

Energy savings using biofuel in a developing-country water distribution system

Alexandra Archer and Brian D. Barkdoll

ABSTRACT

The practical energy minimization algorithm (EMA) is introduced here to determine if a water distribution system (WDS) can be less energy dependent. The EMA is a simple algorithm that can be used by practitioners in the planning and management of WDS. The EMA employs the *Jatropha Curcas* (JC) tree as a source of oil for fueling water pumps. The EMA is demonstrated on a WDS in Senegal, West Africa, and calculates the level of JC production required to be self-sufficient in fueling the water system to meet drinking, sanitation, and JC irrigation requirements. It was found that the EMA successfully showed that the demonstration WDS can be energy self-sufficient to provide recommended amounts of drinking water for the people and enough irrigation for the JC trees, but only if greywater was used to supplement the irrigation and if a mechanical press was used in lieu of a hand press to extract the oil from the JC leaves. An adequate amount of oil was thus produced to power the required mechanical press as well. Payback periods of significantly less than the life of the required equipment indicate the viability of JC oil as fuel and the feasibility of having an energy independent WDS.

Key words | economics, Millennium Development Goals, payback period, poverty, social aspects, sustainability

Alexandra Archer
Brian D. Barkdoll (corresponding author)
Department of Civil and Environmental
Engineering,
Michigan Technological University,
Houghton, MI,
USA
E-mail: barkdoll@mtu.edu

INTRODUCTION

Drinking water systems use significant amounts of energy for pumping water to high-elevation neighborhoods and tanks (Arora & LeChevalier 1998), with up to 80% of the cost being attributed to pumping in the USA (EPRI 2000). Pumping using electricity can also add to greenhouse gas emissions (Levin *et al.* 2002). Reducing emissions is a principal component of the United Nation's (UN) Development Goal (UNDG) on environmental sustainability, but is also true for developed countries. Not only is saving energy, and thereby reducing greenhouse gas (GHG) emissions, for pumping in water distribution systems (WDS) crucial in water conservation (Zhou *et al.* 2013), but also in system modifications (Ghimire & Barkdoll 2010), pumping operations (Stokes *et al.* 2015) and energy metrics (Dziedzic &

Karney 2015). Moreover, also related to this UNDG is access to clean and safe drinking water, which has been a primary goal in international development resulting in improved water supplies across the globe. Disparities still exist, however, between urban and rural populations and between males and females. As the primary water gatherers in many societies, women and school-aged girls suffer the most from water inaccessibility, resulting in missed school days and opportunities to pursue income-generating activities (Hope *et al.* 2012). Of those water distribution systems (WDS or system) implemented, many are not being used due to lack of fuel.

The *Jatropha Curcas* (JC) tree is a potential source of oil for fueling water pumps, since it can be easily propagated,

and is drought resistant, grows rapidly, is non-edible, and has high-oil-content seeds (Pandey *et al.* 2012). The branches of the tree contain latex, which is useful in repelling animals attempting to either eat the leaves or break through a JC hedge around edible crops (Henning 2004). JC requires a minimum of 600 mm of annual average rainfall and annual average temperatures above 20 °C (Simpson & Peer 2009a, 2009b). JC is well suited for growth on degraded and/or dry lands with potentially positive impacts on biodiversity and soil resources through reclaiming these wastelands and providing biological homes for other organisms (Maes *et al.* 2009). Due to having a single deep taproot and four shallower lateral roots, JC can prevent and control soil erosion caused by wind and water (Achten *et al.* 2008). Marginal or degraded lands are typically characterized by lack of water, low soil fertility or high temperatures. Bioenergy crops like JC that can tolerate these extreme environmental conditions, where food crops might fail, may offer the opportunity to put to productive use land that presently yields few economic benefits (FAO 2008). JC produces seeds with a high oil content (30–35%) that can be transformed into biodiesel fuel that has been used to power multi-functional platforms (MFPs) and water pumps for irrigation (Adhikari & Wegstein 2011). JC oil can be used directly in older diesel engines or engines running at a constant speed like pumps or generators (Achten *et al.* 2008), sometimes using degumming agents (Haldar *et al.* 2009). JC oil can also be used as a substitute for the ‘gazoil’ mixture used throughout Senegal and rural Mali where it fuels diesel engines that drive water pumps and grain mills (Henning 2004). JC has the climatic capability of being locally produced in semi-arid communities, where land production is low and poverty levels can be high. According to the Commission on Sustainable Development (2007), it will allow these communities to achieve a greater level of independence and assure a second source of fuel if diesel is either too expensive or simply not available (Eckart & Henshaw 2012). The integrated approach of using JC for rural development ensures that by planting hedges, economic and environmental benefits are also achieved. Four critical aspects of rural development are positively impacted by cultivating JC (Henning 2004): (1) energy supply in the rural area, (2) environment, when used to control erosion, (3) gender empowerment, when the JC cake and oil is used by women for local soap production (The Working Center 2009), and

(4) poverty reduction, when used to generate income through the selling of seeds and providing employment through the various stages of processing (harvesting, pressing, etc.).

