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Solar-LED alternatives to fuel-based Lighting for night fishing

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ABSTRACT

Many of the 12 to 33 million artisanal ("small scale") fishers in the developing world work at night using energy-intensive kerosene lanterns to attract fish to their nets. In Tanzania—where 100,000 such fishers operate, spending US$70 million per year on lighting—we identified current practices and conducted user-centered field tests of LED-based system usability, performance and energy savings potential, and estimated the market size for today's fuel-based lighting. Fishers in the areas we studied spend 35% to 50% of their take-home pay on lighting equipment and fuel. Due to the combination of higher intensity pressurized lanterns, and longer operating hours, Tanzanian fishers use as much lighting fuel as would about 1 million ordinary household lanterns. We found that similar catches could be obtained with battery-powered LED lighting systems, with a simple payback time for the LED system investment of three to four months. The fishers we interviewed were almost universally pleased with the concept behind the lights used in the field tests, and eager to purchase them provided the right price and performance. However none of the LED systems we tested were adequate for this use. Essential product modifications include improved durability and performance in harsh fishing environments. Independent testing and certification would encourage product quality and support consumer confidence as they adopt these highly beneficial new technologies. Our results provide a roadmap for product manufacturers and others interested in deployment, with an overnight-conversion market size of US$17 to US$21 million in Tanzania alone, plus US$6 to US$7 million per year in ongoing replacement expenditures. This potential could well justify retooling and marketing investment on the part of lighting manufacturers.

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Introduction

Fuel-based lighting is pervasive in the developing world (Mills, 2005), and alternatives have been noted since the early 1990s (Dutt and Mills, 1994). Most efforts to understand the current conditions and potential for these 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 fishers 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 l of fuel per night of fishing (and in rare cases up to 3 l 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 carbon dioxide (CO_2) to the atmosphere and a variety of health risks (Mills, 2012).

The aim of the research described in this article 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 fishers 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

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improved or otherwise varied and retested. To gain insight into the broader socioeconomic and market factors potentially impacting the uptake of alternatives, the team conducted extensive interviews with boat owners, fish traders, local experts and institutions.

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

Light and fish

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 fishers to seine (net) around them. There are different interpretations of and explanations for this behavior (Ben-Yami, 1976). The most common one is feeding. One relevant process is that zooplankton move toward light, followed by the fish.

Within East Africa, where our project took place, the main species sought by local fishers 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 toward 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 fishers 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, and 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 commercial fisheries. The use of kerosene lanterns for fish attraction, prevalent in small-scale[1] artisanal fishing in developing countries—the focus of this article—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.

Hence, artisanal night fishers 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 (Fig. 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 (Johnson, 2005). One estimate identifies more than 12 million artisanal fishers 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 fishers, of which 95% live in developing countries (Decoster and Garces, 2007), and a third places the number of fishers (those employed as fishers 30% of their time or more) at 33 million in the developing world alone (Mills et al., 2011). It is not known what fraction of the total is represented by artisanal *night* fishers who use fuel-based lighting to attract fish.

Other authors have identified kerosene-based light attraction techniques throughout the developing world, including elsewhere in Africa [Ghana (Bannerman and Quartey, 2004), Nigeria], Asia [India (Achari et al., 1998; Apte et al., 2007), Philippines, Sri Lanka (GNF, no date)], Indonesia (Van Oostenbrugge et al., 2001), Oceania [Polynesia, Micronesia, and Kiribati (Dalzell, 1992); and Papua New Guinea (Sullivan et al., 2004)], and South America [Brazil (Martins and Perez, 2006)].

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, and 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 on the problem of fuel-based lighting for night fishing in the developing world. A small number of lighting manufacturers have promoted systems based on electrical light for replacing kerosene in fishing applications, and a handful of pilot studies have been conducted, few of which published much hard data (Gengnagal et al., 2013).

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 and 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 *sardinella*, *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 fishers—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*, and in some cases Lates, are caught by light attraction.

