Alternative Energy Pumps to Irrigate Smallholder Farmers' Land: What is the State of the Art?

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Overview

Water is a critical input for significantly enhancing smallholder farmer productivity in Sub-Saharan Africa (SSA) where less than 5% of farm land is irrigated, and in India where 42% of farm land is irrigated. For many years, donors including the Bill & Melinda Gates Foundation (BMGF) have invested in human-powered treadle pump technologies as a point of entry for smallholder farmers unable to afford motorized pumps. In spite of some successes in treadle pump promotion, however, there is a widespread perception that as soon as smallholder farmers can afford to they quickly transition to motorized diesel-powered pumps.[1] While diesel pumps substantially ease farmers' workload, they pollute excessively (both in terms of local air quality and greenhouse gas emissions), pump excessive amounts of water, and put farmers at the mercy of cyclical spikes in fuel prices.

This brief provides an overview of state-of-the-art alternative energy pumps, including technologies available and implementation lessons learned from China, India, Africa, South America and other regions. Through a literature review, written surveys and phone interviews with water pump producers and non-governmental organizations (NGOs) we evaluate the availability, affordability, and adoption rates of alternative energy technologies in developing countries. Specifically, we focus on those technologies that (i) are capable of accessing surface water and lifting groundwater from depths of at least 10 m, and capable of distributing water over at least 1,000m^2, and (ii) might be affordable for smallholder farmers earning $1 to $2 per day. We consider biofuels, solar thermal , solar photo voltaic (PV) , and wind powered engine designs.

Findings suggest that no single alternative energy water pumping system is a "silver bullet" for rural smallholder irrigation needs. Biofuels (including biomass gasifiers, biogas, and biodiesel systems) may prove a successful short- to intermediate-term solution for farmers who already have access to diesel pumps – mixing locally-produced biofuels with diesel fuel to run pumps can slightly reduce pollution and substantially reduce fuel costs. However other problems associated with diesel engines, including high maintenance costs and excessive water use remain even when biofuels are used; the infrastructure costs associated with developing new biofuels sources are also very high. Solar systems eliminate pollution almost entirely, reduce water consumption (by drawing groundwater more slowly over longer periods of time than diesel), and eliminate the need to purchase fuels. However solar systems are typically prohibitively expensive for smallholder farmers – even though over the lifetime of products solar may be economically viable owing to long product lifespans and low maintenance costs. Wind powered pumping solutions have not proven successful to date, with high costs and irregular wind patterns (either too little or too much wind) proving substantial barriers to widespread adoption.

Table 1 presents a summary of the data on these alternative pump options. The following sections present the results of the literature search, describe the methods of the survey and phone interviews, and summarize findings for each alternative technology explored. The concluding sections provide recommendations regarding the availability and potential of water pumps powered by alternative energy, with a focus on those technologies that might be scalable for smallholder farmers in sub-Saharan African and South Asia.

Table 1. **Alternative Energy Pumps at a Glance**

	Energy Source	**Efficiency** (5 hp equivalent)	**Purchase Costs** (5 hp equivalent)	**Operating Costs** (fuel + labor)	**Maintenance Costs**	**Complexity**	**Notes**
Biomass gasifier	Dung, wood, plant material ***with diesel pump***	High *80%*	High *$1,100-$1,600*	Medium-High *Diesel cost plus labor cleaning/ operating*	High *$92-$127/year*	Medium *Unskilled except installation & motor repair*	*Successful in South Asia,* ***not*** *in Africa*
Biogas	Human, animal, plant wastes ***with diesel pump***	Medium *40%*	High *~ $2,500*	Medium-High *Diesel cost plus labor cleaning/ operating*	High *$92-$127/year*	Medium *Unskilled except installation & motor repair*	*Successful in South Asia,* ***not*** *in Africa; Requires many animals.*
Biodiesel	Plant extract-based biodiesel fuel ***with diesel pump***	*[same as diesel]*	*[same as diesel]*	Medium-Low *Cost savings if biodiesel price less than diesel price*	*[same as diesel]*	*[same as diesel]*	*Not viable at small scale – substantial Infrastructure needs (biodiesel plant)*
Solar thermal/ concent.	Solar ***with mechanical or electric pump***	Very Low *1% - 5%*	Medium-High *$600-$3,500*	Very Low	Moderate *Minimal applications to date*	High *Complex system; storage adds cost*	*May require costly accessories, e.g. inverters*
Solar-voltaic	Solar ***with mechanical or electric pump***	Low *7% - 15% though new products claim 50%*	High *$1,250-$3,500*	Very Low	Moderate *$30-$400/year*	High *Complex system; storage adds cost*	*High failure rates; costly accessories, e.g. inverters*
Windmill	Wind ***with mechanical or electric pump***	Low *7%-30%*	Varied *$992 - $2,533*	Very Low	Low *$20-$50/year*	High *Complex system; damage risks*	*Poor adoption rates to date in SSA and SA*

Literature Review

The literature search focused on databases such as Web of Science, Elsevier ScienceDirect and Google Scholar as well as international organizations including the UNEP, the World Bank, and CGIAR. Search terms started broadly and narrowed, for instance 'alternative energy' became 'photovoltaic' and 'gasifier'. Other terms used separately and in conjunction included 'irrigation', 'water pump(s)', 'windpump', 'windmill', 'wind energy', 'solar', 'concentrated solar', 'solar thermal', 'biogas', 'biomass', 'biodiesel', 'jatropha', 'battery', 'battery-powered', 'battery run', 'Sub-Saharan Africa', 'Africa', 'India', 'China', 'Nepal', 'South Asia', 'developing country', 'third world', 'efficiency' and others.[a] Approximately 100 articles were reviewed and 30 were consulted extensively for the literature review and in developing the survey instrument.

Most of the peer-reviewed literature to date focuses on cost analyses and adoption rates of various alternative energy technologies. Many articles show that alternative energy technologies can prove more cost effective than diesel pumps under certain conditions, especially when lifetime costs of the pumping system are considered.[2,3,4,5,6,7,8,9] This is largely due to large maintenance costs associated with diesel pumps. However, adoption of alternative energy technologies remains low. [10,11,12] The existing literature suggests that slow adoption of alternative energy technologies is largely a function of high upfront costs - high capital costs make the technologies unattainable for individual farmers, while collective action problems arise when a system is owned by a community.[13,14,15,16,17] Another basic obstacle is the lack of local means to operate or maintain the alternative energy technologies. Moreover, to date alternative energy pumps have primarily been disseminated on a traditional aid model basis, resulting in a weak sense of ownership among pump owners and operators.[18,19] When pumps fail, there is little motivation to have them repaired.[20,21]

The peer reviewed literature provides relatively little in the way of specific data on pump performance and business and marketing strategies. Capital and maintenance costs are estimated in some cost analyses, but they are rarely broken down by individual product or component.[22,23,24] Other important figures such as irrigation area and flow rates are even less commonly reported. Finally, since most of the academic and practitioner literature to date focuses on dissemination via traditional aid models (where another party donates the technology), marketing and business models or the potential for scale-up are rarely discussed.

Survey of Alternative Energy Pump Manufacturers & Providers

Based on the literature review and consultation with BMGF staff we developed a 28-question survey to systematically compare the characteristics of existing and emerging alternative energy water pump technologies. Using a 5 HP diesel fueled pump as a baseline for comparison, respondents were asked to describe the alternative energy technology produced and/or distributed by their organization, with an emphasis on the potential for the technology to be used by smallholder farms (defined as farmers earning \$1-\$2 per day seeking to irrigate a 1000m^2 parcel).

