on two 100-lumen headlamps, with a very focused beam, which we

[12] For a more detailed discussion of the test designs see the Appendix A.

faced directly towards the surface of the water. The team waterproofed the equipment, where necessary.

We also offered the fishermen small 'reading-style' LED systems (such as the Barefoot Firefly) for on-board lighting needs. Although the fishermen were highly impressed and very interested in them for their homes, they expressed no interest in on-board usage. At Lake Victoria the fishermen need light on-board during the preparation of the nets (prior to setting out the lighting floats) and while bringing in and storing the catch. During these phases of the fishing process the pressure lanterns are back on board anyway and provide the necessary illumination. At the Indian Ocean and Lake Tanganyika the lights are mounted on the sides of the boats, always providing the crew with some light. We encountered the need for an on-board lighting solution only when using submersed lights at the Ocean where the person on the light boat (dinghy) needs light for preparing fishing hooks that are sometimes additionally used to harvest bigger fish.

While most of the technologies were provisioned for solar charging, we grid-charged the systems each day. The matching of battery capacity to solar charging was not part of this field test, but should be considered in designing any commercial system.

At Lake Victoria, we modified the traditional wooden float, which we found to support only about four kilograms, so that it could support the heavier systems. In order to install the LED strips on the float, we built an aluminum frame, to which we attached and experiment with the strings in various angles, quantities and colors (Figure 7). We ultimately abandoned the aluminum construction in favor of easier handling characteristics indicated by the fishermen after using the prototypes (Figure 8)

Figure 7. Lumitronix LED strip system green with aluminum frame

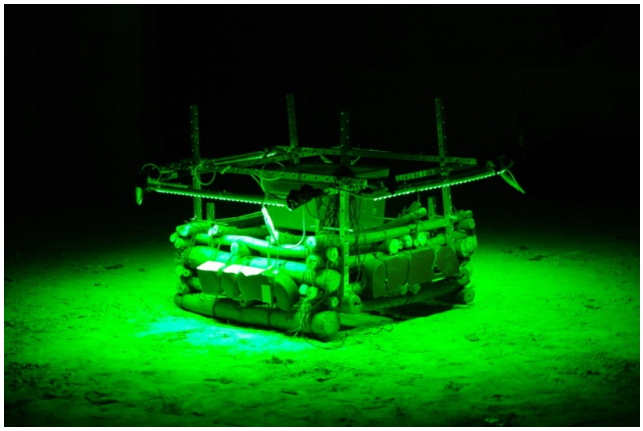


Figure 8. Modified Lumitronix LED strip system white without aluminum frame

We tested the LED strips both above-water and submersed (Figure 9). We used a similar wooden float construction for the PowaPack 5W (Figure 10).

Figure 9. Submersible Lumitronix LED strip system (batteries protected in plastic boxes)

Figure 10. Barefoot Power system

The Trony Sundial came with an internal battery, which was lighter and did not require enhancement of the float supports, with Trony manual illustration (Figure 11). The fishermen later altered the Trony Sundial system according to their liking, facing the lamps straight onto the water rather than at an angle (Figure 12).

Figure 11. Trony System standard mounting

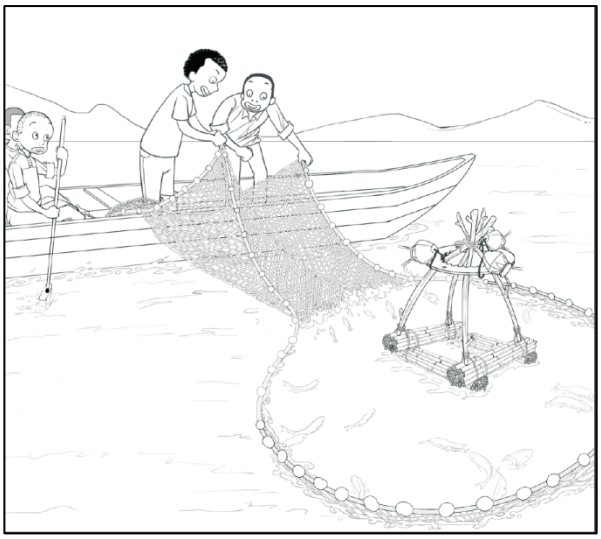


Figure 12. Trony system user-modified mounting

Since at the Indian Ocean the fishing technique does not involve placing lanterns on a float, we tested entirely different designs. First, We reassembled 3 white and 3 green LED strings of the type we used at Lake Victoria, yielding a total light output of 1050 lumens: 540 lumens for the green strings and 510 lumens for the white strings. We tied the green strings to one wooden stick and the white strings to another one, which we submerged on either side of the dinghy. The battery was placed on the dinghy. This way, all four kerosene lanterns, which are usually placed above water, two on either side of the dinghy, were replaced by six strings of LEDs.

Second, as at Lake Victoria, we used three Trony Sundials to replace one kerosene lantern. Due to limited equipment we could only replace two of the four kerosene lanterns on one dinghy with 6 Sundials, with a total light output of 522 lumens or 261 lumens per replacement unit. The remaining two kerosene lanterns were used in the normal fashion so that the dinghy was equipped with 2x3 Sundials and two kerosene lanterns, jointly attracting the fish.

Third, we also tested the submersible light, powered by a standard 12V lead acid dry battery. The fishermen tested it in the following manner: they first let it down fairly deep (around 5 meters) and then gradually raised it to attract fish. This system replaced three kerosene lanterns. The fourth lantern was not replaceable due to on-board lighting needs. Whether it also contributed to attracting fish is not known.

We conducted the most extensive testing at Lake Victoria, over a 7-night period. The fishermen conducted a total of 9 to 26 netting rounds per night, depending on weather and other conditions. This enabled us to collect 48 netting-cycle trials for the kerosene lanterns and a total of 73 trials for the LED systems.

We used *tins* as units of catch measurement. Tins are a common unit for selling Dagaa, with a volume of approximately 3 liters and weight of 3 kilograms per tin**.** We used a scaled plastic drum to report the catch volume of each netting cycle.

In order to account for daily variations in catch size we recorded the yield of the reference system, the traditional kerosene lanterns. Each boat simultaneously used both kerosene and LED systems, with distances between lanterns and netting areas on the order of 200 meters and 30 to 45 minutes between each catch, with one kerosene lantern's catch measured for each fishing round, together with the catch for every LED system used.

Two of the testing nights we spent with the fishermen in their boat on the lake. During two further nights we visited them on the lake during the fishing process with a separate boat. We thoroughly walked through our data recording methodology with them, and had extensive discussions with the fishermen before and after their fishing trip on all testing days.

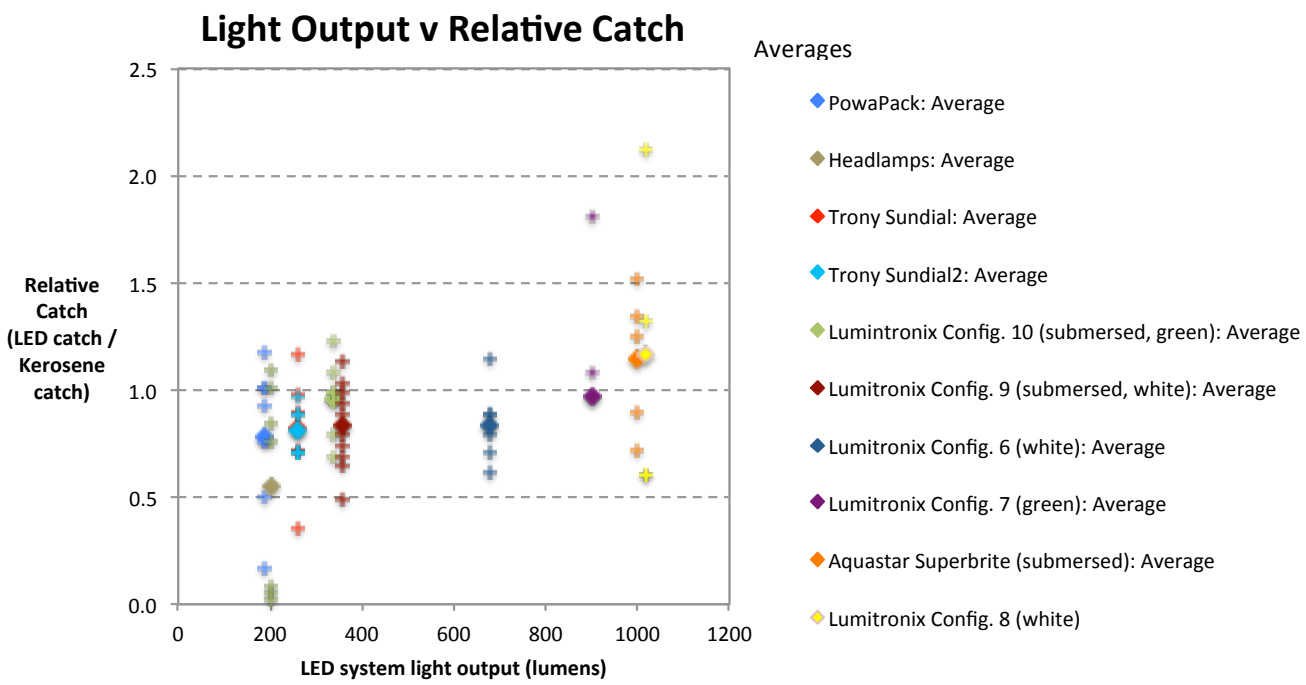
At the Indian Ocean we were able to improvise and test three different systems on two nights, one of which we spent with the fishermen on the boat. For our conclusions we rely on the fishermen's subjective assessments and our own observations since there are less fishing rounds per night (about two to four), high variation in catch volume, and no reasonable measurement unit, since, in each catching round, the fishermen land very large quantities of fish (on the order of 200-700 kg wet weight).

Results

The normalized catch volumes landed by local fishermen during our field trials are expressed as a ratio of catch volume with the LEDs to that with the reference kerosene lanterns (Figure 13). A value of 1.0 or above thus indicates that the LED system performed equal or better than the kerosene lantern (Table 4).

A further metric of interest is catch per unit of light output, obtained by dividing the standardized catch as shown above by the lumen output of each system, multiplied by average yield of the kerosene lantern. Since at the Ocean we could not rely on quantitative measurement units, we present the results in a qualitative fashion.

Figure 13 Light output against catch volume at Lake Victoria: All Systems



** Relative catch is the ratio of catch volume with LED to that with kerosene lighting. The figure shows mean values (diamonds) for each system and their individual scatter (crosses). This plot includes all trials, locations, and lighting system types (above-water and submerged). Note poor performance of headlamps.*

Where the Relative Catch ratio is 0.9 (10% under-catch), the hypothetical cost of lost fish is $1,275 per year, which might be compared to savings of $2,325 per year for the improved lantern, i.e. the fisherman would still be ahead economically. The break-even point would be a Relative Catch ratio of about 0.8. In practice, however, fishermen will continue working until the entire desired catch is attained, thereby attaining the full energy cost savings. Comparisons of relative catch values should not be regarded as highly precise, given the many variables that determine outcomes of a given period of fishing.

Analysis

The fishing process and assessment of catch success is subject to many external variables, all of which cannot be controlled for at once. This complicates the analysis and interpretation of the test results, suggesting that not all differences among outcomes may be indicative of lighting-related effects. Furthermore, the fishing method used at Lake Victoria is particularly sensitive to “handling” issues that stem from lighting system size, weight, and other factors, which determine how easy it is to rapidly remove the light from the netting area (without losing fish) before the nets are raised.