[1] The FAO seems to equate small-scale with artisanal fisheries, a convention we follow for this article. 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.

Fig. 1. Artisanal fishing camp, Lake Victoria.

We initially utilized interviews and literature to study markets in four locations and practices for night fishing in Tanzania, and subsequently worked with local fishers to conduct actual tests of various lighting strategies. We interviewed 113 individuals in 21 interviews during the period March 6 to March 21, 2012. These focused on fishers who use the lamps, and other important players in the value chain.

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

During a typical fishing night, the crew spends 8 to 12 h 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. Based on our interviews, crew members tend to earn between US$70 and US$200 per month, while boat owners earn between US$250 and US$800 per month. Income is highly variable depending on fishing conditions.

Boat owners vary with respect to status and income. Some own just one boat, others run an enterprise with several boats.

Most fish traders operate within a union or business cooperative.

There are important differences between the freshwater and saltwater fishing areas. At Lake Victoria and Lake Tanganyika the night fishers 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 et al., 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).

Lake Victoria

With an area of 68,800 km^2, Lake Victoria is the world's third largest—and Africa's largest—lake, with a shoreline of 3440 km. Night fishing was first introduced there in the late 1960s (Gibbon, 1997), and the fishing technique differs significantly from other locations in the region.

At Lake Victoria, the fishers use rather small boats (*Canoe-style*) – about 4 m long and 1.5 m wide – usually in crews of four. Most boats are rowed. The kerosene lanterns are tied to small wooden floats (60 cm by 60 cm), 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 m to 200 m intervals, and anchored to the ground using rocks.

When the fish have gathered around the lights, the fishers row around one float at a time, releasing the net such that it forms a circle with a diameter of about 30 m, 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 (Fig. 2). The fishers 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.

Lake Victoria hosts Africa's largest inland fishery, with about 175,000 fishers working full-time around the lake. Of these, 31,891 fishers with 8272 vessels are employed in night fishing (Legros and Luomba, 2011) for *Dagaa*. The importance of *Dagaa* for local food supply and economic development is increasingly recognized (Legros and Luomba, 2011).

Lake Tanganyika

Lake Tanganyika is the second largest lake in Africa and one of the world's deepest, with a surface area of 32,900 km^2 and a shoreline of 1828 km. At Lake Tanganyika, lift-net fishing using a catamaran of two slim vessels is the technique most frequently employed. The fishers 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 fishers – 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 l per night) than the usual pressurized kerosene lanterns. A number of fishers asserted that the additional light output does not compensate for the higher fuel consumption in terms of

Fig. 2. Fishing technique at Lake Victoria.

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 10 m long – wait for about three hours about 50 to 100 m apart before they approach to 20 m and connect with two long wooden sticks. They then let a net down to about 100 m. The net itself measures 300 m by 50 m. 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 fishers 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.

Estimates suggest that there are 304 vessels in the Kigoma urban area and 4100 vessels, with perhaps 25,000 fishers 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 fishers 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.

A local expert (personal communication, Kazumbe, 2012) suggested that the total number of vessels on the lake is roughly 8000.

Indian Ocean

The team visited Stone Town, Zanzibar and Pangani on the Tanzania mainland coast. The Tanzania mainland fishing zone is 1450 km long and the Exclusive Economic Zone has an area of 223,000 km^2. Fish diversity, especially in Zanzibar, is great.

We encountered a variety of techniques at different ocean fishing sites. The most common seems to be to use a fairly large boat (8 m), called simply *Boat* or *Boti* by the fishers, equipped with two small *Dinghies*. The large boat has an engine and carries a large net, a purse seine, about 120 m wide, and 26 m deep. About 15–17 fishers 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 fishers. 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. Another method, which we also observed several times, is the use of a medium size boat, equipped with three to six kerosene lanterns, which attract fish. The large boat goes around it (much like with the dinghies) (Fig. 3). 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 fishers 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. In this way, they draw the fish particularly close, just before laying out the net.