Specific variables of interest included:

- Fuel needs;
- Maintenance and operating costs;
- Maintenance needs (i.e. ability to irrigate without breaking down for 75 days/year);
- Transportability and overall ability to meet female user demands;
- Adoption rates in different cultural and environmental contexts; and
- Business model for igniting future private sector investment in delivery & maintenance of the technology.

The complete questionnaire is included as *Appendix I*.

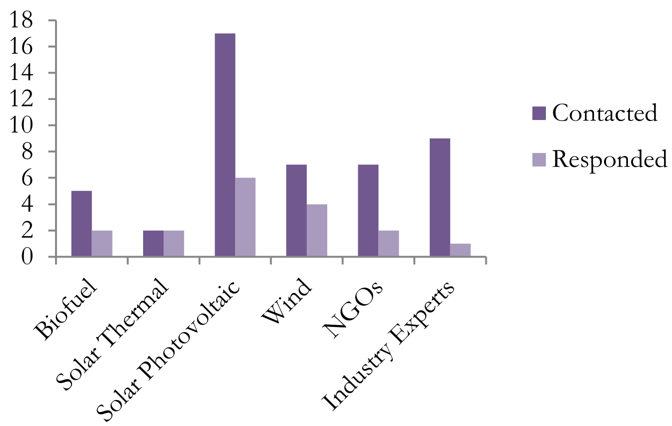
The questionnaire was sent to 30 private companies identified as suppliers of alternative energy pumps. We also contacted eight NGOs involved in alternative energy water pump extension in developing countries, and ten recognized experts in alternative energy technology development. We first contacted respondents via email, and then followed up with phone interviews as needed.

A total of 27 organizations were reached through email and/or phone solicitations. Three expressed no capacity or no interest in providing pumping solutions for smallholder farmers earning \$1 to \$2 per day. Three others provided only limited responses, while another 4 did not respond to requests in time for inclusion in the report. This resulted in a sample of 14 questionnaires and 3 additional extended interviews. The distribution of interviewees and response

[a] This is not an exclusive list of search terms, rather only an illustrative sample of terms used.

rates by technology type is presented in *Figure 1*.

Figure 1. Sample and Response Rates



Findings

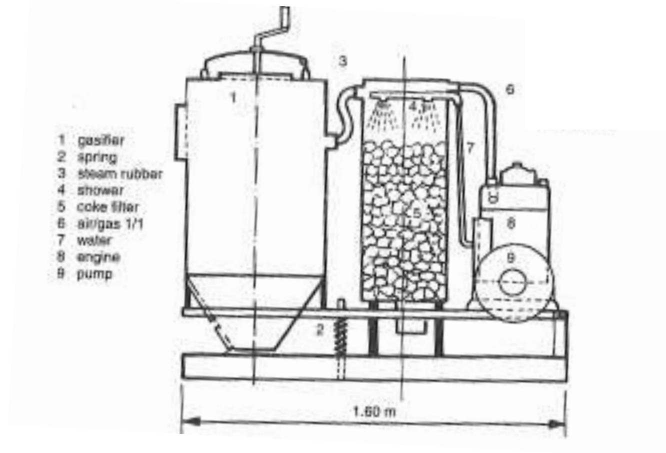
The sections below present: (i) a summary of findings from the peer reviewed literature for each technology; (ii) a summary of findings from our survey of providers of each technology; and (iii) preliminary recommendations for the BMGF moving ahead.

Biofuel Powered Pumps

Biofuel water pump systems can be broken into three categories: biomass gasifier-, biogas-, and biodiesel-based systems. These differ based on both the inputs used and the ultimate fuel itself. Biomass gasifiers use agricultural residues or wood and produce a gaseous fuel; biogas systems use animal waste and also produce gaseous fuels; and finally biodiesel systems use liquid fuels derived from oil producing seeds or plants.[25]

The process used in a **biomass gasifier** is fairly involved; *Figure 2* provides an illustration. Biomass is fed into a gasifier chamber and goes through a process of heating to separate out gaseous fuel from the volatiles (inflammable parts of the biomass). The "producer gas", a gaseous fuel that escapes the biomass, is then condensed into liquid and filtered to remove residual tar and ash. The gas can then be funneled directly into most standard internal combustion engines – most commonly a diesel engine, using a mixture of diesel and producer gas.

Figure 2. Biomass Gasifier Schematic, with 5HP Engine



Source: Fraenkel and Thake, 2006, p.288

Fuel source. According to our review of literature, diesel is necessary for ignition of the motor used in a gasifier system, while producer gas will maintain ongoing combustion. Past research suggests at least 20-30% of fuel consumed must be diesel.[26] For the biomass source, Ankur Scientific Technologies in India produces gasifiers able to run on rice husks, other agricultural wastes, or wood as available.

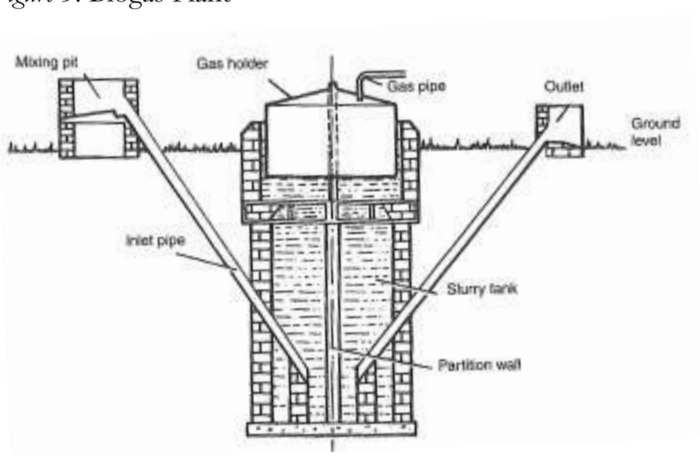
Efficiency. According to the literature review a 5 hp (3.73 kW) gasifier requires between 1.2 and 2 kg of biomass and 0.1 liters of diesel per kWh and can perform with 80% efficiency.[27,28,29] Expected water flow for a 5 hp unit has been estimated at 291,000 liters/day.[30] However no such farm-scale biogas units were encountered in our survey of biofuels companies. The smallest unit provided by Ankur Scientific Technologies (India), for example, is a 10 kW (electrical output) unit, more appropriate for village-level electrification. These larger units can be paired with commercially available electric pumps for irrigation needs.

Purchase and maintenance costs. The literature search suggests capital costs for a 5 hp biomass gasifier range from $1100 to $1600,[31,32] with a typical biomass gasifier unit reliably functioning for 10,000 hours, and the typical diesel engine used in a gasifier system lasting 20,000 hours.[33] Maintenance costs for a 5 hp gasifier are estimated to be $55 per year.[34] Although again, in our survey the smallest commercially available unit was a 10 kW plant from Ankur Scientific Technologies, having a purchase price ranging from $12,000 to $25,000 and maintenance costs of approximately 6% of capital costs.

Biomass gasifier systems also require a substantial amount of skilled labor. In most cases, the gasifier requires an attendant to maintain the biomass input and producer gas build up.[b,35,36] Additionally, the system needs to be cleaned for approximately one hour each day.[37] That said, with proper maintenance biomass gasifiers have proven very reliable. In one study in a rural Indian village, the gasifier was down for maintenance purposes only 185 days over a six year period.[38]

Biogas systems produce a gaseous fuel derived from human, vegetable, or animal waste. The farmer must collect the animal waste and deposit it into the biogas digester. A process of anaerobic digestion occurs within the digester, where the amount of solids needs to be about 8% and the temperature must be constant around 35 degrees centigrade. This ultimately produces a gaseous fuel and a sludge that can be a rich fertilizer. *Figure 3* provides a schematic illustration.