Config	Product manufacturer	Model	Number of LED lamps	Watage per lamp* (W)	Configuration lighting wattage* (all lamps)	Light color	Total* system lumens	Efficacy* (lumens/ W)	Number of kerosene lanterns replaced in trials	Application (ocean or fresh water)	Notes on configuration	Average catch (in tins per k-lumen output)	Netting rounds	Average tins per netting round: LED	Average tins per netting round: Kerosene	Relative catch****	Notes on performance
1	Barefoot Power	PowaPak 5W	4	0.65	2.6	White	190	73	1	Fresh	Lights perpendicular to water. Additional support for traditional float required (battery weight)	22.7	7	4.7	6	0.78	Fishermen considered lamp somwhat too weak, although they liked system overall. Requires improved waterproofing.
2	Trony	Sundial	3	1.48	4.4	White	261	59	1	Fresh	First Setting: Mounted as indicated by the manufacturer, i.e., angled so as to illuminate a wider area.	15.1	5	4.6	5.6	0.82	Fishermen satisfied with overall performance compared to kerosene lantern. Strongly suggest a steeper angle since they think the light would reach deeper and thus attract more fish.
3	Trony	Sundial	3	1.48	4.4	White	261	59	1	Fresh	Second Setting: preferred Iteration by the fishermen, i.e., mounted perpendicular to water.	17.3	6	4.6	5.7	0.8	This adjustment did not convert into increased landings (catch).
4	Trony	Sundial	6	1.48	8.9	White	522	59	2	Ocean	Perpendiclar to water on the outside of the light boats (Dinghies).		1			1	Performed well to replace two lanterns.
5	Lumitronix**	Waterproof SuperFlux LED strips 507mm	4	2.4	9.6	White	680	71	1	Fresh	Oriented at ~45° to water surface. Mounted on aluminum frame at about 30cm above water. Additional support for traditional float required (battery weight)	17	3			N.A.	Aluminum construction too bulky. Difficulty of use resulted in fish loss.
6	Lumitronix**	Waterproof SuperFlux LED strips 507mm	4	2.4	9.6	White	680	71	1	Fresh	Fshermen's prefered configuration: fixed to float without aluminum frame. Additional support for traditional float required (battery weight)	15.6	6	4.8	5.7	0.833	Fishermen satisfied with performance relative to kerosene lantern.
7	Lumitronix***	Waterproof SuperFlux LED strips 507mm	5	2.4	12.0	Green	900	75	1	Fresh	Mounted on aluminum frame perpendicular to water. Due to heavy batteries, additional support for traditional float was required.	12.7	7	4	4.2	0.96	Fishermen preferred white over green. Satisfied with overall performance.
8	Lumitronix**	Waterproof SuperFlux LED strips 507mm	6	2.4	14.4	White	1080	75	1	Fresh	Mounted on aluminum frame perpendicular to water. Additional support for traditional float required (battery weight)	6.7	7	4.8	4.2	1.16	Performed very well.
9	Lumitronix**	Waterproof SuperFlux LED strips 507mm	2	2.4	4.8	White	340	71	1	Fresh	Submersed design. Fixed underneath the traditional float. Additional support for traditional float required (battery weight)	5.9	6	9.7	10.2	0.96	Performed fairly well. System stolen after several testing rounds.
10	Lumitronix***	Waterproof SuperFlux LED strips 507mm	2	2.4	4.8	Green	360	75	1	Fresh	Submersed design. Fixed underneath the traditional float. Additional support for traditional float required (battery weight)	7.9	10	8.5	10.2	0.83	White system performed considerably better.
11	Lumitronix**	Waterproof SuperFlux LED strips 507mm	3	2.4	7.2	White	510	71	2	Ocean	Submersed design. Strips fixed to wooden stick submersed 40cm into the water on the side of light boat.		1			>1	Performed better than kerosene.
12	Lumitronix***	Waterproof SuperFlux LED strips 507mm	3	2.4	7.2	Green	540	75	2	Ocean	Submersed design. Strips fixed to wooden stick submersed 40cm into the water on the side of light boat.		1			>1	Performed better than kerosene. Green better than white.
13	Fishing Lights Etc.	Aqua Star Super Brite 192	1	11	11.0	White	1000	91	1	Fresh	Fixed underneath traditional float.	7.7	5	6.4	5.6	1.14	Best catch results. Fishermen critical of too much luminous output. Fsh behaved strangely. Better performance expected with less light. Strong requirement that a submersible light be able to work above water.
14	Fishing Lights Etc. *****	Aqua Star Super Brite 192	1	11	11.0	White	1000	91	3	Ocean	Lowered into water about 5m and then gradually lifted.		1			>1	System worked better than the kerosene lanterns.
15	Fishing Lights Etc. *****	Aqua Star Super Brite 192	1	11	11.0	Green	1000	91	3	Ocean	Lowered into water about 5m and then gradually lifted.						Fishermen perceived the green as superior to white.
16	Black Diamond	Storm	2	N/A	N/A	White	200	N/A	1	Fresh	Mounted perpendicular to the water surface on the float.	15.1	7	3.3	6	0.55	The Headlamps performed very badly. This might be due to their highly focused light, which only illuminated a very smal spot. Also note that the Headlamps did not provide 100 Lumen each over the whole testing period; their lumen output decreased with battery voltage.

* Wattages and lumen output for PowaPak and Sundial products from Lighting Africa test results. Data for Lumitronix and Fishing Lights Etc. are manufacturer ratings, not independently tested
** Superflux White: 8000k (http://www.leds.de/en/LED-strips-modules-oxid-oxid-oxid-oxid-oxid/Waterproof-LED-modules-oxid-oxid-oxid-oxid/Wasserdichte-SuperFlux-LED-Leiste-507mm-12V-white.html)
*** Superflux Green: 523nm (http://www.leds.de/en/LED-strips-modules-oxid-oxid-oxid-oxid-oxid/Waterproof-LED-modules-oxid-oxid-oxid-oxid/Wasserdichte-SuperFlux-LED-Leiste-507mm-12V-green.html)
**** Relative catch is the ratio of catch volume with LED to that with baseline kerosene lighting. Values in parentheses are the numbers of lamps in each system. 1 “tin” = ~3liters = ~3kg
***** The two types of LED strings were used on a single netting round (one on either side of boat)

Variability

There is high variability in catch volume from day to day (even from netting cycle to cycle on the same day) and location to location. Over the course of our testing rounds, we recorded catch rates between zero and 14 tins per round; the nightly average ranged from around 3 to around 10 tins, with an overall average of 5.5 and a standard deviation of 2.3 (see Figure 13).

This variation may have many real-world causes. Rough weather impedes the travel of light through water since the surface reflects the light unevenly, and turbidity varies. Rough conditions also make the fishermen's work more challenging, which may lead to losses due to net-handling difficulties. Water temperature has an effect on the actual location of fish within the water body at any given time. The fish will also change locations from night to night, and the presence of moonlight reduces yields by illuminating vast areas away from the nets (Mair 2009).

Turbidity

Many factors affect the travel of light through water, as well fish attraction to light, one of the most important of which is turbidity. To that end, water turbidity is much higher at Lake Victoria than the other locations we visited. The Indian Ocean and Lake Tanganyika have very clear water, whereas at Lake Victoria the water has a greenish-brown tint, due to the massive growth of biomass over the last several decades (LVFO 2005). The "Secchi depth" is a standardized measurement for turbidity (based on visibility of a standardized bright object lowered into the water). The LVFO (2005; 2008) reported Secchi depths for Lake Victoria to be between one and two meters in 2005 and 2.74 ± 1.22 in 2008. In comparison, for the Indian Ocean and Lake Tanganyika, Secchi depths averaging 10 meters and more have been reported (Lugomela *et al.,* 2002; Smith 2001). Turbidity can vary within a water body, or according to season, wind, and current.

Turbidity places a severe design constraint on replacement for systems to be used at Lake Victoria. With increased turbidity light travels less easily, and more illumination may be required to attract a given amount of fish. According to our data, this corresponds to a difference of at least 25% in required illumination for otherwise identical system designs at the Ocean and Lake Victoria.

Perceived vs. Recorded Performance

Many of the LED systems were found to catch somewhat less than the kerosene lanterns. However, this was not matched by the fishermen's subjective perception of the systems' performance.[13]

The fishermen reported being satisfied with most of the LED systems. However, they never especially liked the green systems. If we look at the catch per lumen ratio, the PowaPack is the top performer. The fishermen, however, were only interested in absolute catch and thus asserted their preference for other, more powerful systems. This highlights the importance of user-centered considerations and user preferences in thinking about a new system.

The Role of the Individual Lighting-design Factors

Design Constraints: Weight and Handling

Relatively severe design constraints for Lake Victoria result, in part, from the fishing technique used. This technique puts limitations on the weight and bulkiness of a new system, since the fishermen tie their lanterns to fragile floats. For our testing, we had to add additional support for some of the LED test systems. This made them heavier and more bulky. During our fishing trips on Lake Victoria, we observed fishermen struggling with the handling of these systems, making the work more arduous. In

[13] Note that the fishermen recorded the performance of only one of their kerosene lanterns during each netting cycle for comparison to the LED systems.

addition, during the final steps of the netting process, the fishermen must remove the float very quickly from the center of the net to pull in the catch. At this point, some fish always escape. The heavier LED systems took more time to remove and got stuck in the net, and we witnessed many more fish escaping than with the lighter baseline system.

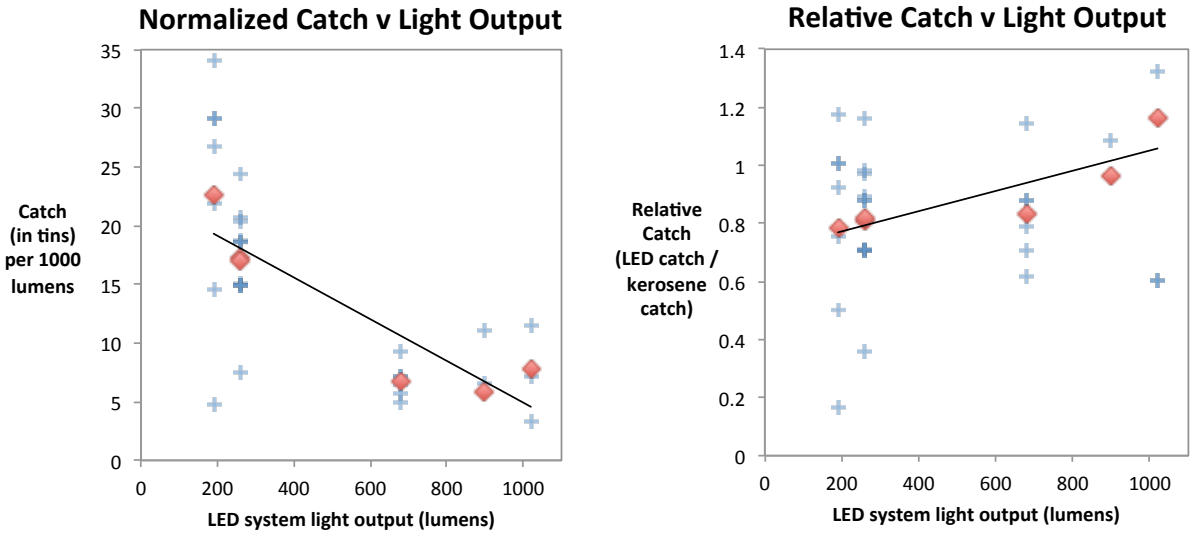
Over the course of the testing period the fishermen became increasingly accustomed to each system, and we improved the systems with respect to bulkiness (by decreasing the system size, adding handles, and covering protrusions that could catch on nets). Due to these initial problems and need for adjustments, we excluded the data from the first night of testing from the analysis. It illustrates, however, the importance of handling: with the initial, bulky system, on this first night the fishermen caught 20% less, with respect to the reference system, than with the user-improved version.

Handling is far less of an issue at both the Ocean and Lake Tanganyika than at Lake Victoria, where the fishermen fix the lights to the boat. This allows for a heavier system that does not need to be repeatedly moved during the netting process. Bulkiness is also less problematic as there is no need for a supporting construction like the one needed on the wooden floats at Lake Victoria.

Light Output

To isolate the role of light output on catch volume from other factors, we exclude the submersible systems and the headlamp system.[14] Variations in catch as a function of LED system light output for each trial at Lake Victoria are shown in Figure 14. Although light output is only one factor in fishing success, we find a significant correlation of 0.465 ($n = 31$, $p = 0.0096$, $R^2 = 0.216$) between light output and relative catch.

Figure 14 Correlation impact of light output on catch volume at Mwanza Gulf, Lake Victoria



Catch normalized per unit of light (left) declines with overall LED system light output. Relative catch (right) is the ratio of catch volume with LED to that with kerosene lighting, and increases with LED system light output. The figure shows averages (red diamonds) for each system and their individual scatter (blue crosses). Above-water lighting only, excluding headlamps

[14] Above water and underwater light distribution differs. We exclude headlamps from our analysis for two reasons. First, their light output steeply declined over the course of the trial due to battery discharge. Also, the headlamps were mounted such that their light was highly focused and perpendicular to the water surface. This setting was supposed to test the repeatedly expressed claim by the fishermen that the fish is only attracted from the deeper waters instead of a wide area. As the headlamps performed poorly and the lumen output was not known, we exclude the headlamps from portions of our analysis.

For relative catch per lumen and light output, we found a significant correlation of -0.70 ($n = 31$, $p = 0.00002$, $R^2 = 0.48$), suggesting that light output shows decreasing returns relative to catch volume. This is consistent with the fact that light decreases disproportionately as it travels through water.