We estimate that there should be around 600 night fishing vessels in Zanzibar and another 600 at the Tanzanian mainland coast (Jiddawi and Khatib, 2007; Sobo, 2001). The number of fishers 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 and Khatib, 2007).

Baseline energy Use and the potential for LED lighting systems

Our field measurements indicated that most night fishers utilize between 1 and 2 l of kerosene each night, per lantern, with a likely average value of 1.25 l.[2] 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 approximately 110,000 lanterns used on the 17,000 boats in the lakes and coastal areas that we studied

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

Fig. 3. Fishing technique at Indian Ocean.

thus utilize about 33 million l of kerosene each year, or a US$47 million annual expenditure assuming local fuel prices, and another US $20 million for lantern maintenance and replacement. Thus, there is a substantial lighting market already in place, spending on the order of US$70 million per year for equipment and fuel (Table 1).[3]

The energy use associated with night fishing in these areas corresponds to greenhouse gas emissions of ~85,000 metric tons of CO_2 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. It is clear that more energy-efficient alternatives to pressurized kerosene lanterns could significantly improve the fishers' economic situation, lower health risks, and 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.

The operational cost of a single kerosene lantern is about US$50 per month (typically divided equally between the boat owner and crew). Of this about a third is spent on lantern maintenance and periodic replacements, and the balance on fuel. The pressurized lanterns initial cost is approximately US$35–US$55 (average around US$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 fishers 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.[4] (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 US$7.30 and thus increase the fishers' profit by 30% to 40%. This equates to a simple payback time of only 3 months. McHenry et al. (2014) estimate that the lifecycle cost of a Solar-LED fishing light is one-tenth that of the baseline kerosene strategy, and one-fifth that of a Solar-fluorescent approach.

Considering the efficiency of kerosene alone we estimate the average catch volume per liter of kerosene to be about 50 kg of (wet) *Dagaa* resulting in gross revenue (before lighting costs) of US$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 fishers 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 fishers' 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, fishers immediately wanted to buy the gear we were using for field tests, undaunted by the high prices, even at a hypothetical price point of US$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, this price 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 2). The total costs to this fishing population of running their kerosene lanterns are thus between US$59 and US$74 million per year. For our market volume estimations, we use an estimated retail price of US$175 for LED systems to replace each kerosene lantern, including the charging/storage infrastructure supporting it, which seems by far more realistic than the US$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 US$17 to US$21 million and an annual replacement sales volume[5] of US$6 to US$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 fishers. The baseline energy use, potential savings, and additional revenue potential for these additional applications are not estimated here.

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 US$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.

The medium-term feasible sales volume we thus estimate to be about US$4 to US$5 million for initial market penetration, and US$1 to US$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 33 million artisanal fishers in the developing world. Assuming, for illustration purposes only, that 10% conduct night fishing using one

[3] Includes shorelines of entire lakes and the Tanzania ocean coast plus Zanzibar. Assumes 20 nights per month of night fishing, 1.25 l kerosene per lantern per night, US $1.40 (2250 TSH) per liter fuel price, and 2.55 $kgCO_2$/l kerosene emissions factor. Does not include the uses of lanterns at home, for net handling within the boats, or for work on shore.

[4] 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.

[5] 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.

Table 1
Summary of interviews; fisher populations; energy use, expenditures and emissions.