Figure 3. Biogas Plant



Fraenkel and Thake, 2006, p.291

Fuel source. The biogas produced can be used directly in a typical diesel engine if mixed with diesel at about a 1:5 diesel to biogas ratio. Additionally, there are pump engines that have been developed specifically for 100% biogas[39], however in a developing country context adapting existing diesel pumps to the new fuel source can be expected to be less costly in terms of purchase price and training.

Efficiency. Because of reliance on diesel engines for combustion, biogas systems are comparable to diesel systems in terms of water flow and length of engine life. The efficiency of a biogas engine is about 40%,[40] with water flow at roughly 782 m^3 per day for a 15 m^3 plant and 5 hp engine.[41] A typical biogas plant will last 25 years, and the typical diesel engine used with biogas will last 20,000 hours.[42] The biogas plants themselves require 25 kg of wet dung to produce 1 m^3 biogas; effectively narrowing the field of farmers who could employ these devices to those with at least four cows, twenty pigs, or 500 poultry. [43,44,45]

Purchase and maintenance costs. Capital costs for a 15 m^3 biogas plant have been estimated to be $2,559[46] although no current commercial providers of biogas systems were identified through the literature search or survey. An unskilled laborer is required to maintain operation of the system and provide necessary repair and maintenance.[47] Maintenance needs are fairly simple, confined to general upkeep of the exterior of the plant, replacement of hosepipes every other year, and replacement of gas holders every ten years.[48] Such costs range between $92 and $127 per year.[49,50]

Biodiesels represent a final biofuel technology. Biodiesels are liquid fuels derived from animal fats, vegetable oils, or grease.[51] The simplest and oldest method for vegetable oil extraction is through mechanical expellers, typically either through a manual or engine driven press. These methods produce extracting efficiencies of 60% and 75-80% respectively.[52,53] There are chemical extraction methods, but these require more time and hard-to-find chemicals; additionally, they have not been shown to be economical at a small scale.[54] The extracted oil is then mixed with an alcohol catalyst to produce biodiesel.[55]

Fuel source. Biodiesel can be used in standard diesel engines directly, or can be mixed with diesel.[56] Respondents to our survey recommended a 50-50 ratio of biodiesel to diesel as most appropriate. Although past studies warn the use of biodiesels may result in delayed ignition problems and can lead to engine corrosion when excessive water is present,[57] our interview with Africa Biofuel and Emission Reduction (East Africa) suggests that such problems are becoming less common as more advanced fuel filtration methods emerge.

[b] The producer gas collects and must be vented or burned off.

Efficiency; purchase and maintenance costs. Biodiesel, unlike biomass or biogas systems, requires no additional on-farm investments to use – farmers can simply use existing diesel pumps, but instead of buying diesel they buy biodiesel. Of course, a major limitation of biodiesel is the substantial infrastructure investment required to develop local sources of biodiesel – small-scale biodiesel generation has not yet proven efficient, but Africa Biofuel and Emission Reduction (East Africa) insist that once established a larger biodiesel facilities could provide biodiesel at prices lower than conventional diesel. This company currently produces biodiesel in Kenya, Tanzania and Uganda derived from Croton megacarpolus seeds (a non-edible seed from a tree indigenous to Africa), with a target price of $35 per barrel.

Because it is a direct substitute for diesel, once biodiesel is adopted the operating and maintenance costs associated with a biodiesel system are the same as the pre-existing diesel system.

Biofuels Experiences, Conclusions & Recommendations

Both biomass gasifier- and biogas-powered systems have been used extensively in South Asia, particularly China, India, and Nepal.[58] Recent estimates suggest that these technologies account for the largest use of alternative energy in the region, but also suggest that these technologies are used far less than circumstances, such as the widespread availability of biomass energy, suggest they should.[59,60] Meanwhile, projects in Africa have mostly failed, with an overwhelming majority of biomass and biogas plants no longer operational after only a few years.[61]

There may be several reasons for this. First, because the fuel plants are self-contained systems, they have to be built at the water source, which limits transportability and leads to ownership problems.[62] Additionally, many biomass feedstocks are used for other purposes that compete with usage as fuel.[63] Finally, perhaps the most serious constraint on the expansion of biomass gasifier and biogas-powered systems in Africa, as cited by survey respondents, is a lack of human and social capital to manage the plant once established.

The founder and manager of Ankur Scientific Technologies described some of these challenges: "Even in India," he said, "we have had problems with communities not organizing to support the electrical plant. The problem is even worse in Africa. And at least in India it is relatively easy to find people with enough training to run the plant; this is not easy in Africa."

Past efforts by the Indian government to quickly electrify rural areas through biomass gasification plants may have neglected the importance of community preparedness and training, much to the chagrin of private sector partners. Indeed, in the past Ankur Scientific Technologies worked extensively with the Indian government – only 5 years ago up to 90% of total sales were government contracts – to use biomass gasifier systems to electrify roughly 100 villages in rural India. Today however only 10% of Ankur Scientific Technologies sales are to government – the remainder are through private sector contracts (according to the respondent, this is in part owing to frustration with government projects, and in part due to increased global fuel prices and increasing interest in energy alternatives to reduce carbon emissions).

The implications for BMGF are twofold: (1) in the short-to-medium term, investments in biomass and biogas systems are more likely to work in South Asia, where the technology is relatively familiar to farmers and where private sector implementing partners are readily available; (2) in the medium-to-long term, the BMGF might focus on capacity building in Africa, possibly partnering with private companies like Ankur Scientific Technologies to develop community organizations and train local operators to pave the way for private sector biofuels expansion.

The potential for biodiesel production for smallholder farmers also appears limited to date. The literature indicates that biodiesel production is almost exclusively limited to larger scale endeavors.[64,65,66] As a result, there are no estimates for capital and maintenance costs for an on-farm biodiesel production system. Further, respondents confirmed that there are relatively few large-scale biodiesel plants in Africa to date, so most farmers in Africa could not switch to biodiesel at present even if they wanted to.

Constraints to biodiesel expansion in Africa differ somewhat from constraints to other biofuels. Like with biomass systems, in some contexts reliance on biodiesel could lead to farmers sowing more energy crops and fewer food crops, leading to food security concerns.[67] But the approach of Africa Biofuel and Emission Reduction has emphasized working with farmers and landowners to integrate biodiesel trees into cropping lands (agroforestry), suggesting that it may be possible to increase domestic fuel production and increase per-hectare incomes, all without substantially threatening food crop production. The key constraints to biodiesels identified by our survey respondents are instead (1) obtaining the financial capital investments required to construct large-scale biodiesel processing plants, and (2) mobilizing landowners and communities to provide sufficient biodiesel sources (e.g., Croton tree plantings) to meet local fuel needs.

Unfortunately with all biofuels many of the problems with diesel pumps – air pollution, maintenance costs, excessive water pumping –remain. On the other hand, a major advantage, particularly for biodiesels, is that farmers can simply use their existing diesel infrastructure. While there is a need for a stable supply of good quality biodiesel for farmers to purchase, the needs for additional capital investments and training of farmers are minimal.