Presumably due to the far higher water clarity, at the Indian Ocean less total light output was required to match the kerosene lanterns in terms of catch volume. All systems tested performed at least as well as the kerosene system. The 2x3 Trony Sundial system replaced 2 kerosene lanterns, which implies 261 Trony lumens per kerosene lantern. The assembly of our submersed LED strings, with 2x3 LED Strings as a replacement for 4 kerosene lanterns, was also perceived superior to the kerosene lantern, which implies less than 255 LED lumens needed to replace one kerosene lantern. The Aqua Star Fishing Light, which replaced three kerosene lanterns, with light output of less than 333 lumens necessary to replace one kerosene lantern. However, these metrics may be misleading. The fishermen left one kerosene lantern running as they asserted they needed on-board illumination in order to line-fish from the dinghy and catch addition fish during the idle time when fish began to gather around the lights.

Diffusion and Angle

The question of light distribution and angle applies only to above-water designs, as the submerged lines were multidirectional. Nearly all fishermen we interviewed at Lake Victoria suggested that the light must face *chini kabiza*, that is, straight down onto the water in order penetrate as deep as possible. In order to assess this claim, we tested the Trony system in two variations. First, the standard mounting as indicated by the manufacturer, which results in wider distribution over the water surface. Second, we had the fishermen adjust the system such that the lamps faced directly towards the water (see Figure 12). Furthermore, we tested the highly focused light of waterproof 100 lumen headlamps,[15] oriented perpendicular to the water surface. The results are shown in Table 4.

The headlamps performed very poorly. We assume they were too focused. Also, the results indicate no meaningful difference between the standard Trony and the user-improved version. Furthermore, it is noteworthy that the Trony system with 261 Lumens is nearly as effective as the 4 strands of LED string system with 680 Lumens (Trony: 0.82 vs. LED-Strings: 0.83).

We conclude that a wider distribution of the light as opposed to a downward-facing design is the more effective solution. Theoretically, the advantage of a downward-facing design is its angle. On the one hand, a steeper angle implies lower reflection losses at the surface. However, a calm water surface is not to be expected. It seems that the angle-effect is offset by size of illuminated area, which is greater when a wider distribution of light is chosen, even if great depth penetration is not achieved. Because light travels more easily through air than through water, it is inefficient to focus too much light in one spot. There may also be an adverse effect from choosing too bright and focused a light: the fish will stay at a distance from light that is beyond that level, as evidenced by the shading practices performed by some fishermen as the fish get closer to the lanterns before the nets are closed.

These considerations are confirmed by the distribution patterns of the different systems, which we recorded with a light meter on a four-by- four meter grid (see Appendix A). Comparing the standard Trony mounting with the 4 LED strings system we find that while in the center of the grid pattern the LED string system provides far greater illumination, towards the extremes this difference is nearly eliminated. This is due to the different angles of the two systems.

The Trony system as well as the PowaPack 5W use single and tight clusters of LEDs, respectively, while the LED strings by design rely on a linear series of closely interposed LEDs. The design of the former two

[15] Unlike all other systems the headlamps light output was observed to decline significantly over the course of testing. Thus the 200 lumens might not be accurate for the entire testing.

prototypes appears favorable since the illumination areas of the individual lamps do not overlap. Also, the former systems use reflectors, which may further enhance their efficacy.

We found that 2.5-times higher lumen output was needed when strings of LEDs were used as compared to point sources as in the Trony and PowaPack designs.

Submersed vs. Above-Water Design

At Lake Victoria, we tested three different submersible lights. Of these, the 340-lumen system, consisting of two white LED strings, performed particularly well when replacing a single kerosene lantern. The 360-lumen system, consisting of two green LED strings, not as well. This may be the result of its color. The third system, a 1000-lumen submersible fishing light performed similarly to above-water designs. In this last case, however, the fishermen reported that the light was too powerful, inducing erratic behavior among the fish. Comparing the light output of the LED strings in submersed vs. above-water design in terms of relative catch, we found that in the white specification the submersed version performed better than the above water version (0.96 vs. 0.83) although the submersed design uses only half the lumens of the above water design. In the green specification the submersed design worked slightly less well than the above water design, yet with only 40% of its lumen output (0.83 vs. 0.96). However, upon comparing these submersible designs with the off-the-shelf products, they do not perform any better in terms of efficiency.

At the Indian Ocean, the picture is clearer. The employment of submersed lights appears especially promising at this venue. In fact, the LED strings assembly turned out to be the fishermen's favorite system. The fact that the submersed LED strings system's relative efficacy was higher than that of the above-water Trony Sundial system supports this finding.

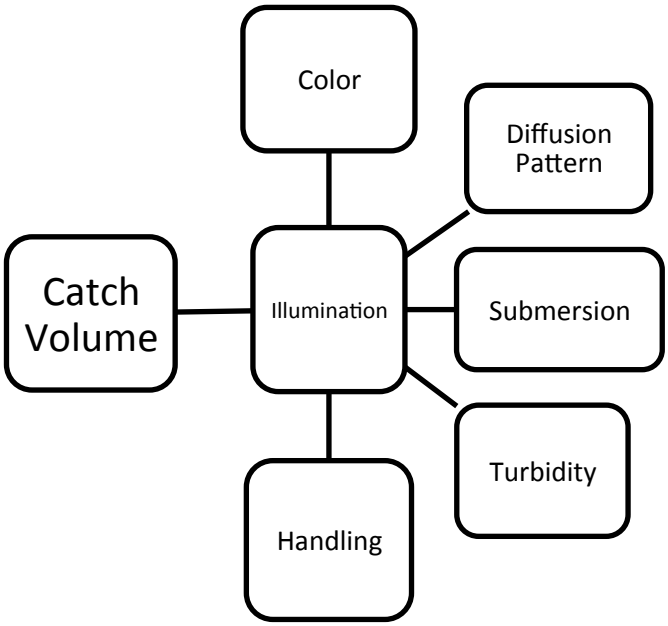
Color

The fishermen at Lake Victoria were convinced that white light would be more effective than green light. Our test results confirmed this: of the two green systems we employed, one worked somewhat less well than the comparable white design, and the other performed considerably less effectively.

Results were again different at the ocean, where the fishermen preferred the green version. It seemed that the fish surrounded the green light more readily than they did the white light. The fishermen were accustomed to working with colored light. In the final phase of the fishing process they usually cover their kerosene lanterns with colored plastic buckets in order to bring the fish in close, since too bright a light would keep the fish at a certain distance from the lantern. They reported red as their favorite and green as their second favorite color. They utilize red buckets to draw the fish from short distances, while the green system we tested was used to draw fish from further distances.

Drawing on these results, we interpret the factors we investigated to have following relationship: luminous flux (lumens) is the primary determinant of catch volume; we found a high positive correlation among the two. However, secondary factors have an effect on catch volume indicated by more/less light output needed to replace one kerosene lantern. These include color, light distribution, water clarity (turbidity), and fish lost during netting based on how quickly the lantern can be removed from inside the netting area (handling), and whether or not the light is above water or submerged (Figure 15). This implies that when the secondary factors are taken into account carefully, the light output needed to replace one kerosene lantern can be minimized.

Figure 15. Illumination and other factors influencing catch success.



Factor	Effect on required light output
Color	White ~20% more effective than green at Lake Victoria. Green better than white at Ocean and Lake Tanganyika.
Diffusion Pattern	Point sources 2.5 times more effective than stringed LEDs
Submersion	No quantitative estimation possible.
Turbidity	At least 25% more output needed in turbid waters.
Handling	Handling issues resulted in 20% less catch.

Product Design Recommendations

While we have observed considerable demand for improved lighting from fishermen who experimented with the LED test systems, we have not identified any off-grid LED products that are suitable as-is for this market segment. Based on our field experience, we can offer guidance to manufacturers seeking to serve this market.

In spite of uncertainties and high variability in catch volumes, the test results suggest various essential technical requirements. Replacement products may take inspiration from our test results but will have to undergo a multi-stage trial-and-error development process in order to be validated and optimized. Trade-offs between performance and price, handling and price, durability and performance and so on may need to be made at many stages in development and commercialization. Viability and simplicity considerations may override performance considerations. Addressing consumer preferences, perceptions, and knowledge is particularly important.

We are convinced that there is no single solution for all fishing circumstances. While there are many general recommendations, appropriate for any fishing application, diverse fishing techniques dictate additional varying needs with respect to lighting product design.

General Recommendations

At all field locations, the fishermen indicated a strong preference for a single and reliable system than continuing to use their kerosene lanterns as a backup for cloudy days that are not sufficient to fully recharge the batteries, and would pay a premium for products that could reliably achieve this. The fishermen also desire the ability to use the lamps at home when not fishing.

Reliance on water-cooling for submersed lamps should be avoided. The submersed light we used relied on water-cooling, that is, it could only be operated inside the water. The fishermen did not like this, since on the one hand it is impractical in handling, as they cannot have it lit on the boats, while on the other hand it rules out home lighting options.

A widely desired feature of any system is the ability to charge mobile phones.

Light Output and Optical Distribution

Wide-beam distribution (but with a degree of angular control such that all light hits the water surface) is superior to highly focused optics. Multiple sources are needed for each application (freshwater and ocean fishing alike)—perhaps 4 to 10 light sources per boat, depending on fishing methods. Battery and charging components capable of supporting multiple sources should be considered as a more economical approach than individually self-contained lanterns.

The ideal level of luminous flux varies by use case. Less output is required if water conditions are clear. Point sources were found to be more efficient than strings of LEDs. While there is significant correlation between light output and catch, the optimal level of luminous flux will depend critically upon other factors, such as distribution (point sources vs. stringed LEDs), handling and so on. In determining such an optimal level, we therefore recommend getting these factors right first, like employing point sources with reflectors and an easily handled systems. Provided these factors are accounted for, our data suggest that at Lake Victoria a light output of around 300 lumens will be necessary to replace one pressure lantern, while at the ocean and at Lake Tanganyika 200 – 250 lumens would suffice.

Note, however, that by employing different kinds of reflectors and designs, other than those we tested, manufacturers might be able to even lower this number.[16] For reference, a typical pressurized kerosene lantern produces about 1000 lumens.

Durability

Durability may be the single-most important characteristic for a successful product. The lighting systems are continuously exposed to harsh environmental conditions such as (salt-) water, dirt, and physical impacts. Insufficient durability will spoil the market by eroding confidence in new technologies such as LED lighting. Although our testing lasted for only a short time period, we experienced major durability issues with nearly all systems. Specifically, the LED string's plugs failed at the ocean, despite the fact that we had added additional safeguarding with duct tape. After two days of drying, the lights would work again, but this is neither acceptable nor is it likely to be a reliable strategy over time. Despite being promoted by the manufacturer for night fishing, the Trony Lamps, although not submersed, developed condensation behind the protection glass after only two weeks of use (see Figure 16). The Barefoot PowaPack is not intended for use close to water, which became manifest as it needed extensive waterproofing prior to testing. Further, we found scratches on the protection glass

[16] In fact, Yafei Wang, in testing different designs at Lake Victoria, sees the possibility of replacing one kerosene lantern with as little as 200 lumens.

after testing. The AquaStar fishing light can be operated only when submersed; however, the fishermen did not welcome this constraint and it is to be expected that they would use it above water and hence compromise its lifetime.

Maintenance is generally problematic. Only very few fishermen know about electronics. Further, it seems difficult to implement preventive maintenance practices, as they are not customary with the existing kerosene lanterns.

Figure 16. Trony Lamps with water inside

Batteries

Due to long operating hours the batteries are required to have a relatively high capacity and should last for many charging cycles. The fishermen use the lights for 6 to 11 hours per night, about 20 days per month. The matching of load to battery will determine how deeply the battery is discharged each night. Having a proper charge controller is essential for maintaining battery life. Battery weight must be limited for systems mounted to floats. Most batteries used in these experiments were adequately sized for the task. Battery capacity was adequate in most of the configurations we tested (assuming fully charged each day).

Another factor influencing the characteristics of an appropriate battery is the choice of the power source. In the few fishing areas where it is available, grid-based charging might be the economically preferred option, and the fishermen we interviewed were very familiar with the technology. Among the alternative power sources are PV solar panels and petrol/diesel generators. Nearly all fishermen we interviewed (even in areas with access to the grid) expressed the preference for a PV-powered solution. If the choice of the power source is PV, oversizing both panel and battery should be seriously considered. Fishing is especially favorable during the rainy season, a period with less intense solar radiation. In some areas, fishermen may even stay out more than one day.

Whether to use an external battery or integrate it with the lamp heavily depends on battery quality, weight, and the kind of battery used. To have a small and light battery inside the lamp is favorable as long as it provides illumination for the full night, and that the (relatively short) lifetime of the battery does not restrict the overall lifetime of the system or its replacement does not adversely affect its durability and waterproofness.