	Lake Victoria	Lake Tanganyika	Ocean-Zanzibar	Ocean-Mainland	Total
Interviews					
Fishermen	35	22	16	21	94
Captains*	–	–	2	1	3
Boat owners	5	–	1	–	6
Traders	4	–	–	–	4
Local experts	1	3	1	1	6
Total	45	25	20	23	113
User population					
Number of boats	8272	8000	600	600	17,472
Lanterns per boat	4	7–10	8	8	
Energy use and expenditures					
Kerosene use (M liters/year)	10	20	1	1	33
Kerosene cost ($M/year)	14	29	2	2	46
Maintenance cost ($M/year)	6	12	1	1	20
Total lamp operating costs ($M/year)	20	41	3	3	66
Emissions					
CO2 emissions (metric tonnes/y)	25,312	52,020	3672	3672	84,676

* Average value for Lake Tanganyika.

lantern per four fishers, there would be 300,000 to 825,000 lanterns with an overnight replacement value of ~US$50 to US$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 fishers over a period of several weeks, we field-tested six commercially available off-grid lighting devices, arranged in 15 lighting configurations (Fig. 4). Several of the initial designs were improved in the field according to the fishers' suggestions and preferences. In particular, we used off-the-shelf products Barefoot PowaPack 5 W, with a total of 190 lumens (lm) and the Trony Sundial with a total of 261 lm per system, both of which come with their own matched battery. We further used Lumitronix waterproof Superflux LED strips in white, producing 170 lm, and in green, producing 180 lm each (peak wavelength 523 nm), and the Fishing Lights Etc. Aqua Star Super Brite 192, producing 1000 lm of white light. These latter two systems were powered with a 12 V lead acid dry battery. We also built a prototype relying on two 100-lumen headlamps, with a very focused beam, which we faced directly toward the surface of the water. The team waterproofed the equipment, where necessary.

We also offered the fishers small ‘reading-style’ LED systems (such as the Barefoot Firefly) for on-board lighting needs. Although the fishers were highly impressed and very interested in them for their homes, they expressed no interest in on-board usage. At Lake Victoria the fishers 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. We ultimately abandoned the aluminum construction in favor of easier handling characteristics indicated by the fishers after using the prototypes.

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

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

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 lm: 540 lm for the green strings and 510 lm 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

Table 2
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	4800	4800	110,688
Feasible percentage	30%	15%	50%	80%	24%
Feasibly replaceable	9926	10,200	2400	3840	26,366