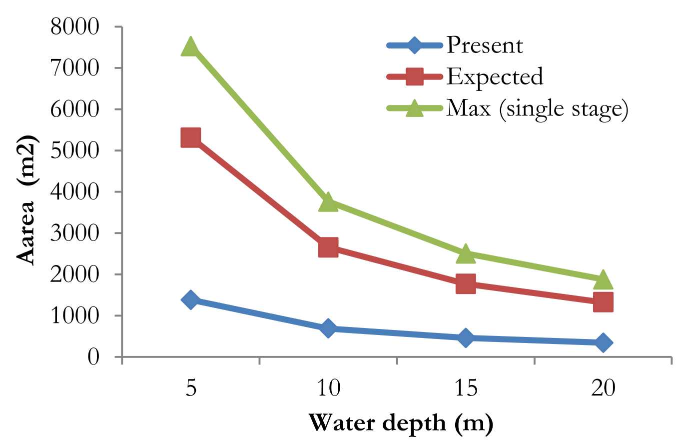
This does suggest that the largest financial advantages of biodiesel might arise less from farm-level savings (the focus of the BMGF), and more from national-level reductions in dependency on imported fuels. Biomass gasifiers and biogas (along with the other alternative energy technologies discussed below) actually reduce on-farm fuel purchases, and might therefore be a more appropriate target for BMGF investment. Biodiesel is simply a cleaner, more locally-sourced fuel alternative – a role for the BMGF in this regard might therefore be to advocate for increased government investment in biodiesel infrastructure for the national-level benefits it provides.

Solar Powered Pumps

Solar powered pumps are available in three basic categories: concentrated solar, solar thermal and photovoltaic (PV). Concentrated solar and solar thermal pumps account for a small share of the global solar powered pump market. Solar PV systems are more common, but extremely expensive to purchase. We review each technology in greater detail below.

Concentrated solar and solar thermal pumps rely on thermal energy that is converted into mechanical energy as a gas or vapor through a steam engine, typically a Rankine or Stirling engine.[68,69] Although powerful engines at large scales, smaller-scale systems are unable to draw water at great speed or from great depths. The solar thermal pump graph below illustrates how system efficiency translates into area irrigated when pumping from different depths using a prototype pump produced by the Practica Foundation (cost: $3,500; although a $600 model is under development). Assuming water application of 5 $l/m^2/day$, when this prototype steam pump lifts water from 10 meters depth it can irrigate about 690 m^2. Proposed improvements to this system, however, might raise this area to 2,000 m^2 or more in the foreseeable future.

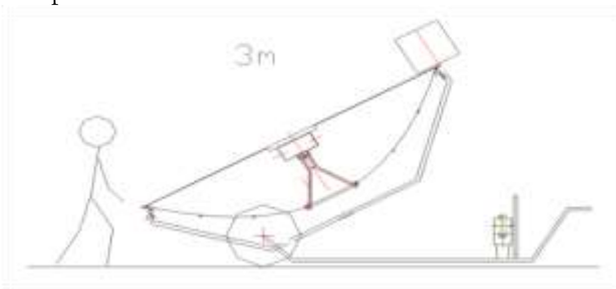
Figure 3. Solar Thermal Water Pumping Coverage



Source: Practica Foundation Report, 2010

Fuel source. The solar collector for a concentrated solar or solar thermal system is either a flat surface or a parabolic dish or trough that focuses the thermal energy to heat the fluid within creating a pressurized vapor (*Figure 4*). This pressurized vapor powers a piston engine that pumps water.[70] Concentrated solar systems are higher temperature devices, requiring fluids such as mineral oils or molten salts, while also using water for cooling purposes.[71] Solar thermal systems are usually low- and medium-temperature devices, using fluids with lower boiling points.[72] However many of such fluids are toxic, highly inflammable, or difficult to obtain in a developing country context (or all of the above). Recognition of this problem has spurred recent efforts by the Practica Foundation to develop a solar thermal system using only water as the volatile liquid.

Figure 4. Wheelbarrow-Mounted Solar Thermal Water Pump from Practica Foundation



Source: Practica Foundation Report, 2010

Although water requires higher temperatures to boil, this new system – most of which is produced within Ethiopia – eliminates one hazard (and cost) of solar thermal pumps.

Efficiency. Concentrated solar technology does not appear to be used in water pumping. It is used almost exclusively in large power plants; as of 2008 seven power plants accounted for all global concentrated solar power.[73] Additionally, concentrated solar systems require complex and expensive sun tracking technology and internal fluids.[74] No small-scale applications of this technology were found in the literature or through consultation with practitioners and experts in the solar field.

Solar thermal water pumps meanwhile have also not proven to be a commercially viable technology to date.[75] As shown in *Table 2,* lab tests and field pilot studies from the Practica Foundation consistently report system efficiencies from 0.6% to, even in exceptional cases, only 5-7%.[76,77] However, cutting-edge field experiments today suggest this may be a future area of great potential. To date two firms (SunVention and the abovementioned Practica Foundation) have announced the development of relatively low-cost solar thermal pumps with engine efficiencies approaching 50% (though full system efficiencies remain in the range of 7% or more).[78,79]

Table 2. Current and expected future efficiency of the Practica Foundation thermal steam pump system

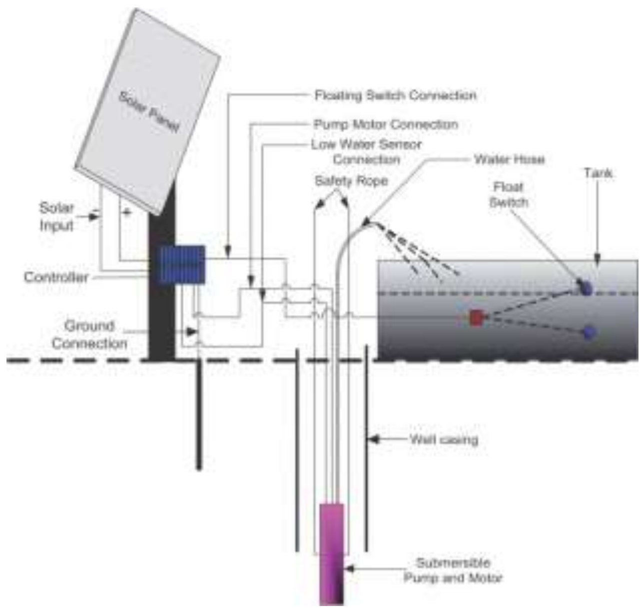
	Present	**Realistic design goal**	**Max (single stage)**	**Max (double stage)**
Collector	45%	60%	80%	80%
Carnot	4.0%	7.5%	7.5%	14.8%
Engine	50%	70%	70%	70%
Pump	70%	80%	85%	85%
Solar in / water out	0.6%	2.5%	3.5%	7%

Source: Practica Foundation Report, 2010

Purchase and maintenance costs. Again, concentrated solar systems are non-viable at smallholder scales. With solar thermal, although purchase costs are high by smallholder farmer standards ($1,250 to $2,500 for the SunVention product, or $3,500 for the commercially available Practica Foundation pump) lower-cost options, as in the case of the Practica Foundation's work in Ethiopia, are in the pipeline. Indeed, the Practica Foundation's recent estimates suggest that a solar thermal system capable of replacing a 5 hp diesel pump could be produced for as little as $610, using local (Ethiopian) materials. Moreover, once established the annual operating and maintenance costs of solar thermal systems are minimal (roughly $66, compared to $600 or more for equivalent diesel systems depending on the price of fuel), suggesting the possibility of a full return on investment in less than a single growing season. More detailed cost-comparisons are provided at the end of this section.