Dimming is desirable for minimizing power consumption and extended battery life. It also plays an important role in fishing practices at the Ocean and Lake Tanganyika, where dimmed light is used to keep the fish at a short distance of the boats. Dimming can also extend the illumination time by enabling fishermen to tailor the light output to the conditions in a given water body at a given time.

Location Specific Needs

The needs at Lake Victoria are in some respects substantially different than those observed at the Ocean and Lake Tanganyika where they are relatively similar.

Color

We found that different colors are desired in different circumstances, and suggest that in a future testing red light should also be considered for ocean applications in addition to white and green. At Lake Tanganyika fishermen reported from earlier tests conducted for the Millennium Challenge

Account – Tanzania (MCA-T) that green light worked better than white light. However, some fishermen stated a preference for white light despite the slightly better measured catch with green light. Manufacturers may consider offering systems with adjustable color qualities.

Other contexts will likely require other considerations. Shrimp fishermen in Sri Lanka report requiring yellow or orange light (Rodrigo 2010).

Dimming or Step-switching

There also is a need for a dimming option (or discrete step-switching) at the Ocean and Lake Tanganyika due to the fishing technique employed. The technique of covering the kerosene lanterns just before landing the catch is the current improvised method of dimming to draw the fish closer to the light source. This feature would also make the lights more versatile for home use when not fishing.

Submersible Lights

Unlike at Lake Victoria, we observed meaningful improvements in catch volume when using submersed lights at the Ocean and Lake Tanganyika, where the water is clear. This allows replacing more kerosene lanterns with the same lumen output. A further very positive aspect of the submersed lights is that it is easier for the fishermen to observe the fish and decide when to place their nets.

Weight and Handling

The bulkiness and weight of the lighting system must be minimized in cases where the light sits on a float and must be moved rapidly before the net is closed. The weight of all components must be carefully considered, as the traditional floats will support weight up to about 4 kilograms. We found that the PowaPack's battery was insufficient to provide light for the entire night, and a larger/heavier battery may exceed the capacity of traditional floats. Handling turned out to be a problem due to bulkiness and weight with some of stringed LED systems as well as with the PowaPack. Strategies for enabling the battery to remain in the boat, with a waterproof cable to the float seem highly unpractical due to distance and fishing process. The separation between boats and floats is too great at Lake Victoria, but distances are small at Lake Tanganyika.

A significant factor with respect to feasible designs at the Ocean and Lake Tanganyika is the lesser importance of weight and handling (thanks to the lights being attached to the boats and not require movement during the netting process). Due to the fishing technique employed at these venues, there are fewer constraints on the weight and bulkiness of the system. Here, the tradeoff between weight and price can tip decisively towards price at the cost of a heavier system.

Market Implementation Considerations

It is not known how many people conduct night fishing around the world, but with 12 to 18 million artisanal fishermen, if even 10% of them did so and used similar practices to those we have observed the global market would be 4 to 5 times that we have identified for this part of Africa. GNF (no date) indicates that 85,000 shrimp fishermen in Sri Lanka alone using 100,000 liters per night of kerosene, essentially doubling the energy expenditure that we've estimated in this report.[17]

Large-scale uptake of alternative lighting systems in the fishing market will depend on the availability of good products. For the fishermen, the profitability of a new system will depend critically on its price-lifetime relationship. A product launched prematurely could jeopardize not only the producer's reputation but also that of the entire technology category. Low-quality LED products have spoiled markets in other fields of use.

[17] As no primary source or study was cited, this number should be independently confirmed.

Pricing and Ownership

The boat owners we interviewed indicated a very rough willingness to pay of ~$250 for a multi-lamp system replacing a single pressurized kerosene lantern. This is approximately six-times the cost of the pressurized kerosene lanterns they currently use, which provides a strong indication of their dissatisfaction with their current lights and how highly they would value improved lights.

In our experience, it would take approximately four LED lamps such as those we tested from Trony and PowaPack to replace a single kerosene lantern. The exact amount depends on water clarity and other factors. That said, four such lamps, with a shared solar panel and batteries would very approximately cost $175, which is well below the willingness-to-pay threshold. However, those products are not, in their current form, suitable and would require further improvements (and presumably higher retail cost) to ensure acceptable durability.

A potential system can be either sold as a whole or be rented to the fishermen. Rental comes with the advantages that the initial costs are kept as minimal as possible and that the durability risk remains with the enterprise providing the service. In a rental model, charging can be performed centrally as well. Despite these advantages the fishermen we interviewed strongly and consistently stated that they would prefer to buy a system instead of renting it.

Selling the systems instead of renting them would increase the likelihood that they are taken good care of. The fishermen we interviewed explained that they also want the systems to be at their camp so they do not have to transport the batteries somewhere else to have them recharged. Independent charging enterprises could service user-owned as well as rented lamps (per the cellphone analogy). This would be especially interesting for financially strong boat owners who are willing to invest in the new technology and own several boats at the same camp. The business model of a charging enterprise is already widely established in the form of services for off-grid mobile-phone owners.

Sales Organization and Trade Channels

In tandem with a technological offering, is the requirement of an effective market deployment method. A key difficulty is the fact that the target buyers are dispersed, which makes distribution and service difficult. At Lake Victoria, for instance, there are many fishermen on the lake's many islands. On the other hand, these buyers are far less dispersed than the general population, and only a subset of all fishermen own the lamps, resulting in a relatively small target buyer pool that congregates around fishing hubs and is already serviced by fishing supply chains.

Since a new system may have a high initial price, financing options should also be considered. In both cases, the key to a successful implementation should involve local organizational structures and trade channels, which could well compensate for the dispersed nature of the market, given that the market is in fact served by the existing system.

Fish Traders

The most powerful local organizational structure we encountered consists of the trade channels provided through local traders and processors. The majority of Dagaa are caught in remote areas with little or no or connection to the densely populated urban areas. This is especially the case at Lake Victoria and Lake Tanganyika and only to a smaller extent at the Ocean. The traders travel to the fishing villages where they buy in larger quantities and transport the product to the central markets for sale at higher price.

These traders are well suited as potential sales agents for a new lighting system. They typically have long-standing business relationships and personal contacts with the fishermen, and are always aware of their current location and economic situation. The fishermen trust traders, which can be

instrumental in convincing the fishermen to invest in a new technology. Furthermore the incremental costs for distribution are very little if this channel is used. The traders already travel to the islands and the shipping capacity that is later needed to transport the fish is largely unused on the return route to the fishing sites. The traders could function as creditors, or intermediaries with larger microfinance institutions. They bear little risk of loss since they have long-term business relationships to the fishermen and could, for example, deduct the debt from the price they pay for the fish or even take fish in barter.

Boat Owners

The boat owners could play various roles. Typically the responsibility of buying the fishing gear and lamps lies with the boat owner. Boat owners are relatively financially sound (the investment in a boat and gear like nets is comparably substantial).[18] Nevertheless, we also encountered fishermen who stated that they would also buy the systems themselves. As a scoping estimate, assuming five fishermen per boat translates to 20,000 boat owners in this area, or an average lantern demand of approximately $1,000 per customer (5-6 lanterns).

Beach Managing Units (BMUs)

A further structure worth noting is the BMUs. At Lake Victoria in particular, the BMU network musters a high degree of organization. Beginning with the organization and representation of single fishing sites, the BMU network's hierarchy reaches to lake-wide and even national levels. At all levels, representatives of the main stakeholders can be found. This network represents an important piece in the distribution system (Ogwang *et al.,* 2009). The BMU network may also be valuable insofar as financing is concerned. In Tanzania, BMUs are less common at the Indian Ocean than at the inland lakes.

Theft

Like durability, theft has the potential to jeopardize the profitability of a new system. In our experience, theft may be a problem at Lake Victoria. In one of our last testing rounds, for instance, one of our systems was stolen while in use on the lake by a passing motorized vessel. Some of the fishermen we interviewed at Lake Victoria reported theft to occur occasionally within the fishing camps. At the Ocean, this was far less of a problem. At most landing sites, the fishermen employ security guards to watch their boats, engines, and gear.

Warranty Protection

Product warranties would reduce investment risks for the fishermen, boat owners and potential creditors. This would speed the process of building trust and willingness to experiment with the new technology. If a warranty is considered it must coincide with the implementation strategy such that the costs of compliance (e.g., transportation) are minimal for all parties. This is again only possible when using already existing and dependable trade channels. One risk of warranties is the solvency and reliability of the company behind them. In a startup environment such as this, buyers may understandably have low confidence in a warranty.

[18] The investment a boat-owner (at Lake Victoria) typically undertakes consists of a boat (between $600 and $1,000), a net and the necessary buoy and robes (~$600), four kerosene lanterns (~$125). At other locations such as the Ocean or Lake Tanganyika where they use much bigger boats, nets, more lanterns and even outboard engines (the commonly used Yamaha 40HP outboard engine costs used around $2,000 and new about $5,000). (This is also why the investment at the Ocean and Lake Tanganyika is sometimes shared by several investors.)

Independent Product Ratings and Truth-in-Advertising

No independent product testing or evaluation protocols exist for products intended for night fishing. Lighting Africa has launched a highly successful program for household lighting, but at present the procedure does not cover the use cases relevant to fishing. As in other domains, lighting buyers would benefit from independent quality control. Particular modifications to the current procedure would include waterproofness, more rigorous ruggedness testing, adequate light production for fishing, and adequate operating time per battery charge. Moreover, to be certified by Lighting Africa, products must offer a warranty.

Environmental and Health Considerations

Greenhouse Gas Emissions

We estimate the annual CO_2 emissions of the 110,000 pressurized kerosene lanterns in use at the locations we studied to be in on the order of 85,000 metric tons per year (Table 2). This is about 1.3% of the total CO_2 emissions from Tanzania in 2009[19], excluding the lifecycle emissions caused by the kerosene transport and the lanterns themselves. As noted above, while the lamp count is relatively low, the fuel-use rates and hours of operation are uncharacteristically high.

Kerosene Spillage

There are anecdotal reports that kerosene spills associated with night fishing occur and cause water pollution. We did not observe significant evidence of this. Nearly all kerosene tanks we tested seemed fairly impervious. Furthermore the fishermen also stated that they retire leaking lanterns since they don't work properly if the pressure is not maintained in the tank. Jostling of the lanterns in rough waters seems not to result in kerosene spillage. Nonetheless we observed the fishermen deliberately release some kerosene in the process of relighting their lanterns (each lantern twice per night) because this way they expunge water from the valves. Local researchers at TAFIRI (personal communication, Philemon Nsinda 2012) claimed to not be able to detect kerosene in the lake water.

Overfishing

Artisanal fisheries are generally considered to be highly sustainable, with dominant local consumption of the fish and the use of low-impact small-scale fishing vessels. However, the risk of overfishing in conjunction with any change in technology has to be considered--especially if such changes increase profits. The problem of overfishing takes different forms at the different locations.

At Lake Victoria where night fishing focuses on the Dagaa, overfishing does not seem to be an issue. The Dagaa biomass in the lake is estimated to exceed 1.3 million metric tons with an annual catch of 0.5 million tons (LVFO 2012a). Given the very fast growth and short lifecycle of the Dagaa, the LVFO suggests that it may be exploited sustainably at an annual level of 70% catch. Nsinda (2005) points to the unexploited offshore Dagaa stocks, where the current fishing methods do not reach, and thus recommends a technical advance in fishing techniques such as the ones employed at Lake Tanganyika in order to exploit these stocks.

According to O'Reilly *et al.,* (2003), progressive warming of lake waters has led to declines in the stocks of 30-50% of both Lake Tanganyika Dagaa and of Perch or Lates, over the last 60 years. Given this situation, Kimirei and Mgaya (2004) recommend resource management measures to avoid overfishing. Since there is little water circulation in the lake, only the water layers from the surface to 200 meters

[19] <http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crid=> United Nations Statistics Division; Refers to anthropogenic energy-derived emissions of carbon dioxide and excludes other greenhouse gases; land-use, land-use-change and forestry; and natural background flows of CO2

below the surface provide a viable habitat for the fish. The layers below 200 meters do not contain sufficient oxygen. Due to warming effects, those deep layers tend to ascend, thus diminishing the stock of the fish (Crowell 2007; Gibbon 1997). This pressure on the fish populations has also contributed to price increases noted earlier in this report.

At the Indian Ocean we did not encounter reports of overfishing of the species caught by night fishing. Importantly, as described in detail above, the LED lights tested did not result in increased fishing yields.

In any event, our results do not indicate any tendency for increased yields due to the use of more energy-efficient light sources. The issue should be revisited at each location.