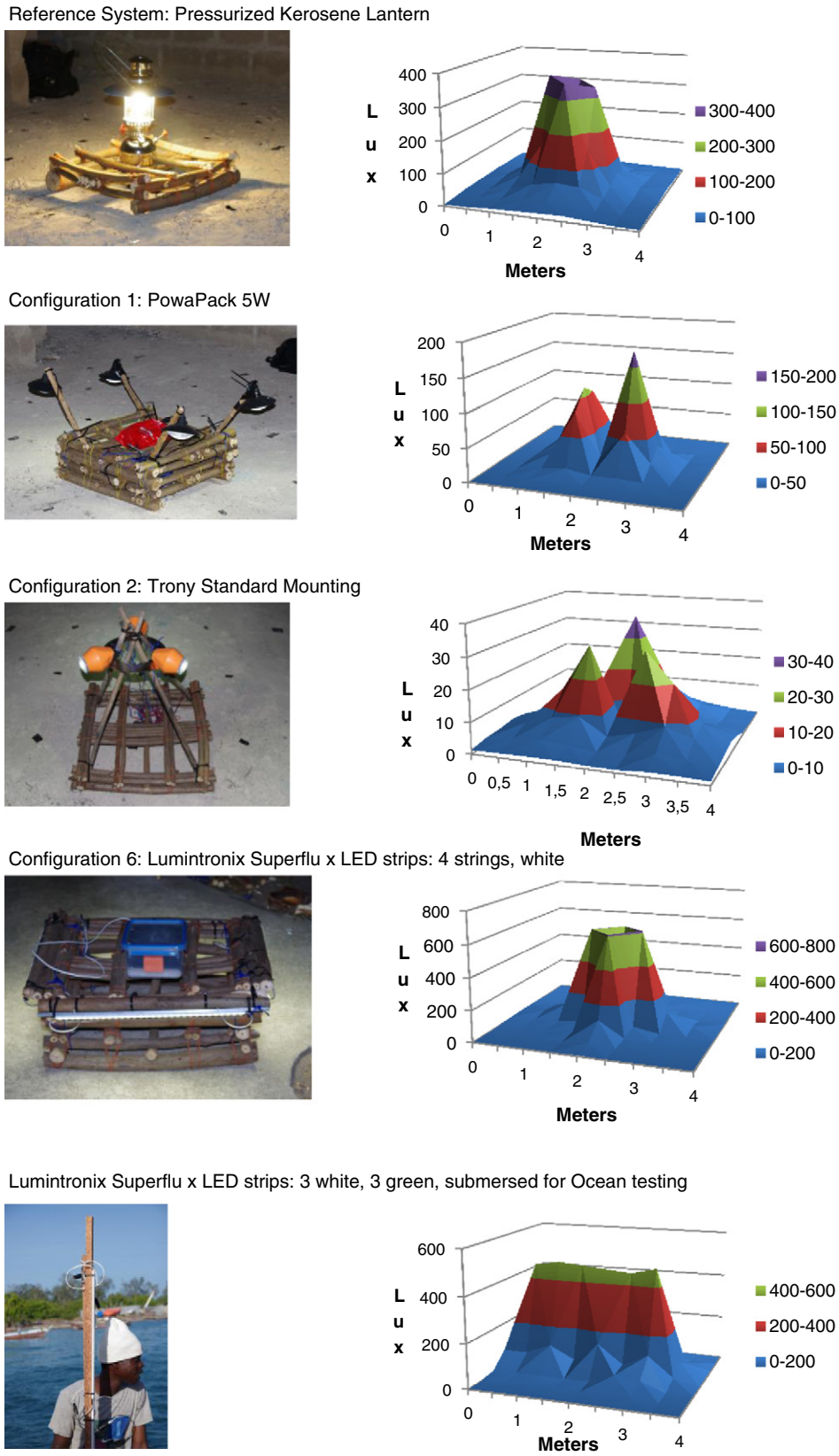

Fig. 4. Selected examples of devices tested, with photometrics showing light-distribution geometry.

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.

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 lm or 261 lm per replacement unit. The remaining two kerosene lanterns were used in the normal fashion so that the dinghy was equipped with 2 × 3 Sundials and two kerosene lanterns, jointly attracting the fish.

We also tested the submersible light, powered by a standard 12 V lead acid dry battery. The fishers tested it in the following manner: they first let it down fairly deep (around 5 m) 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 seven-night period. The fishers 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 the local metric of *tins* as units of catch measurement. Tins are a common unit for selling *Dagaa*, with a volume of approximately 3 l and weight of 3 kg 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 m and 30 to 45 min between each catch, with one kerosene lantern's catch measured for each fishing round, together with the catch for every LED system used.

We spent two testing nights with the fishers in their boat on Lake Victoria and trained them on the data-collection protocol. During two further nights we visited them on the lake during the fishing process with a separate boat. At the Indian Ocean we were able to improvise and test three different systems on two nights, one of which we spent with the fishers on the boat. For our conclusions we rely on the fishers' 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 fishers land very large quantities of fish (on the order of 200–700 kg wet weight).

Results

The normalized catch volumes landed by local fishers during our field trials are expressed as a ratio of catch volume with the LEDs to that with the reference kerosene lanterns (Fig. 5). A value of 1.0 or above thus indicates that the LED system performed equal or better than the kerosene lantern.

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 the 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.

Where the Relative Catch ratio is 0.9 (10% under-catch), the hypothetical cost of lost fish is $1275 per year, which might be compared to savings of $2325 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, fishers 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.

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.

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 Fig. 5). Causes range from weather conditions, water temperatures, turbidity, and lunar cycle.