JC oil is combustible in conventional engines and, therefore, makes a suitable biofuel. The high viscosity of JC does, however, tend to cause deposits and potential clogging of various engine parts. The viscosity can be lowered either by the addition of diesel fuel or by pre-heating the JC oil, perhaps with engine exhaust (Pradhan *et al.* 2014). For the purposes of this study, it is assumed that the engines have been modified to run cleanly on JC oil.

The objective of this study is to introduce and demonstrate a new practical algorithm to determine what is needed to minimize or eliminate energy consumption in a WDS through the use of JC biofuel.

DESCRIPTION OF COMMUNITY AND REQUIREMENTS

The demonstration system is from a rural village in Senegal, W. Africa, in a desert climate (Archer 2015). If values different from the input literature value assumptions made here are known for a specific WDS, then those could be used instead. The current WDS operates intermittently, due to the high expense and lack of availability of diesel to operate the pump that conveys water from the well to the system reservoir tank. Water flows by gravity from the tank to the villages and neighborhoods (Figure 1). Prior to applying the energy minimization algorithm (EMA), the system was upgraded to provide enough water to each junction to satisfy WHO minimum standards of 20 L/c/d and a continuous supply, thereby minimizing the amount of time villagers (typically women) must spend gathering water every day. The EMA helped identify the amount of JC trees to be planted and irrigated to make the WDS diesel independent.

PRACTICAL EMA

When analyzing the amount of energy independence of a WDS there are several possible variables to be considered. If an overly expensive and labor-intensive option is used, then the potential for the users performing the necessary

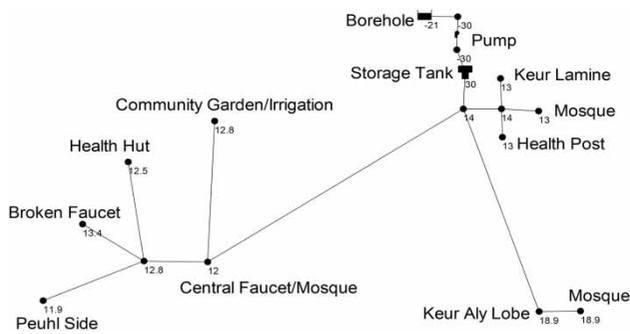


Figure 1 | Demonstration system. Numbers denote elevation in meters.

regular operation and maintenance tasks become insufficient and system failure is more likely. This is the motivation for the EMA proposed here. The pertinent decision variables include, in order of progressing JC production complexity: (1) simply using a hand press for JC oil extraction, (2) irrigating the JC with greywater, (3) also irrigating the JC from the water system, even though this will require more JC oil for pumping, and (4) adding a mechanical press instead of a hand press, even though the press will require more JC oil to fuel it.

JC trees can be planted in a community space or some trees distributed throughout the service area. Care must be taken in the planting of JC in a neighborhood or household that village growth, comfort, and safety are not compromised. Greywater from the service area can be directed into the JC area to reduce the amount of irrigation water needed from the water system itself. Approximately 70% of the water used by the users can either be collected in a container or dumped on the JC trees or flow by gravity through a ditch or pipe from the house to the JC trees, although the distance between the greywater source and the JC trees should be as close as possible to facilitate this. Dumping the greywater on the JC guarantees that all the greywater will reach the JC, but may take some amount of labor. Having a ditch will not take any labor but some greywater will be lost to infiltration and evaporation. A pipe will eliminate these evaporation and infiltration losses but is more costly. The energy density of JC is comparable to that of diesel, which allows for approximately the same volume of JC to be used for the same pumping time when diesel is used for the pump engine (Pramanik 2003). To eliminate gumming

it is recommended that phosphoric acid at a concentration of four percent is added to the JC oil, and stirred for ten minutes, settled for 1 week, and decanted (Haldar *et al.* 2009). Therefore, unless some diesel is added to the JC oil to reduce viscosity for the reduction of fuel gumming in the engine parts, relatively equal amounts of JC oil as diesel are typically used. (Haldar *et al.* 2009). If a user has reason to believe otherwise, then modifications to the proposed algorithm may be introduced.