Human Health Concerns

The use of kerosene lanterns creates various health risks (Mills 2012). At the Indian Ocean, fishermen on the small dinghies are most exposed[20] to the bright light of the kerosene lanterns (Figure 17). While fishing they frequently check the illuminated water below the kerosene lanterns for fish so that they can hail the larger ship that carries the net as soon as there are enough fish circling around the light, subsequently moving their gaze to very dark conditions. One interviewee stated that it takes several hours after each night of fishing before they regain their full eyesight. We were also told that many of the former small-boat crewmembers suffer from poor eyesight at greater age. This information, together with the greyish milky tinge we observed in many fishermen's eyes, suggests that they may experience cataract issues as a result of the extensive, intense and direct exposure to bright light.

Figure 17. Working in close proximity to very bright pressurized mantle lanterns

Although problems with eyesight were also repeatedly reported at Lake Tanganyika, it seems less a severe problem than at the Indian Ocean, perhaps because the observed fishing technique includes longer phases where the fishermen can avert their eyes from the light of the kerosene lanterns.

One would assume that air-quality concerns would be lower in this outdoor context than for indoor lighting applications. However, vertigo was often reported to us by the fishermen at the Ocean and Lake Tanganyika to be caused by the vapor of the kerosene lanterns. Secondary health considerations are, however, significant wherever kerosene is part of the local economy. These include explosions of lanterns when kerosene is adulterated with other fuels, fuel ingestion by children, structural fires, and burns (Mills 2012).

Other Studies

We identified six other pilot projects that were also concerned with replacing kerosene lanterns used by artisanal fishermen in developing countries (see Appendix B for details). The projects were conducted in Kenya, Sri Lanka, and Tanzania. Few of the studies published provide much hard data.

[20] Sitting in small dinghies for several hours nightly, these fishermen work in very close proximity to the lanterns.

Yafei Wang found that three of the Trony Sundial lamps (total of 261 lumens) were sufficient to replace one kerosene lantern at Lake Victoria. He also claims a linear relationship between light output and catch volume. Osram never collected hard data, recording only perceived satisfaction indicating that their 600-lumen CFL is sufficient to replace one kerosene lantern at Lake Victoria. Three of the studies were performed by or in cooperation with specific product manufacturers seeking to serve this market, and in those cases comparisons among multiple lamp types were not performed. The new lighting systems were based on LEDs or compact fluorescent lamps.

As in our research, some of these studies encountered problems with the quality and durability of proposed replacement products.

Conclusions

A significant market potential for the uptake of LED lighting products by night fishermen could justify tooling and marketing investment on the part of lighting manufacturers. We identified an existing annual expenditure of ~$70 million for fuel and lamps by fishermen at four sites (Lake Victoria, Lake Tanganikya, Zanzibar island, and the ocean coastline on Mainland Tanzania). The retail value of LED lighting systems that could replace these is $17 to 21 million, plus a $6 to 7 million per year ongoing annual replacement rate, with perhaps a potential market penetration of 25% in the near term.

While smaller in aggregate, the target audience is in many ways easier to reach than conventional household customers. They are more concentrated geographically (around lakes and shorelines), have exceptionally high baseline costs both for fuel and lamp purchase and maintenance, and the cost and handling of lighting is a much larger burden than in a household context (e.g., 35-50% of revenues for fishermen versus 1 to 5% of income in households).

The artisanal fishing industry also has existing structures for operations and distribution in place that would be readily adapted to creating a value chain necessary to deploy alternative lighting systems. Trade groups that coordinate commerce at the fishing areas could distribute lights and perhaps even provide credit-purchase mechanisms and/or centralized charging services.

The fishermen we interviewed were almost universally pleased with the concept behind the prototype lights, and eager to purchase them given the right price and performance. However, while the potential is substantial, none of the existing off-grid lighting products we tested were adequate for this use—although one was ultimately intended as such—but they could be improved obtain the durability and performance in harsh environments required for this market. Different fishing conditions such as calm/rough and clear/turbid water call for different designs and varying fishing techniques pose different constraints on factors such as weight. Independent testing and certification would help ensure product integrity and support consumer confidence as they adopt these new technologies.

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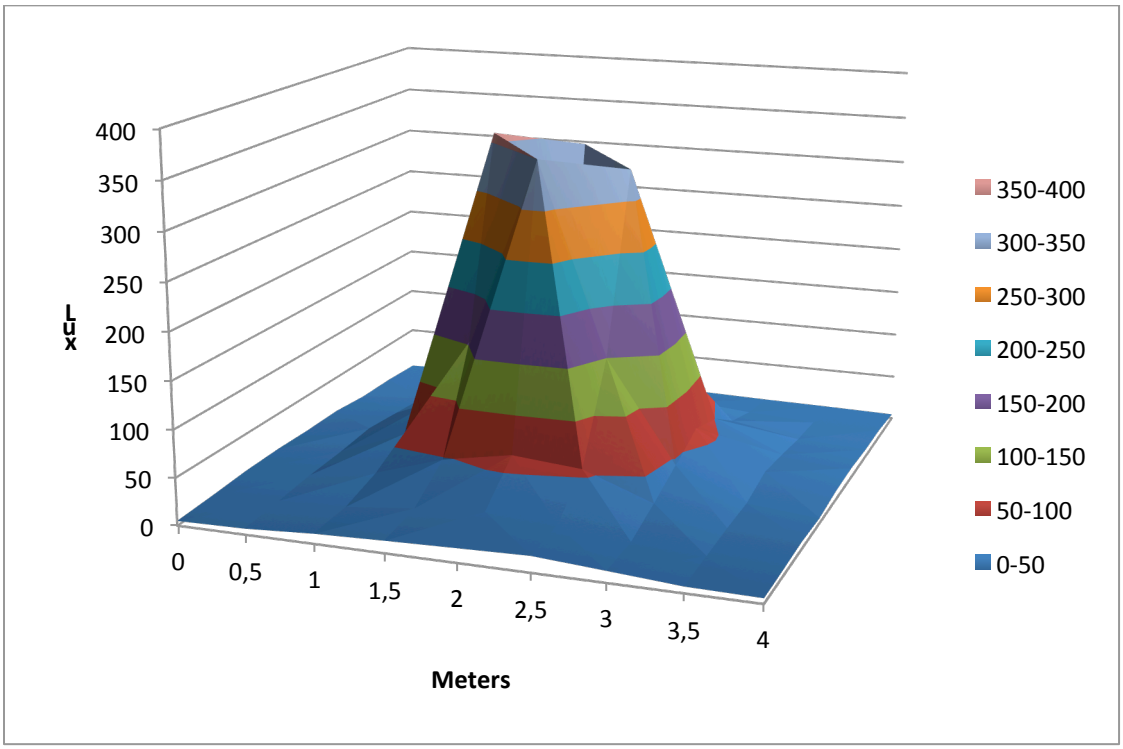
Appendix A: Illuminance distributions of the Systems Tested

This section provides detailed information about the illumination patterns of the systems tested.[21] For this purpose we used a 4 by 4 meter grid with spaces of 0.5 meters. Placing the lighting systems in the center of the grid, we measured the illuminance (lux) (using an Extech HD450 illuminance meter) of each system at 48 points. In interpreting the following graphs please note the changing vertical scales. Apparent asymmetries in the distribution patterns may have various causes including different mounting, individual differences among lamps of the same kind and perspective.

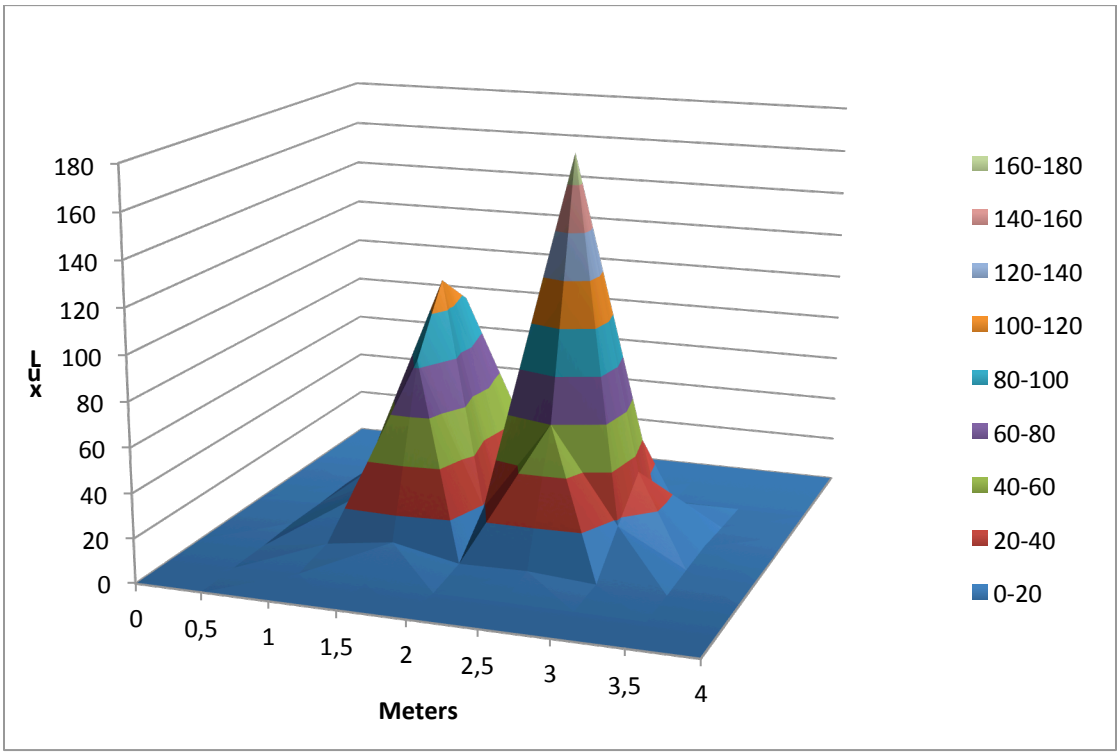
4 * 4 meters on-location grid for illumination measurements

[21] The information for configurations 13, 14 and 15 are not available. All used the Fishing Lights Etc. Aqua Star Super Brite 192. This lantern can only be used when submersed in water (otherwise overheating), which makes illumination testing insensible. Systems 9 to 12 were also submersible but relied on the Lumitronix Superflux LED Strips which can also be operated above water. The measurements were taken in air.

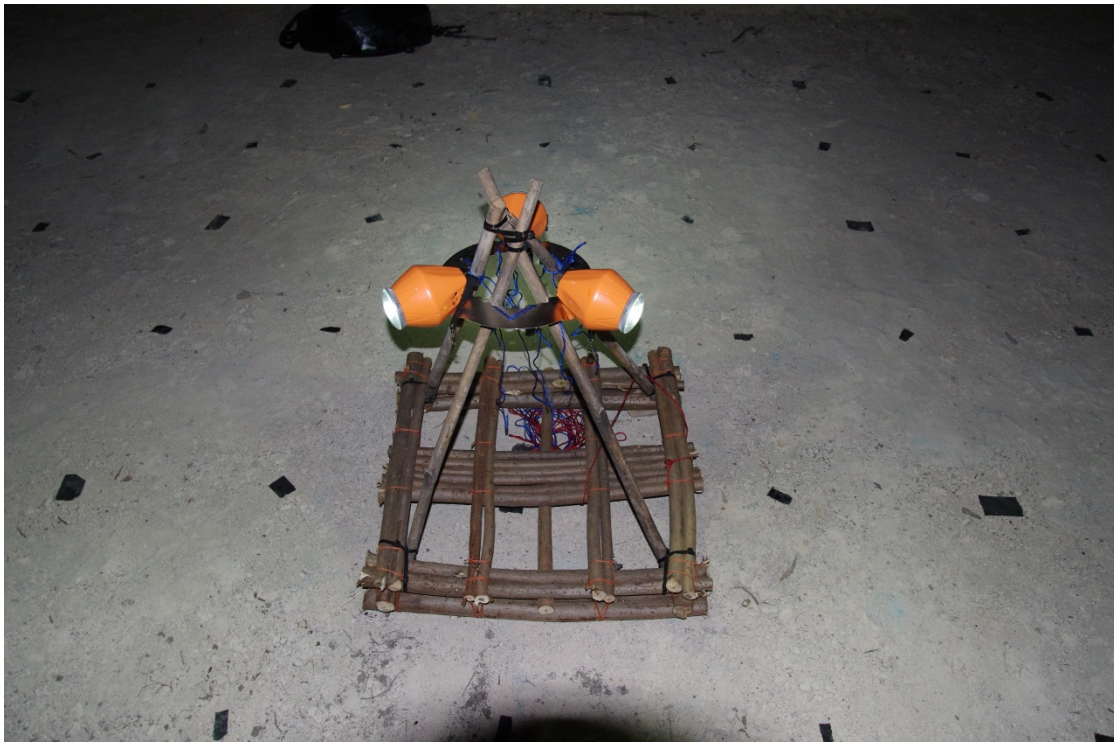
Reference System: Pressurized Kerosene Lantern