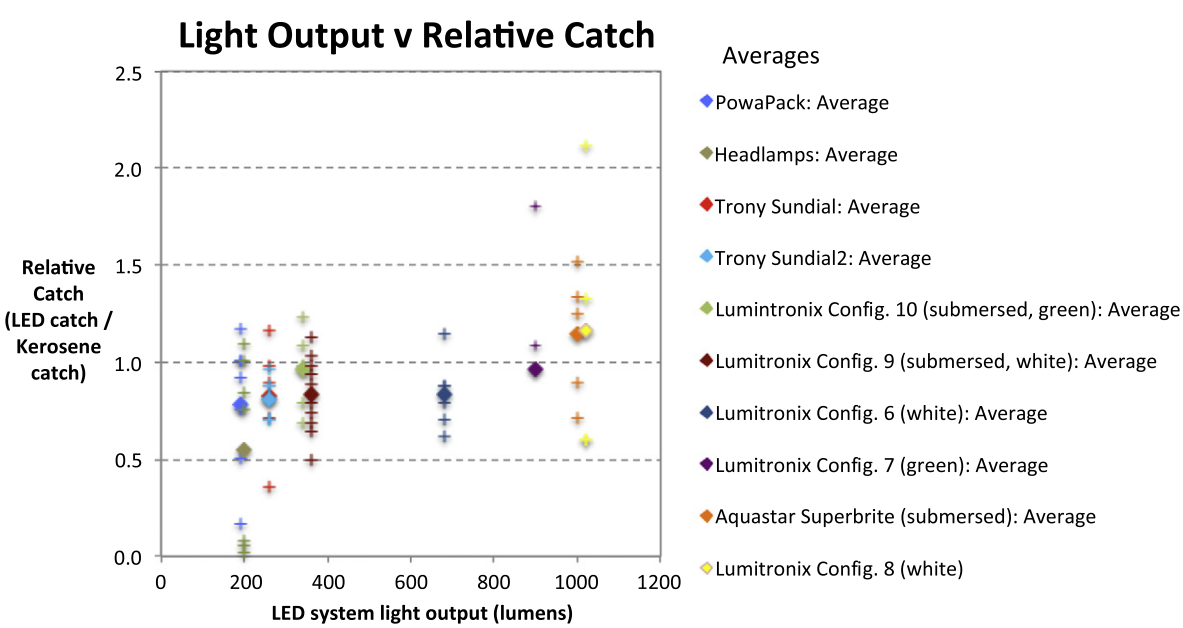

Fig. 5. Light output versus catch volume at Lake Victoria: All Systems. *Relative catch is the ratio of catch volume with LED to that with kerosene lighting. The figure shows mean values (diamonds) for each system and their individual scatter (crosses). This plot includes all trials, locations, and lighting system types (above-water and submerged). Note poor performance of headlamps.

Many of the LED systems were found to catch somewhat less fish per unit of illumination (but provided more higher illuminance) than the kerosene lanterns. However, this was not matched by the fishers' subjective positive perception of the systems' performance.

Over the course of the testing period the fishers 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 at Lake Victoria the fishers caught 20% less, with respect to the reference system, than with the user-improved version. At the other locations, lights were affixed to the boats, alleviating this concern.

To isolate the role of light output on catch volume from other factors, we exclude the submersible systems and the headlamp system.[6] Variations in catch as a function of LED system light output for each trial at Lake Victoria are shown in Fig. 6. 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.

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.

Findings relevant to product design

While we observed considerable demand for improved lighting from fishers who experimented with the LED test systems, we did not identify any off-grid LED products that are suitable as-is for this market segment. 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. Addressing consumer preferences, perceptions, and knowledge is particularly important.

While there is no single solution for all fishing circumstances, the fishers at all field locations 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 fishers also desire the ability to use the lamps at home when not fishing.