An MFP consists of a simple diesel engine, which is used to produce electricity and power agricultural processing equipment such as an oil press for JC seeds (Grimsby *et al.* 2012). Using an engine-driven screw press, which can be powered by an MFP, 70 to 80% of the oil present in the seeds can be recovered (Achten *et al.* 2008; Ofori-Boateng & Lee 2011; Eckart & Henshaw 2012; Nahar & Ozoreshampton 2015), although it was assumed here that the incorporation of an MFP can increase the percent of usable oil recovered from each tree to a value of 23% to 55%, to be conservative. JC oil can be used directly to fuel the simple diesel engine used in MFPs (Eckart & Henshaw 2012). The possibility exists for a community group to create a formal organization to request and purchase an MFP, which is then subsidized by international organizations, private investors, or various non-governmental organizations. Local skilled workers can be in charge of installing, maintaining, and repairing the MFPs. A case study in Mali found the MFPs provided higher incomes, improved quality of life and social status, and allowed women to pursue educational opportunities and economic activities by freeing up 2–6 hours of a rural Malian woman's day (Simpson & Peer 2009a, 2009b).

Cost implications of the system can be quantified by the payback period (PP). PP is defined as the period of time required for a project to recover invested funds (Accounting Explained 2015) and incorporates initial, maintenance, and interest costs over time. The formula is used when cash inflows are uneven from year to year, as is the case in this study, when diesel prices are ideally lessening annually based on the increasing seed yields and resulting amount of JC oil produced in a given year. Alternatively, present worth or net present value methods could be used.

The EMA comprises the following steps (Figure 2):

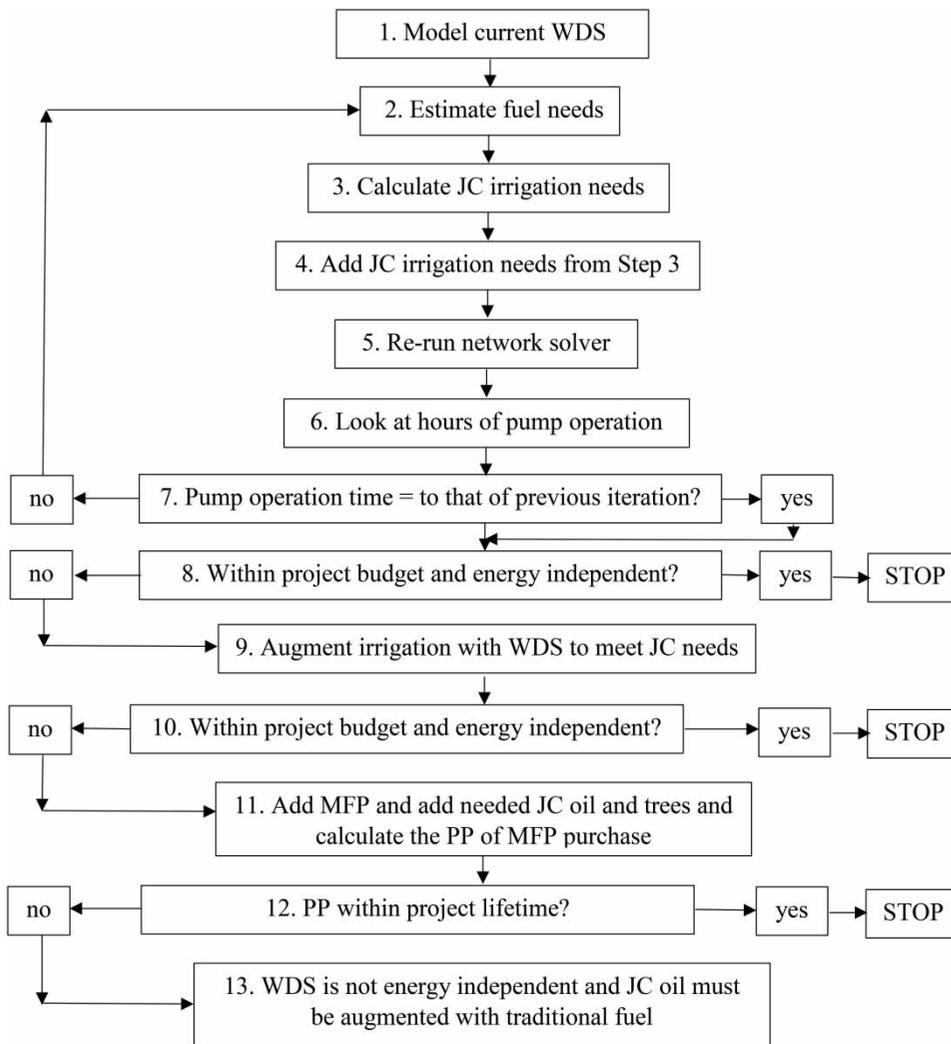


Figure 2 | EMA flowchart.