In contrast to concentrated solar and solar thermal systems, **photovoltaic (PV) systems** are much more complex consisting of a PV array, inverter, motor, pump, and a water storage tank or a battery to store energy.[80]. The PV array is made up of PV cells typically created from silicon wafers. These silicon slices can come in different types, but the most common and most efficient are mono-crystalline silicon cells.[81] A sample photovoltaic powered electric water pump setup is pictured in *Figure 5* below.

Figure 5. Solar Water Pumping System



Source: Meah et al., 2006

Fuel source. For a PV pump to be a viable option, it has been recommended that solar irradiation should be greater than 3.5 kW/m^2 in the least sunny month where irrigation is needed.[82] The only fuel source for the system is the sun; although moderately costly add-ons such as a tracker can greatly increase the efficiency of a given set of panels.

Output from a PV system also varies substantially over the course of the year. Water flow from PV pumps is a function of array size, array efficiency, the borehole, and pumping head[83], but water flow is not constant. Water flow is highest during the sunniest parts of the day and the year[84]. Studies have estimated water flow from a 20 m borehole in Namibia to range from a minimum of 2.5 m^3 to maximum 42 m^3 per day, while a 25 m borehole in Benin ranged from 20 m^3 per day to 30 m^3 per day. A daily average of 74 m^3 per day was realized from a 45 m borehole in Algeria, while a daily average of 60 m^3 per day came from a 10 m borehole in India.[85,86,87,88] There are so many variables involved in water flow that output varies significantly even using the same array. Consequently systems need to be configured specifically to each site.[89]

Efficiency. Efficiency in most PV systems ranges from 7% to 15%[90], with PV arrays beginning to lose efficiency as temperatures increase significantly beyond 25˚ C.[91,92] The output of PV arrays is direct current (DC)[93]. Without an inverter, the PV array would require a DC motor. However, DC motors consist of a brush and commutator that require significant maintenance and deteriorate quickly.[94] There are brushless DC motors, but these are more expensive and harder to find.[95] Alternating current (AC) induction motors are more 'rugged [and] reliable', more common, and require less maintenance.[96] But an inverter is necessary to use an AC motor. That said, inverters are also beneficial for the system because they can optimize matching of power between the PV array and the motor.[97] However, most PV pump failures are the result of a failed inverter, "despite not being more complicated than the typical radio."[98]

Purchase and maintenance costs. The PV arrays themselves are exceedingly expensive – according to survey respondents it will cost as much as $1,400 or more for panels capable of replacing a 5 hp diesel engine at 5m lift. Commercially available PV modules have purchase costs around $4/W.[99,100] These prices coincide with reports in published studies using 0.9 and 1.8 kW PV arrays, with PV array purchase prices ranging from $3000 to $7000.[101,102,103,104]

Another major upfront purchase is the electrical pump. PV pumps come in three different types: submersible, surface, and floating. Submersible pumps are used in deep wells; surface pumps are used in shallow wells or surface water; floating pumps are used in reservoirs.[105] For low head pumping, submersible pumps are more effective.[106] Types of submersible pumps include centrifugal pumps, screw pumps, and piston pumps. Centrifugal pumps are the most commonly used with solar arrays.[107,108] However, these pumps 'are particularly site specific'; any changes in water level of the borehole can dramatically affect efficiency.[109] Piston pumps and screw pumps, and positive displacement pumps in general, are seen as more reliable in the face of changing conditions.[110,111] Pumps, motors, and inverters range in cost from $1000 to $1500.[112,113] Overall system costs reported in our survey are reported in *Table 3* below.

Table 3. Solar PV System Prices

Company	Price Reported	Description
Global Solar Water Power	$16,255.50	2 hp system (equivalent to diesel 5 hp), 1,000 m^2 coverage, 10m depth
Sun Motor	$4,000	M10 pump + 400 W PV + accessories
Solar Water Tech.	$1,675 - $2,175	85 W to 170 W systems; small plots only
Phaesun	*Not reported*	Varies substantially based on location
Bright Stars	*Not reported*	Designed for 1 – 1.5 hectare scale
Shanghai Roy Solar	$450	Disposable pumping unit; no more than 21 liters/hr in full sun

Source: Author Survey, 2010

Note that the above table includes at least one pump – Shanghai Roy Solar – that is insufficient for smallholder irrigation needs. Global Solar, Sunmotor and Phaesun on the other hand all offer potentially applicable pumps, and all have experience in developing countries.

A final cost with solar PV systems is energy storage. The literature provides mixed evidence on whether excess energy from solar systems is better stored in a battery or used to fill a reserve water tank. Most practical applications of the systems have suggested the use of a water tank[114,115,116,117] so that all the energy from the PV array is used to pump water. Stored water can be stored several days, so that water can be counted on even when the PV array cannot run.[118] Batteries can provide extra energy for lighting or other energy needs; however, using batteries for alternative applications implies a choice between pumping less water or obtaining a larger PV array.[119] Batteries also represent a substantial recurring cost and require consistent maintenance,[120] and batteries tend to run down especially quickly in more adverse conditions.[121] Few data were found on costs of a water storage tank, with one estimate suggesting a reserve water tank would cost as much as $3,500.[122] An alternative option where possible would be digging a water storage pond.

Solar Field Experiences, Conclusions & Recommendations

Knowledge to date in the field of small-scale solar thermal pumping technologies is limited. However the work underway through the Practica Foundation suggests affordable, locally-produced irrigation technologies may be a possibility in the near future. Annual cost comparisons of the proposed Practica Foundation solar pump with solar PV and diesel are presented in *Table 4*, suggesting a payback for the solar thermal pump over a diesel pump in *less than a single season*.

Table 4. Solar System Price Comparisons

Pump	Purchase Price	Annual Operating Cost
Solar thermal	$610	$66
Solar PV	$1,700	~$0
5 hp Diesel	$200	$570

Assumptions: A 70m^3/day solar pump, lifting from 5m, running every day for 8 hrs, is assumed to replace most 5hp diesel pumps.

Source: Practica Foundation, 2010

These pumps remain in the testing phase. However if these performance estimates prove accurate, substantial BMGF support for immediate expanded availability of this system may be justified, as well as support for vigorous private market development.

For solar PV maintenance and reliability are considered the key strengths of the system. Our survey respondents suggested that little to no maintenance was required for their products with the exception of pump replacement, especially when pumping sandy water. Commercially available PV arrays are usually guaranteed to last 25 years, and pumps can be expected to last ten years or more.[123] Indeed, five out of the six solar companies that completed our survey claimed their product's durability exceeded 10 years. Annual maintenance cost estimates vary widely, ranging from $30 to close to $400 for larger systems.[124,125,126] But even the higher levels of maintenance costs would result in net savings for many farmers currently purchasing diesel fuel.

However, two survey respondents (both non-PV vendors) noted that theft of PV arrays – which are very valuable and relatively easy to move – can be a major concern for smallholders. Furthermore, like the case of biofuels, experience to date shows adoption rates are higher and maintenance costs are lower in India as compared to Africa, possibly because of the wider availability of the technology, including components and experienced maintenance workers in India.