- 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. At Lake Victoria a light output of around 300 lm will be necessary to replace one pressure lantern, while at the ocean and at Lake Tanganyika 200–250 lm would suffice. For comparison, a non-directional pressurized kerosene lantern emits approximately 1000 lm. Turbid conditions appear to call for approximately 25% more luminance.
- Durability may be the single-most important characteristic for a successful product. Although our testing lasted for only a short time period, we experienced major durability issues with nearly all systems.
- Due to long operating hours the batteries are required to have a relatively high capacity and should last for many charging cycles. The fishers use the lights for 6 to 11 h per night, about 20 days per month. Battery weight must be limited for systems mounted to floats.
- Nearly all fishers we interviewed (even in areas with access to the grid) expressed the preference for a PV-powered solution. Fishing is especially favorable during the rainy season, a period with less intense solar radiation. In some areas, fishers may even stay out more than one day.
- To have a small and light battery inside the lamp is favorable to external location 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.
- Dimmability 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.
- We found that different colors (white versus green) are desired in different circumstances. Shrimp fishers in Sri Lanka report requiring yellow or orange light (Rodrigo, 2010). Red should be tested in the future.
- We observed meaningful improvements in catch volume when using submersed lights at the Ocean clear freshwater conditions. 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 to observe the fish and decide when to place nets. Reliance on water-cooling for submersed lamps should be avoided, as fishers cannot use it on the boats or in home lighting.
- 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. Up to 20% of the fish can be lost if the lighting system is difficult to remove from the net. The weight of all components must be carefully considered, as the traditional floats will support weight up to about 4 kg. 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.
- A widely desired feature of any system is the ability to charge mobile phones.

Market implementation considerations

It is not known how many people conduct night fishing around the world, but with 12 to 33 million artisanal fishers, if even 10% of them fished at night using practices similar to those we have observed, the global market would be 12 to 33-times that we have identified in Tanzania. GNF (no date) indicates that 85,000 shrimp fishers in Sri Lanka alone using 100,000 l per night of kerosene, essentially doubles the energy expenditure that we've estimated in this report.

A large-scale uptake of alternative lighting systems in the fishing market will depend on the availability of good products. For the fishers, 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 (Alstone et al., 2014).

Pricing and ownership

The boat owners we interviewed indicated a very rough willingness to pay ~$250 for a system replacing a single 1000-lumen pressurized kerosene lantern. This is approximately six-times the first cost of the pressurized kerosene lanterns they currently use, which provides a

[6] Above water and underwater light distribution differs. We exclude headlamps from our analysis because their light output declined steeply over the course of the trial due to battery discharge, and they were mounted such that their light was highly focused and perpendicular to the water surface.