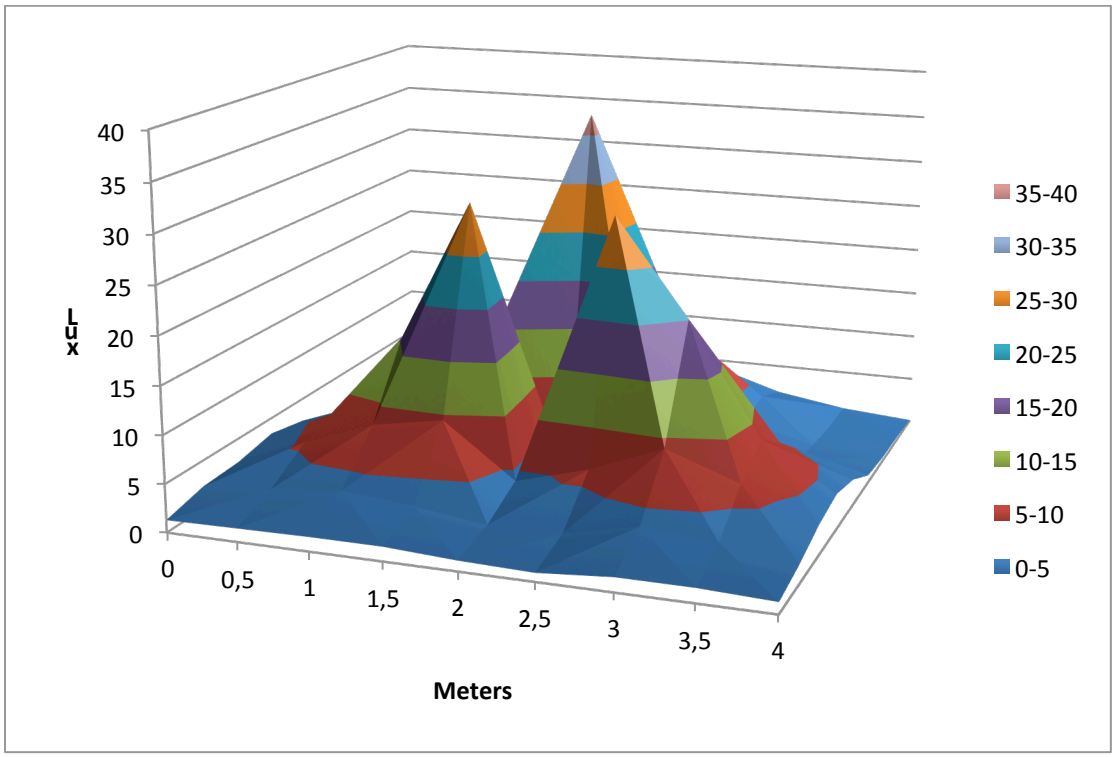


Configuration 1: PowaPack 5W

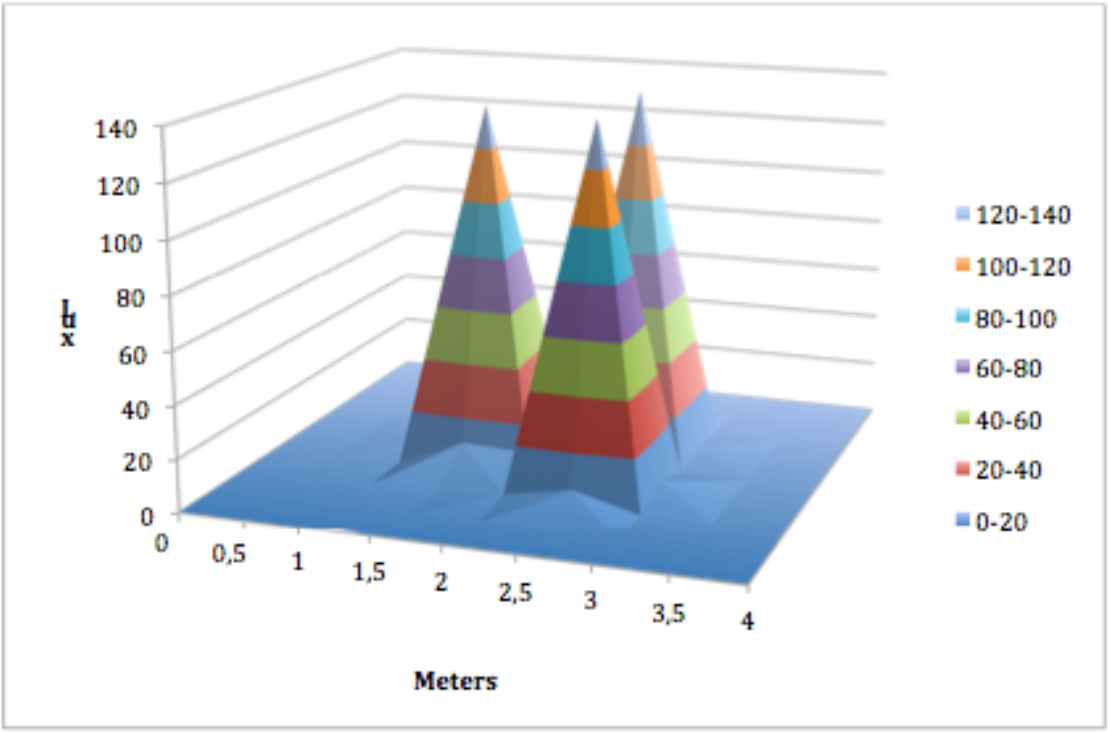

180
160
140
120
100
80
60
40
20
0
Lux
0
0,5
1
1,5
2
2,5
3
3,5
4
Meters
160-180
140-160
120-140
100-120
80-100
60-80
40-60
20-40
0-20

Configuration 2: Trony Standard Mounting

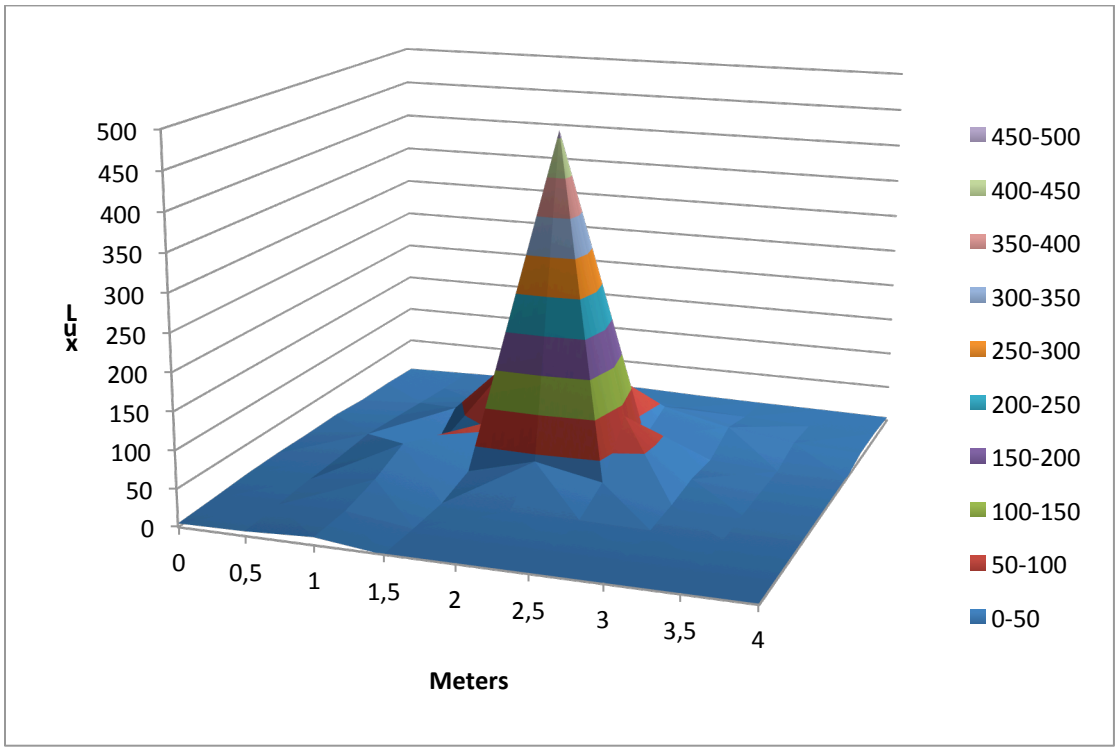




Configuration 3: Trony User Improved

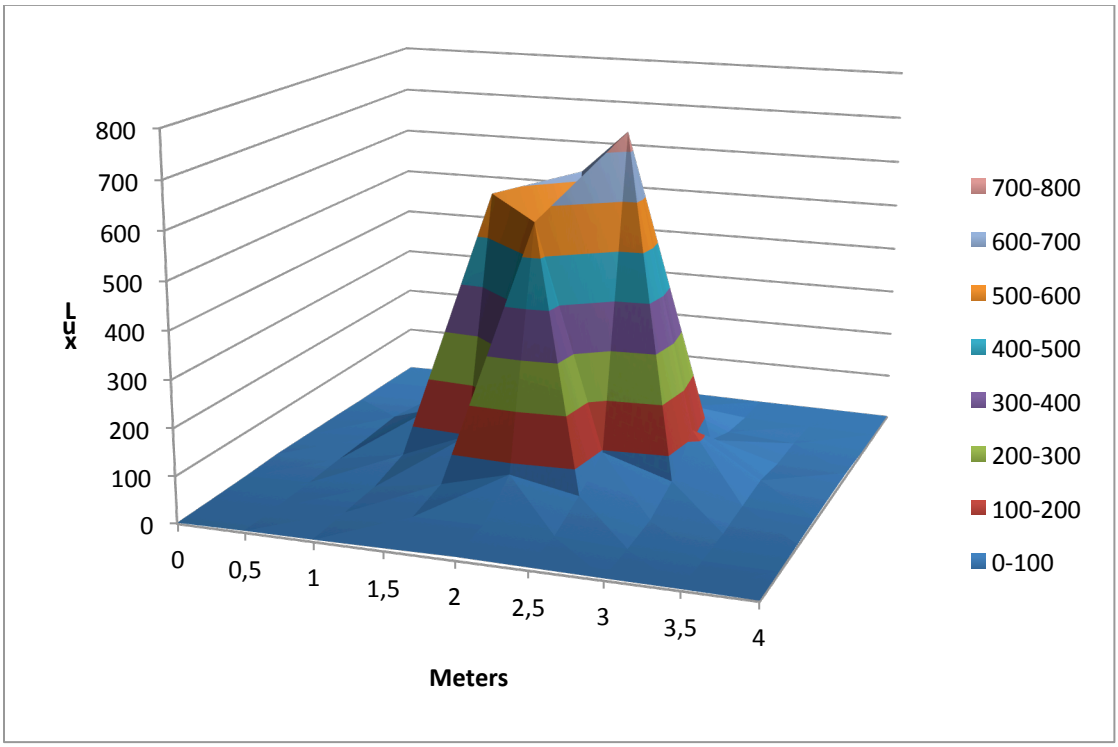


Configuration 4: Trony Ocean Setting[22]



Configuration 5: Lumintronix Superflux LED strips: 4 strings (white)