It is therefore difficult to make recommendations for the BMGF regarding solar PV technologies for two reasons. First, in spite of the relatively low maintenance costs of solar PV systems, the upfront costs of such a system are extremely high, creating high risks for smallholders (or for the BMGF if it were to assume these upfront costs through grants or loans) in the event that systems fail. While purveyors of solar technologies unanimously claim their products are durable, an assessment of past PV projects suggests system failure may be fairly common. In a 2001 study in Thailand, 45% of PV systems failed, most within seven years.[127] In Mexico, 40% of PV systems failed over the course of ten years.[c,128] Even in the US, one system out of eleven no longer worked after ten years, while all systems suffered some sort of failure (though most US residents had the means to fix the problem).[129]

Second, the lack of adoption of PV technologies raises the question of whether farmers might have reason to resist solar PV – for example, while diesel engines may be costly to operate and require frequent repair, farmers know that diesel is a *readily available fuel* (if costly), and when their machine breaks *they know how to fix it.* In this sense, a $200 diesel engine with known operating costs and known maintenance needs may be more appealing than a $1,400 solar pump with no operating costs and *unknown* maintenance needs (including the possibility of total system failure and crop loss). One potential role for the BMGF to address this uncertainty problem might therefore be to develop a pump insurance network – or become a sort of insurer of last resort – whereby farmers whose pumps fail may obtain a replacement pump immediately while repairs are conducted, or may receive compensation for lost crops in the event that pump repair or replacement is not possible.

Windmill Pumps

Windmill pumps come in two basic categories: mechanical and electrical.

Fuel source: **Mechanical windmills** use converted wind power to directly pump up water, using a piston pump or compressed air.[130] **Electrical windmills** convert wind power to electrical energy. This energy can be stored in a DC battery or used directly to power an electric pump, usually centrifugal pumps.[131,132] As a result, electrical windmills can be built at a distance from the water source, while mechanical windmills cannot.[133] Additionally, because of battery storage electrical windmills can match irrigation needs to energy input and avoid the common problem of overmatching water to irrigation need.[134]

Mechanical windmills require an average wind speed of at least 3 m/s, whereas electrical windmills require an average wind speed of at least 5 m/s.[135,136]

Efficiency. Mechanical windmills have a conversion efficiency ranging from 7%-27%, while electrical windmills differ only slightly, with efficiencies of 12%-30%.[137]

Purchase and maintenance costs. One study suggested the capital costs for common windmills in India range from $992 to $2,533. The lower end model had a higher water flow, about 92 m^3 per day as compared to 29 m^3 per day.[138] Typical water flow is a function of the wind speed, size and efficiency of the rotor, the efficiency of the pump, and the pump head.[139]

Windmills can be hard to build and maintain. All windmills must be built up high, typically at least 10 meters.[140] This often requires professional assistance with a winch or tower to build and maintain wind turbines.[141] Additionally, windmills are hardware intensive, and routine operation wears on the system, with high winds and unexpected storms posing an additional threat. High winds can result in broken parts that may be hard to find in rural areas[142]. However, windmills typically are reliable and can be expected to run for extended periods with relatively little maintenance or oversight.[143,144] Typical maintenance costs have been estimated at 2%-5% of capital costs, or about $20-$50 per year.[145]

Wind Field Experiences, Conclusions & Recommendations

Windmill pumps do not appear to be commonly used in

[c] Interestingly enough, most users still rated their PV system as excellent or good, both on reliability and water production.

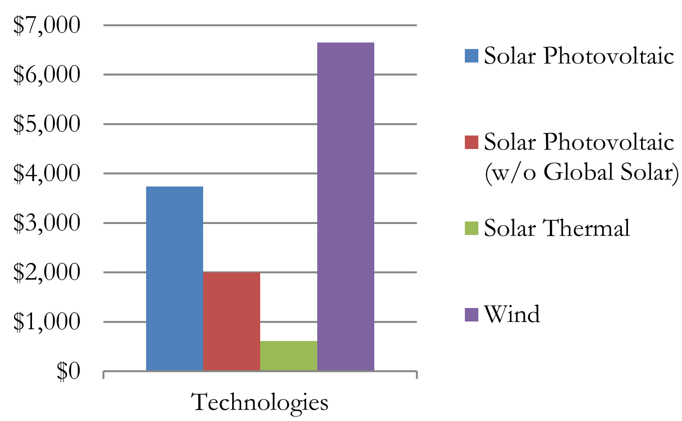
either South Asia or sub-Saharan Africa. In India only a little over 1,000 windmill pumps have been installed since 1993,[146] while one company marketing windpumps in Africa, Kjito Windpower, reports sales of only 400 pumps over the last 29 years.[147]

In our survey both Unitron and Eveready Kestrel reported both experience and interest in expanding operations to South Asia and sub-Saharan Africa; however given the limited applicability (wind does not always arrive when it is needed) and substantial price tag (in excess of $10,000 for a 5 hp – equivalent system) the BMGF might hesitate to invest in wind in the immediate future.

Comparisons of Alternative Energy Options

Several of the studies reviewed in preparing this brief specifically compare costs of diesel and alternative energy systems. On average, the assumed cost of a diesel engine capable of irrigating a 1,000m² plot is $200. No alternative energy technologies to date approach this initial capital cost. *Figure 4* contrasts the purchase costs of various technologies as reported in our survey.

Figure 4. Purchase Price Comparisons



Source: Author Survey, 2010

As clearly shown above, the Practica Foundation solar thermal engine outperforms all technologies encountered in this review in terms of affordability. Wind is very costly in terms of purchase price, as is solar PV (although the price for solar PV is lower when the Global Solar pump system – priced at over $16,000 – is excluded from the average.)

Of course an increasing number of analyses consider the costs over the lifetime of the product. Studies in Namibia and Benin, for example, have shown PV pumps to be consistently more cost effective over a lifetime than diesel pumps.[148,149] Each of these studies base cost assumptions on data from their unique situation, thus the generalizability of these findings should be carefully considered. In studies with conservative fuel escalation rates, i.e. predictions that the cost of fossil fuel will grow slowly, diesel systems will remain a more cost effective choice than most alternative energy pump systems.[150,151,152] However, with fuel escalation rates greater than 3% in India and even 25% in Algeria, PV pumps become a much more financially attractive alternative.[153,154] Even under conservative fuel price escalation rates, one study in India has shown that biogas systems throughout India and windmills (in one particular Indian state) are more cost effective systems.[155]

Recommendations

Any BMGF investment in alternative energy water pump technologies development, delivery, or market creation will require careful consideration of local contextual variables including the availability of (i) the necessary fuel source (is there sufficient wind to power a wind pump? sufficient biomass to feed a biomass gasifier?) as well as (ii) sufficient human capital (trained workers to maintain alternative energy equipment) and (iii) social capital (organized communities able to afford technologies that might be more efficient at community-level scales).

More broadly, the results of this review and survey suggest the following general conclusions:

- *For short-term reductions in pollution and fuel imports, focus on biofuels*

Biodiesel in particular may prove an area where the BMGF's comparative advantage – as a large foundation capable of mustering resources and assuming substantial risk – may prove valuable. Africa Biofuel and Emission Reduction (East Africa) is one potential partner moving ahead in this area. However it should be emphasized again that the rewards from investments in biodiesels are more likely to accrue at the national level (reduced imports) rather than the farm-level. Therefore the BMGF should

NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

also consider leveraging government investment in the biodiesel sector where appropriate.

Investments in biomass gasifiers seems unlikely to be successful at the smallholder level. However village-level electrification through biomass gasifiers may be a possibility – as described by Ankur Scientific Technologies in India. In this area the BMGF might best act as a coordinating body, helping to develop village organizations and train locals in the management and maintenance of biogas plants.

- *For short- to medium-term reductions in farmer spending, focus on solar thermal pump development*

Nothing else encountered in this study even approaches the potential cost savings advertised by the Practica Foundation. If their newly developed solar thermal pumps prove to work as promised, these products may have extraordinary potential to reduce smallholder expenditures and improve livelihoods amongst low-income farmers. Several preliminary technical and performance documents from the Practica Foundation are included as a supplement to this report for further review.