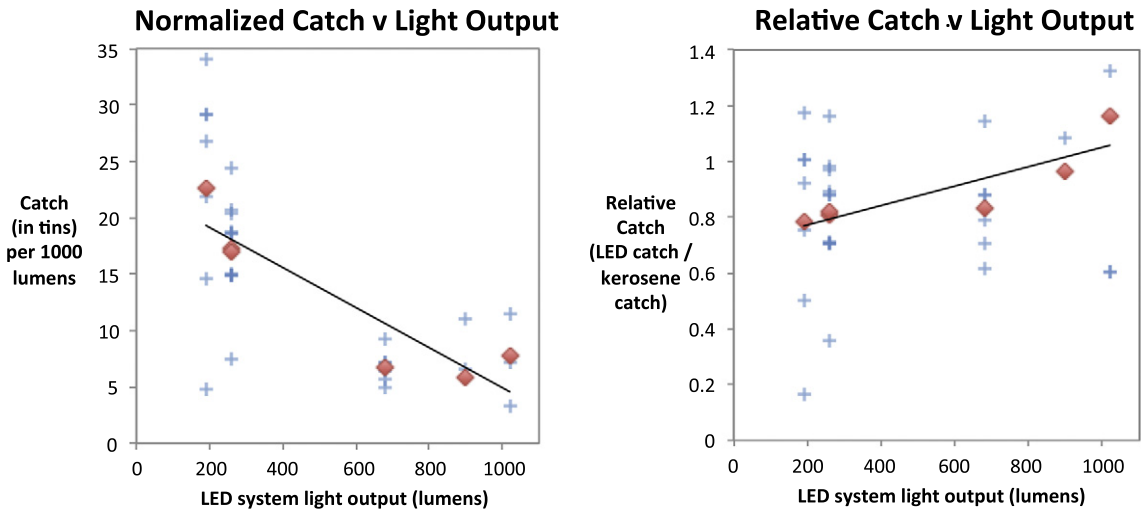

Fig. 6. Correlation of impact of light output on catch volume at Mwanza Gulf, Lake Victoria. Catch normalized per unit of light (left) declines with overall LED system light output. Relative catch (right) is the ratio of catch volume with LED to that with kerosene lighting, and increases with LED system light output. The figure shows averages (red diamonds) for each system and their individual scatter (blue crosses). Above-water lighting only, excluding headlamps. Data from trials at Lake Victoria. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

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 pressurized kerosene lantern. That said, four such lamps, with a shared solar panel and batteries would likely cost well below this willingness-to-pay threshold.

A replacement system can be either sold as a whole or be rented to the fishers. 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 fishers we interviewed consistently stated that they would prefer to own their system, which does not rule out a role for independent charging enterprises.

Sales organization and trade channels

In tandem with a viable technological offering is the requirement of effective market deployment. A key challenge is that the target buyers are dispersed, which makes distribution and service difficult. At Lake Victoria, for instance, there are many fishers 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 fishers 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. 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 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 fish in larger quantities and transport the product to the central markets.

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 fishers, and are always aware of their current location and economic situation. Furthermore the incremental costs for distribution are very little if this already-established 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 also function as creditors, or intermediaries with larger microfinance institutions. They bear little risk of loss since they have long-term business relationships with the fishers and could, for example, gradually deduct the debt from the price they pay for the fish or even take fish in barter.

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. Nevertheless, we also encountered crewmembers who stated that they would buy the systems themselves. As a scoping estimate, assuming five fishers per boat translates to 20,000 boat owners in this area, or an average lantern demand of approximately $1000 per customer (5 to 6 lanterns).

The previously mentioned labor organization, particularly the Beach Management Units (BMUs), represents an important piece in the distribution system (Ogwang et al., 2009). The BMU network may also be valuable insofar as financing is concerned.

Independent product ratings, truth-in-advertising, and warranty protection

No independent product testing or evaluation protocols exist for products intended for night fishing. Lighting Global 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.

Product warranties would reduce investment risks for the fishers, 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.

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 1). This is about 1.3% of the total CO_2 emissions from Tanzania in 2009, 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 fishers 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 that the fishers 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 being 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 must be considered—especially if such changes increase profits. The problem of overfishing takes different forms at the different locations.

At Lake Victoria, overfishing does not seem to be an issue (LVFO, 2012a), although the bycatch of non-targeted fish varieties has played a role in loss of biodiversity. 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), the 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. 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.

A recent pilot project focused on ocean fishing in India did find increased yields (The Power Times, 2013). The issue should be revisited at each location

Human health

The use of kerosene lanterns creates various health risks (Mills, 2012). At the Indian Ocean, fishers on the small dinghies are most exposed to the combustion products and bright light of the kerosene lanterns. 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 is 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. Although problems with eyesight were also repeatedly reported at Lake Tanganyika, it seems less of a severe problem than at the Indian Ocean, perhaps because the observed fishing technique includes longer phases where the fishers 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 fishers 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).

Conclusions

It is important to segment end-user markets when evaluating off-grid lighting energy use and the potential for improved technologies. The use of light by night fishers represents a use case that differs markedly from traditional applications, as the lighting needs are much higher and hours of operation much longer.

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

While far smaller in aggregate, this market segment 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 fishers 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.

The assessment of this atypical application of grid-independent lighting benefitted significantly from a participatory evaluation process in which end-users critique the proposed technology and suggest design revisions. The fishers we interviewed and who tested alternative lighting systems 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 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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