[22] No pictures of the Trony Mounting at the Ocean available. Instead of the kerosene lantern (on the picture) we used three Trony lamps which were tied to the plank to replace one kerosene lantern.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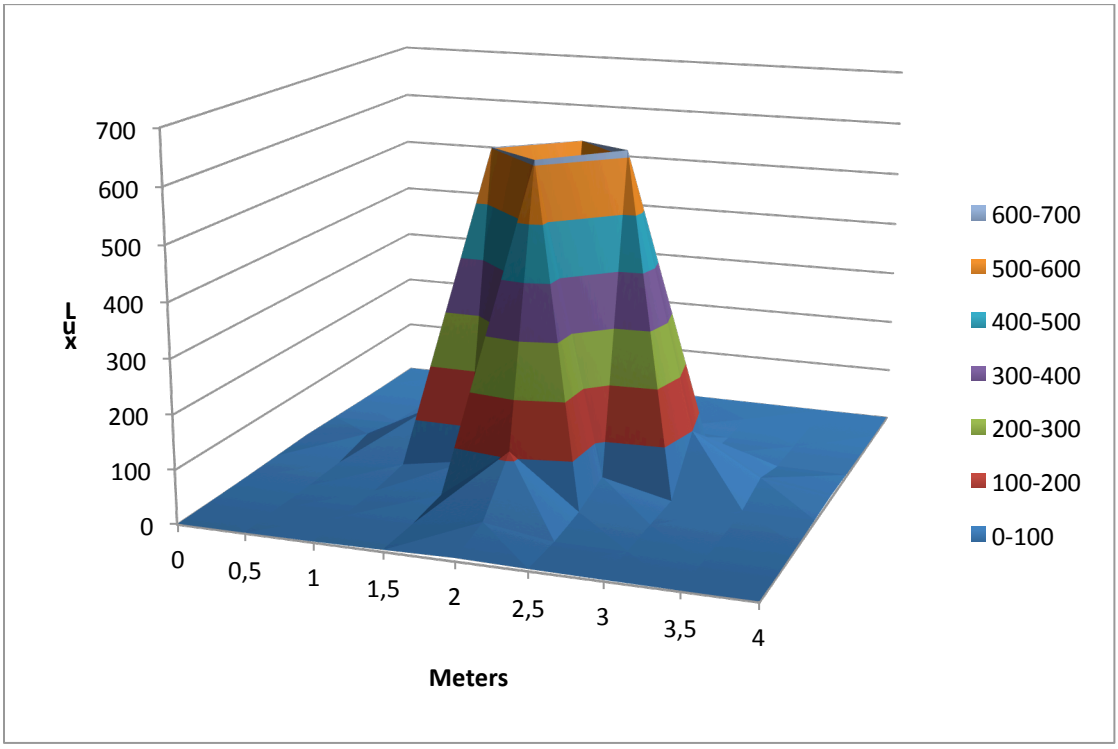
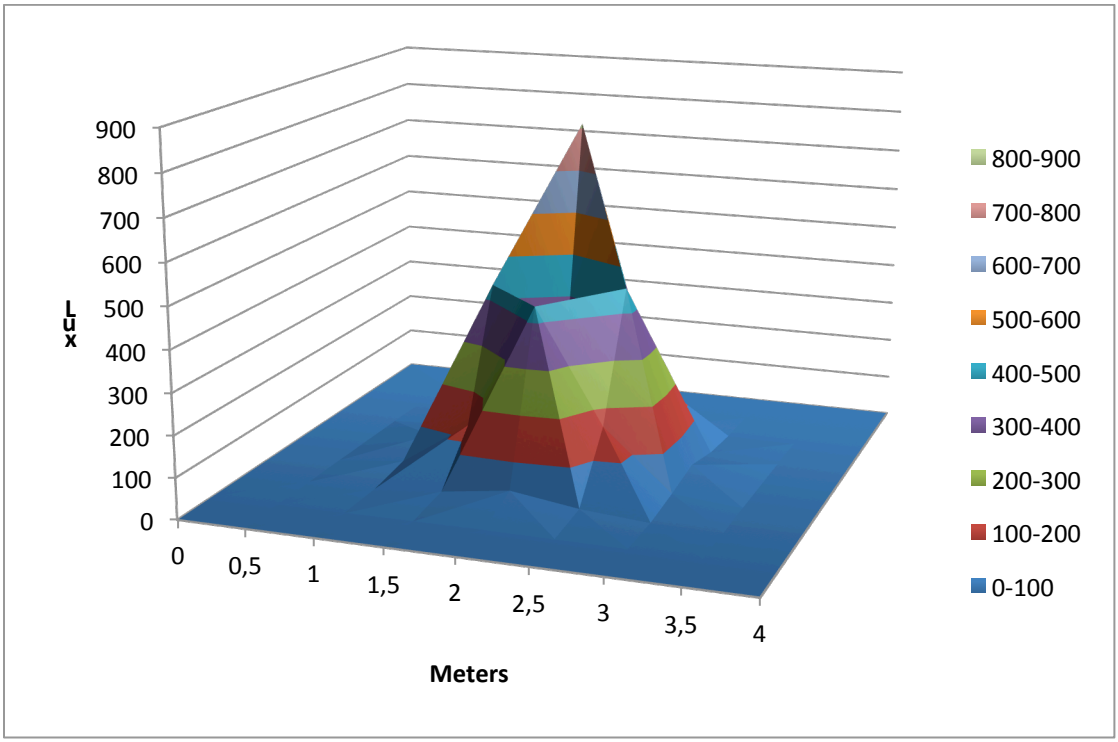
700
600
500
400
300
200
100
0
Lux
0
0,5
1
1,5
2
2,5
3
3,5
4
Meters
700-800
600-700
500-600
400-500
300-400
200-300
100-200
0-100

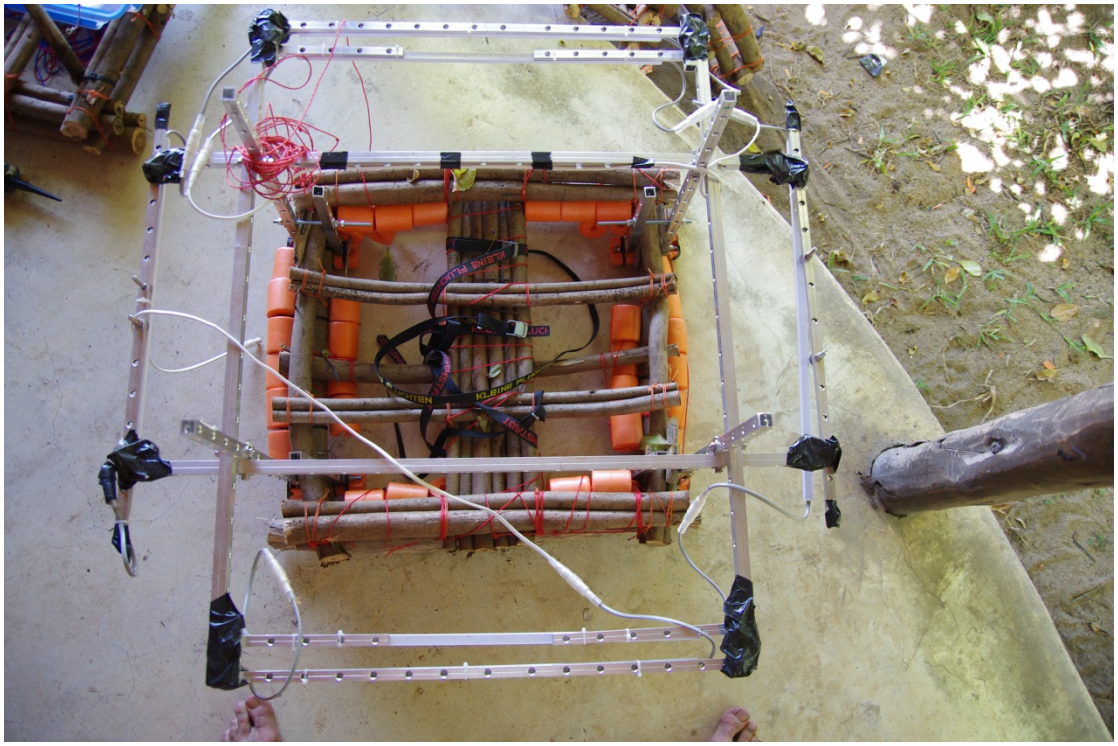
Configuration 6: Lumintronix Superflux LED strips: 4 strings, white, user-improved

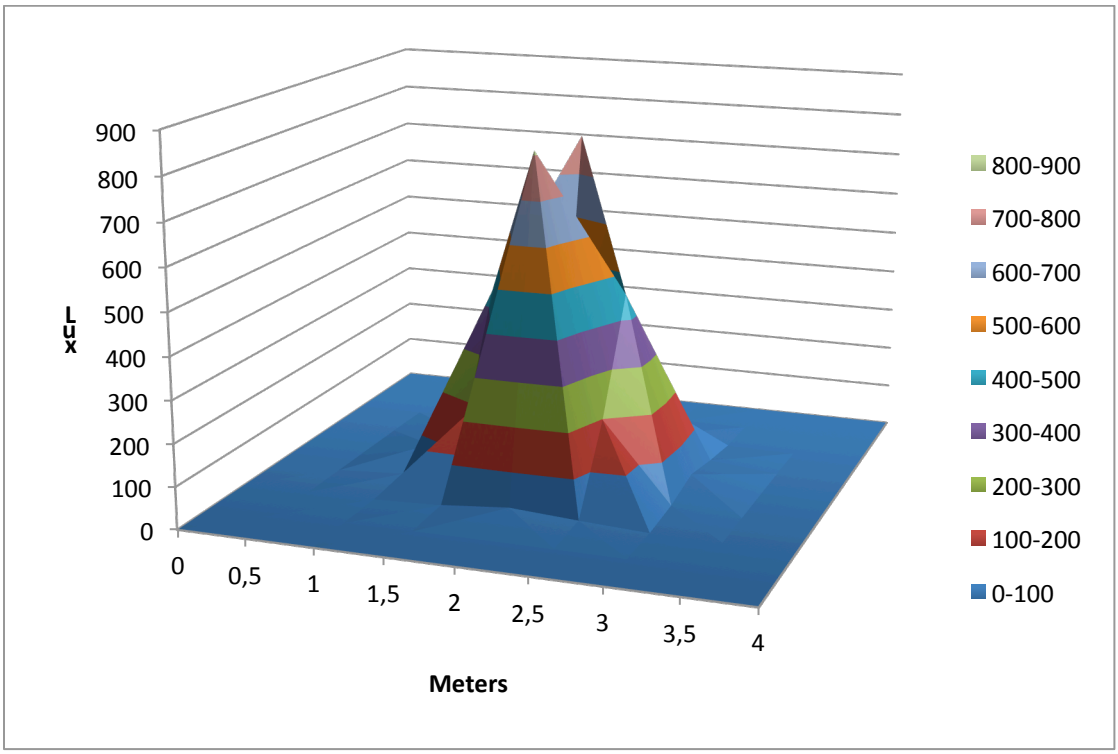


Configuration 7: Lumitronix Superflux LED strips: 5 strips (green)

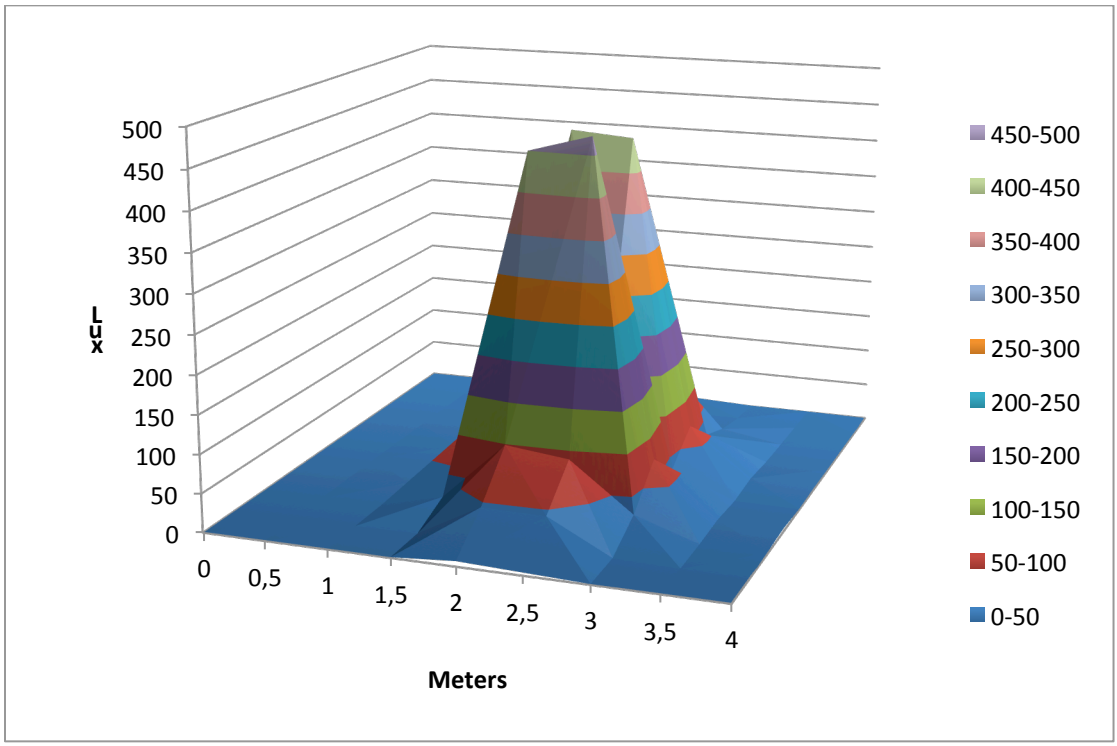


Configuration 8: Lumitronix Superflux LED strips: 6 strips (white)