- *Invest in wind technologies with caution.*

Wind-powered water pumps may be a valuable alternative energy source in some areas; however widespread adoption appears unlikely – and perhaps undesirable given the high capital costs and mixed performance record associated with these technologies at present.

References

Abdolzadeh, M., and Ameri, M. (2009). Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. *Renewable Energy, 34,* 91–96.

Achten, W. M. J., Verchot, L., Franken, Y. J., Mathijs, E., Singh, V. P., Aerts, R., and Muys, B. (2008). Jatropha bio-diesel production and use. *Biomass and Energy, 32,* 1063–1084.

Adriaans, T. (2006). Suitability of solvent extraction for *Jatropha curcas*. Eindhoven: Fact Foundation.

Amigun, B., Sigamoney, R., and von Blottnitz, H. (2008). Commercialization of biofuel industry in Africa: A review. *Renewable and Sustainable Energy Reviews, 12,* 690–711.

Argaw, N., Foster, R., and Ellis, A. (2003). *Renewable energy for water pumping applications in rural villages.* Golden Colorado: NREL.

Awulchew, S. B., Lemperiere, P. and Tulu, T. (2009). Pumps for small scale irrigation. Retrieved from the International Livestock Research Institute: http://www.ilri.org/InfoServ/Webpub/fulldocs/IWMI_IPMSmodules/Module_4.pdf

Bender, Martin. (1999). Economic feasibility review for community-scale farmer cooperatives for biodiesel. *Bioresource Technology, 70*, 81–87

Betka, A, and Moussi, A. (2004). Performance optimization of a photovoltaic induction motor pumping system. *Renewable Energy, 29,* 2167–2181.

Bouzidi, B., Haddadi, M., and Belmokhtar, O. (2009). *Renewable and Sustainable Energy Reviews, 13,* 879–886.

Buragohain, Buljit, Mahanta, Pinakeswar, and Moholkar, Vijayanand S. (2010). Biomass gasification for decentralized power generation: The Indian perspective. *Renewable and Sustainable Energy Reviews, 14,* 73–92.

Burney, Jennifer, Woltering, Lennart, Burke, Marshall, Naylor, Rosamond, and Pasternak, Dov. (2010). Solar-powered drip irrigation enhances food security in the Sudano-Sahel. *Proceedings of the National Academy of Sciences, 107,* 1848–1853.

Chandwalker, K., and Oppen, M. V. (2001). Solar power for irrigation, the small solar thermal pump: an Indian development. *Refocus, 2,* 24–26.

Chaurey, Akanksha, and Kandpal, Tara. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. *Renewable and Sustainable Energy Reviews, 14,* 2266–2278.

Cope, Gideon, Aghdasi, Farhad, and Dlamini, M. D. (1997). A review of the photovoltaic industry and its development in Africa. *Solar Energy, 59,* 217–225.

Dasappa, S., Paul, P. J., Mukunda, H. S., Rajan, N. K. S., Sridhar, G., and Sridhar, H. V. (2004). Biomass gasification – a route to meet energy needs. *Current Science, 87,* 908–916.

Delgado-Torres, Agustín M. (2009). Solar thermal heat engines for water pumping: an update. *Renewable and Sustainable Energy Reviews, 13*, 462–472.

Espericueta, A. D. C., Foster, R. E., Ross, M. P., Avilez, O. M., Rubio, A. R. P. (2004). *Ten-year reliability assessment of photovoltaic water pumping systems in Mexico.* Retrieved from http://globalcitizen.net/Data/Pages/2428/papers/2009100219223302.pdf

Fraenkel, Peter, and Thake, Jeremy. (2006). *Water lifting devices: A handbook*. Rome: FAO.

Francis, George, Edinger, Raphael, and Becker, Klaus. (2005). A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in Inida: Need, potential and perspectives of *Jatropha* plantations. *Natural Resources Forum, 29,* 12–24.

Haas, Michael J., McAloon, Andrew J., Yee, Winnie C., and Foglia, Thomas A. (2006). A process model to estimate biodiesel production costs. *Biosource Technology, 97,* 671–678

Jagadeesh, A. (2000). Wind energy development in Tamil Nadu and Andhra Pradesh, India: institutional dynamics and barriers – a case study. *Energy Policy, 28,* 157–168.

Jumbe, Charles B. L., Msiska, Frederick B. M., and Madjera, Michael. (2009). Biofuels development in Sub-Saharan Africa: Are these policies conducive? *Energy Policy, 37,* 4980–4986.

Kaunmuang, P., Kirtikara, K., Songprakorb, R., Thepa, S., and Suwannakum, T. (2001). Assessment of photovoltaic pumping systems in Thailand – one decade experience. *Solar Energy Materials and Solar Cells, 67*, 529–534.

Kumar, Atul and Kandpal, Tara C. (2007). Renewable energy technologies for irrigation water pumping in India: A preliminary attempt towards potential estimation. *Energy, 32*, 861–870.

Meah, Kala, Ula, Sadrul, and Barrett, Steven. (2008). Solar photovoltaic water pumping – opportunities and challenges. *Renewable and Sustainable Energy Reviews, 12,* 1162–1175.

Nambia Ministry of Mines. (2006). Feasibility assessment for the replacement of diesel pumps with solar pumps. Windhoek, Namibia: Ministry of Mines and Energy.

Natural Innovation Foundation. (2010). Innovation: SunPulse Water – solar thermal water pump. Retrieved from http://www.naturalinnovation.org/index.php/innovators/33-sunpulsewater

NREL. (2010). 2008 Solar technologies market report. Retrived from http://www.nrel.gov/analysis/pubs_solar.html

Odeh, I., Yohannis, Y. G., and Norton, B. (2006). Influence of pumping head, insolation and PV array size on PV water pumping system performance. *Solar Energy, 80,* 51–64.

Odeh, I., Yohannis, Y. G., and Norton, B. (2010). Simulation procedure for the co-optimization of photovoltaic water pumping systems. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 224,* 629–640.

Vasudevan, Palligarnai T., and Briggs, Michael. (2008). Biodiesel production – current state of the art and challenges. *Journal of Industrial Microbiology and Biotechnology, 35,* 421–430.

Practica Foundation. (2007). Thermal solar pumps. Retrieved from http://www.practicafoundation.nl/services/r-d/thermal-solar-pumps/

NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

Purohit, Pallav. (2007). Financial evaluation of renewable energy technologies for irrigation water pumping in India. *Energy Policy, 35,* 3134–3144.

Purohit, Pallav, and Kandpal, Tara. (2007). Techno-economics of biogas-based water pumping in India: An attempt to internalize CO_2 emissions mitigation and other economic benefits. *Renewable and Sustainable Energy Reviews, 11,* 1208–1226.

Ravindranath, N. H., Somashekar, H. I., Dasappa, S., and Jayasheela Reddy, C. N. (2004). Sustainable biomass power for rural India: Case study of biomass gasifier for village electrification. *Current Science, 87,* 932–941.

Short, T. D., and Oldach, R. (2003). Solar powered water pumps: The past, the present, and the future. *The American Society of Mechanical Engineers, 125,* 76–82.

United Nations Economic and Social Commission for Asia and Pacific. (1991). Solar powered water pumping in Asia and the Pacific. Bangkok, Thailand: UNESCAP.

Zeller, B. (2003). *Assessment of the economic performance of a solar thermal water pump for irrigation in semiarid India* (Master's Thesis). Retrieved from http//www.troz.uni-hohenheim.de/research/Thesis/MScAES

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[1] Awulchew, S.B., Lemperiere, P. & Tulu, T. (2009). Pumps for Small Scale Irrigation. Retrieved from the International Livestock Research Institute: http://www.ilri.org/InfoServ/Webpub/fulldocs/IWMI_IPMS modules/Module_4.pdf
[2] Argaw et al., 2003
[3] Burney et al., 2010
[4] Buragohain et al., 2010
[5] Dasappa et al., 2004
[6] Kumar and Kandpal, 2007
[7] Namibia Ministry of Mines, 2006
[8] Purohit, 2007
[9] Purohit and Kandpal, 2007
[10] Kumar and Kandpal, 2007, p.869
[11] Buragohain et al., 2010, p.78
[12] Purohit, 2007, p.3135
[13] Argaw et al., 2003
[14] Burney et al., 2010
[15] Buragohain et al., 2010
[16] Dasappa et al., 2004
[17] Kumar and Kandpal, 2007
[18] Short and Oldach, 2003,
[19] Meah et al., 2008
[20] Amigun et al., 2008, p.697
[21] Espericueta et al., 2004
[22] Purohit, 2007
[23] Bouzidi et al., 2009
[24] Purohit and Kandpal, 2007
[25] Fraenkel and Thake, 2006, p.278-280
[26] Fraenkel and Thake, 2006, p.285-287
[27] Purohit, 2007, p.3139
[28] Ravindranath et al., 2004, p.934
[29] Kumar and Kandpal, 2007, p.868
[30] Purohit, 2007, p.3134
[31] Purohit, 2007, p.3138
[32] Kumar and Kandpal, 2007, p.868
[33] Purohit, 2007, p.3139
[34] Purohit, 2007, p.3139
[35] Fraenkel and Thake, 2006, p.288
[36] Ravindranath et al., 2004, p.938
[37] Fraenkel and Thake, 2006, p.289
[38] Ravindrath et al., 2004, p.938
[39] Fraenkel and Thake, 2006, p.292
[40] Purohit and Kandpal, 2007, p.1215
[41] Purohit, 2007, p.3140
[42] Purohit, 2007, p.3139
[43] Purohit and Kandpal, 2007, p.1215
[44] Kumar and Kandpal, 2007, p.865
[45] Fraenkel and Thake, 2006, p.295
[46] Purohit, 2007, p.3138
[47] Purohit and Kandpal, 2007, p.1214
[48] Purohit and Kandpal, 2007, p.1212
[49] Purohit and Kandpal, 2007, p.1217
[50] Purohit, 2007, p.3138-3139
[51] Vasudevan and Briggs, 2008, p.421

[52] Achten et al., 2008, p.1069
[53] Adriaans, 2006, p.9
[54] Achten et al., 2008, p.1070
[55] Achten et al., 2008, p.1070
[56] Vasudevan and Briggs, 2008, p.422
[57] Achten et al., 2008, p.1075
[58] Fraenkel and Thake, 2006, p.292
[59] Kumar and Kandpal, 2007, p.869
[60] Buragohain et al., 2010, p.78
[61] Amigun et al., 2008, p.697
[62] Fraenkel and Thake, 2006, p.288
[63] Buragohain et al., 2010, p.79
[64] Bender, 1999, p.83
[65] Haas et al., 2005, p.672
[66] Francis et al., 2005, p.19-21
[67] Jumbe et al., 2009, p.4981
[68] Delgado-Torres, 2009, p.462
[69] Fraenkel and Thake, 2006, p.260-261
[70] Chandwalker and van Oppen, 2001, p.24-26
[71] NREL, 2010, p.74-75
[72] Fraenkel and Thake, 2006, p.260
[73] NREL, 2010, p.10-12
[74] NREL, 2010, p.74
[75] Zeller, 2003, p.8
[76] Delgado-Torres, 2009, p.462-464
[77] Zeller, 2003, p.9
[78] Practica Foundation, 2007
[79] Natural Innovation Foundation, 2010
[80] Odeh et al., 2006, p.51
[81] Fraenkel and Thake, 2006, p.248
[82] UNESCAP, 1991
[83] Bouzidi et al., 2009, p.880
[84] Fraenkel and Thake, 2006, p.257-8
[85] Burnley et al., 2010, p.1849
[86] Namibia Ministry of Mines, 2006, p.64
[87] Bouzidi et al., 2009, p.884
[88] Purohit, 2007, p.3140
[89] Agulchew et al., 2009, 160-162
[90] Fraenkel and Thake, 2006, p.256
[91] Abdolzadeh and Ameri, 2009, p.93
[92] Purohit, 2007, p.3135
[93] Fraenkel and Thake, 2006, p.254
[94] Odeh et al., 2006, p.52
[95] Odeh et al., 2010, p.635
[96] Odeh et al., 2006, p.52
[97] Fraenkel and Thake, 2006, p.254
[98] Short and Oldach, 2003, p.77-78
[99] Meah et al., 2008, p.1172
[100] Fraenkel and Thake, 2006, p.250
[101] Burnley et al., 2010, appendix
[102] Purohit, 2007, p.3138
[103] Namibia Ministry of Mines, 2006, p.59
[104] Kumar and Kandpal, 2007, p.868
[105] Meah et al., 2008, p.1167
[106] Fraenkel and Thake, 2006, p.255
[107] Fraenkel and Thake, 2006, p.254
[108] Short and Oldach, 2003, p.78
[109] Short and Oldach, 2003, p.78
[110] Short and Oldach, 2003, p.78
[111] Fraenkel and Thake, 2006, p.254
[112] Burney et al., 2010, appendix
[113] Meah et al., 2008, p.1172
[114] Bouzidi et al., 2008, p.880
[115] Burney et al., 2010, p.1848
[116] Meah et al., 2008, p.1166
[117] Omer, 2001, p.249
[118] Short and Oldach, 2003, p.77-78
[119] Short and Oldach, 2003, p.78
[120] Short and Oldach, 2003, p.78
[121] Fraenkel and Thake, 2006, p.255
[122] Burney et al., 2010, appendix
[123] Burney et al., 2010, appendix
[124] Purohit, 2007, p.3139
[125] Kumar and Kandpal, 2007, p.868
[126] Bouzidi et al., 2009, p.884
[127] Kaunmuang et al., 2001, p.531
[128] Espericueta et al., 2004, p.117
[129] Meah et al., 2008, p.1169
[130] Argaw, 2003, p.29-30
[131] Awulchew et al., 2009, p.155
[132] Argaw, 2003, p.30
[133] Fraenkel and Thake, 2006, p.218
[134] Argaw, 2003, p.30
[135] Argaw, 2003, p.32
[136] Fraenkel and Thake, 2006, p.240
[137] Argaw, 2003, p.31
[138] Purohit, 2007, p.3138-3140
[139] Awulchew et al., 2009, p.157
[140] Fraenkel and Thake, 2006, p.226
[141] Argaw, 2003, p.66
[142] Argaw, 2003, p.67
[143] Fraenkel and Thake, 2006, p.217
[144] Jagadeesh, 2000, p.165
[145] Purohit, 2007, p.3139
[146] Purohit, 2007, p.3135
[147] http://www.kijitowindpower.com/references/world/world.htm
[148] Nambia Ministry of Mines, 2006, p.58-59
[149] Burnley et al., 2010, p.1851
[150] Purohit, 2007, p.3140
[151] Bouzidi et al., 2009, p.885
[152] Kohle et al., 2002, p.162-163
[153] Bouzidi et al., 2009, p.885
[154] Kohle et al., 2002, p.162-163
[155] Purohit, 2007, p.3140