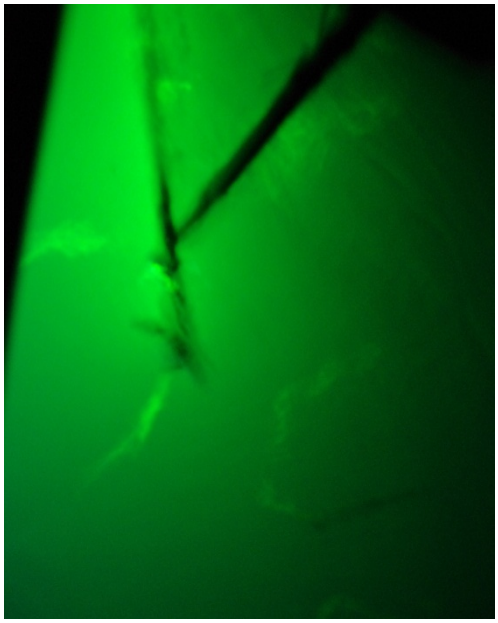




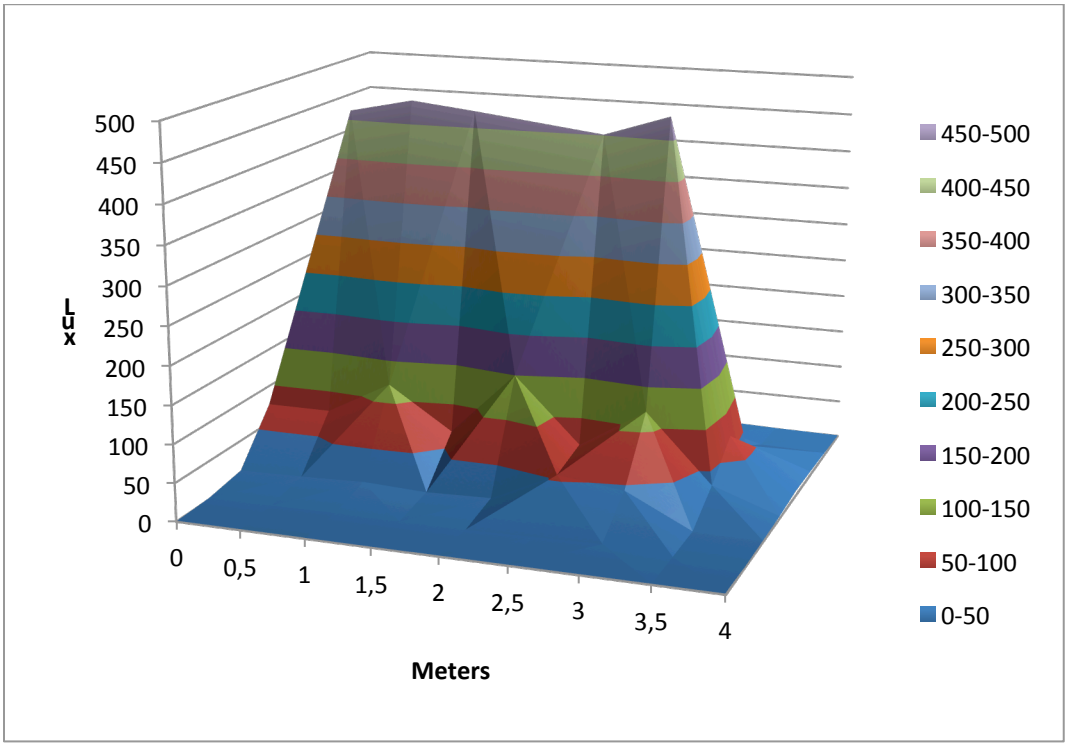
Configurations 9 and 10: Lumintronix Superflux LED strips: 2 white strips, 2 green strips, submersed



Configurations 11 and 12: Lumintronix Superflux LED strips: 3 white, 3 green, submersed for Ocean testing



The pictures show the LED strip design used for testing at the Ocean. The left pictures shows the wooden stick that was used to mount 3 LED Strips. The right picture shows the 3 green LED strips as they are used in replacement for 2 kerosene lanterns.


500
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Lux
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1
1,5
2
2,5
3
3,5
4
Meters
450-500
400-450
350-400
300-350
250-300
200-250
150-200
100-150
50-100
0-50

Appendix B. Previous pilot projects

We identified several other pilot projects that were also concerned with replacing kerosene lanterns of artisanal fishermen in developing countries.

Osram O-Hub

Organizations: OSRAM, the Global Nature Fund, Siemens Stiftung, the European Union, Light for Life and Thames Electricals[23]

Location: Lake Victoria, Suba District (Kenya)

Start: 2008

Technical Details: Batteries (LiFePO4 – 100Wh), Lamps: 11W, 12V – CFL (600 Lumen), 8 hrs runtime.[24]

Further Information: <http://www.osram.com/osram_com/sustainability/products/off-grid-lighting/we!-hub/index.jsp> (Accessed November 1, 2012)

A prominent approach to replacing the fishermen's kerosene lanterns with electrical lights is the Osram O-Hub project. It was launched in 2008 as a cooperation of six different organizations: *OSRAM, the Global Nature Fund, Siemens Stiftung, the European Union, Light for Life and Thames Electricals*.

Osram and its partners focused their efforts around the implementation of so called *O-Hubs*. These are battery charging stations which are mainly powered by PV solar panels.

Osram O-Hub in Suba District (Kenya)[Source: Osram]

There are currently three O-Hubs, all are located in the Suba district in Kenya. Each O-Hub can recharge up to 300 batteries per day. As a replacement system for the kerosene lanterns, Osram uses 11W CFL lamps (600 Lumen) powered by a rechargeable battery. Osram recently added UV water purification systems and cell-phone chargers to their O-Hubs.

[23] http://www.osram.com/osram_com/sustainability/products/off-grid-lighting/we!-hub/index.jsp
[24] http://www.osram.com/osram_com/sustainability/products/off-grid-lighting/products-for-off-grid-lighting/index.jsp

O-Lamp Basic and O-Box (Battery) [Source: Osram]

Osram works on a renting out business concept. In exchange for a deposit the O-lamp basic and the battery is rented out to the fishermen. To run it the fishermen have to travel to the next O-Hub station on a daily basis to change the discharged battery for a charged one.

It is notable that Osram claims to have identified 175,000 fishermen using pressurized kerosene lanterns for night fishing.[25] Our data based on official surveys by the LVFO (Lake Victoria Fisheries Organizations) found only about 33,000. Also their implementation model based on centralized power stations and the rental of lighting systems and batteries is contrary to what our research indicated as desired by end users. Reports about OSRAM's success vary.

Global Nature Fund Sri Lanka:

Organizations: Global Nature Fund, EMACE Foundation, Sri Lanka, Nagenahiru Foundation, Infineon, OSRAM, Wisons

Location: South-West Wetlands of Sri Lanka

Start: 2010

Technical Details: For Canoe Fishermen: CFL with 12V, 4-6Amp sealed lead acid battery

For Ja-Katu Systems: 6LEDs with 12V, 20Amp sealed lead acid battery

Further Information (all accessed November 1, 2012)

http://www.wisions.net/files/seps_project_descriptions/SEPS_Summary_EfficientLighting_SriLanka_SE124.pdf

<http://www.infineon.com/cms/en/corporate/press/news/releases/2010/INFIMM201006-056.html>

<http://www.globalnature.org/31740/PROJECTS/Terminated-Projects/Mangroves-Sri-Lanka/Workshop/02_vorlage.asp>

<http://www.nagenahiru.org/projects/renavable_energy.html>

<http://sundaytimes.lk/100725/Plus/plus_15.html>

[25] http://www.osram.com/osram_com/press/press-releases/_business_financial_press/2008/project-in-kenya/index.jsp (Accessed November 1, 2012)

The Global Nature Fund (GNF) targeted the use of kerosene lanterns in the South-Western wetlands of Sri Lanka. They identified that kerosene lanterns were used by canoe fishermen and for catching prawns with the Ja-Katu technique. The costs of the traditional kerosene lighting systems account to about 30% of their income. Per month they accumulate to €15/SLR2500 for each canoe fishermen and €50/SLR8200 for a Ja-Katu team of 7 to 8 fishermen. The seven kerosene lamps used for one Ja-Katu system have a fuel consumption per night in the range of 3.0 to 3.5 liters. This relatively low amount of fuel use may indicate that non-pressurized lanterns are used in this location.

"Supported by the LED Light for you (LLFY) partners OSRAM and Infineon, Diana Electronic has developed a robust, watertight, low-cost alternative to replace the fishermen's kerosene lamps."[26] The LEDs are amber-colored OSRAM LEDs of type Golden Dragon.[27]

LED System for Ja-Katu Prawn Fishing

(Source: NagenahiruFoundation)

CFL Lights for Canoe Fishermen

(Source: Sunday Times)

During the project, the GNF introduced 504 CFLs (powered by 12V, 4-6Amp sealed lead acid battery) for the canoe fishing and 50 LED systems (6LEDs powered by 12V, 20Amp sealed lead acid battery) to replace Ja-Katu systems that consist of 7 kerosene lights each. Also six service centers were set up to

[26] http://www.infineon.com/cms/en/corporate/press/news/releases/2010/INFIMM201006-056.html
[27] http://eetweb.com/news/Sri_Lankan_Fishermen81010/

ensure the sustainability. Solar-PV electricity generation was deemed not yet viable due to highly subsidized grid electricity in the area.

The GNF estimates the number of fishermen using kerosene lanterns to be about 85,000 in all water bodies of Sri Lanka. It is also noteworthy that the GNF also indicated the occurrence of kerosene spillage that contaminates both catch and water. This was not found during our research in Tanzania.

Catching Prawns with Ja-Katu Technique

TASEA

Organizations: TASEA (Tanzania Solar Energy Association), Zara Solar Ltd.,

Location: Lake Victoria, Mwanza Area (Tanzania)

Start: 2008

Technical Details: CFL (18W) and sealed lead acid battery (12V; 24Ah)

Further Information: TASEA

In 2008 the TASEA Mwanza Branch investigated in cooperation with Mohammed Parpia from Zara Solar Ltd. (one of the major PV-Solar Distributers in Tanzania) the feasibility of replacing the fishermen's kerosene lanterns with locally available products.

Tests were conducted using a Sundaya Multilamp CFLs (rated at 1000 Lumen) and sealed lead acid battery (12V; 24Ah). Although TASEA reported satisfactory initial feedback by the fishermen, no attempts to implement the system were undertaken. TASEA pointed to significant durability issues. The batteries started to fail after 6 months of field tries and the lights showed problems with the waterproofness. Also, they assessed the total costs of a system to be too high. This is not surprising given the lower efficacy and poorer durability of fluorescent systems compared to LEDs.

Trony

Organizations: Trony Solar Holdings Co. Ltd., Yafei Wang

Location: Lake Victoria

Start: 2011

Technical Details: LED (87 lumens, white) and internal Battery (rechargeable $LiFePO_4$)

Further Information: trony.com

Trony Solar Holdings Co. Ltd. investigated in cooperation with Yafei Wang the potential application of their TSL01 to night fishing. They modified the TSL01 with respect to LED-type, battery capacity, and housing. The project was halted in 2012 due to durability issues that could not be resolved economically.

In the course of testing, Yafei Wang collected some interesting data. Unlike our data his tests imply that 3 Trony lamps (total of 261 lumens) generate a similar catch volume as one kerosene lantern. He also claims a linear relationship between light output and catch volume.

MCA-T project at Lake Tanganyika

Organizations: MCA-T (Millenium Challenge Account) and Sustainable Power Solutions Ltd.

Location: Lake Tanganyika

Start: 2012

Technical Details: various LED systems powered by 110Ah Lead Acid Batteries

Further Information: <http://www.mca-t.go.tz/en/about-us-v15-70/vision/projects-v15-96/the-energy-sector/activities.html> (Accessed November 1, 2012)

As part of a general MCA-T project to improve electrification in the Kigoma region (the north western part of Lake Tanganyika) the project investigated the use of electrical lights for night fishing. They conducted some primary testing with various LED lights of green and white color, submersed versus above-water designs, and varying illumination distribution patterns.

UC Berkeley – Lumina Project at Kutch, India

Organizations: UC Berkeley Students & Lumina Project

Location:Kutch, Gujurat, India (villages of Sudhamavaas and Paiya)

Start: 2007

Technical Details: various LED systems powered

Further Information: < http://luminanet.org/xn/detail/6566781:Comment:434> (Accessed November 1, 2012)

A submersible LED fishing light was designed but not tested. Focus was primarily on on-shore uses of light by fishing communities, including fish processing. Extensive focus group discussions were convened and a variety of candidate LED products were tested.