1. Model current WDS in a network solver using user demands for continuous, sufficient amounts to meet water needs according to the desired drinking water standards.
2. Estimate fuel needs based on the number of hours the pump is running and the amount of JC oil needed to fuel the pump for the required pumping time.
3. Calculate JC irrigation requirements to meet these fuel needs.
4. Add additional water demands in the WDS model for JC irrigation needs.
5. Re-run solver.
6. Look at the results for pump hours of operation.
7. Perform additional trials by repeating Steps 2 and 6 until the pumping time does not increase from the previous trial. Upgrade system with larger pipes or tanks to handle the increased water demands, if necessary.
8. If solution is within the project budget and is energy independent, then stop. Otherwise use greywater to augment irrigation.
9. If solution is within the project budget and is energy independent, then stop. Otherwise use an MFP to extract JC oil.
10. If solution is within the project budget, is energy independent, and the PP of purchasing the mechanical press is less than the project design life, then stop. Otherwise additional funds and/or some diesel or electricity must be used to supplement the use of JC.

Pipes, tanks, tank upper water level set points, and pumps may need to be enlarged to accommodate flow requirements to maintain adequate pressure values throughout the WDS. These changes are assumed to not affect water quality, but this should be considered for each WDS.

ALGORITHM DEMONSTRATION PROCEDURE

EMA Step 1: A hydraulic model of the current WDS was created using EPANET 2.0, a program developed by the US Environmental Protection Agency to simulate hydraulic flow within a pressurized pipe network (EPA 2000). The goal was to provide enough water to meet the WHO guidelines for basic access of 20 liters per person per day, while also supplying enough water to irrigate JC for seed production (WHO/UNICEF 2015) in sufficient quantities to make the WDS energy self-sufficient. System-wide pressures were desired to be at a minimum value of 20 psi (14 m of head) and a maximum value of 100 psi (70 m of head) (Mays 1999).

EMA Step 2: The system pump is powered by a diesel engine generator. An engine power of 6.7 kW was selected as the closest representative of the system generator. This generator consumes diesel at a rate of 3.0 liters per hour.

EMA Step 3: JC was used as an intercropping species incorporated into farmers' groundnut fields. A plant spacing of 15–25 cm was chosen (Openshaw 2000). 0.9 kg of dry seed per meter of hedge (Jongschaap *et al.* 2007) was used when calculating yield for the rain-fed, groundnut intercropped JC planting schemes. A yield of 2.5 tons/ha/yr for rain-fed plants was used (Achten *et al.* 2008). This value was chosen to be conservative compared to other reported yields ranging from 0.5–12 tons/ha and 5 tons/ha (Jongschaap *et al.* 2007). To extract the oil, the traditional technology of a hand-operated groundnut oil press was used when calculating process time and total oil production. The following data was taken from a case study conducted in Senegal (Simpson & Peer 2009a, 2009b). Using an antique groundnut press, 25% of the oil was recovered from the seeds and 25 kg of seeds were processed every 4 hours. Thus, a ratio of 4.375 kg of JC seeds to produce 1 liter of oil was used, although a higher yield has been observed (Adhikari & Wegstein 2011).

Based on the success of individual households producing JC for oil in Nepal (Karlsson & Banda 2008; Adhikari & Wegstein 2011) the likelihood of households producing the required amounts in all 196 households was thought promising. Total rainfall for the Koungeul Region of Senegal averaged 487 mm from 1990 to 2009 (Weingart 2015). The ideal, recommended irrigation amounts vary widely for JC. An optimal growth rate of the trees was found when 1,200 mm of water was available for the plants throughout the year (Beerens 2007; Jongschaap *et al.* 2007). Using this value, an additional 713 mm of water must be applied to meet the optimal water availability. The dry season for Keur Samba lasts approximately 300 days. To apply 713 mm over the dry season, it was assumed that the plants must receive 2.6 mm per day or 9.50 liters per plant per day, although that may be a conservative estimate since plants will require dry periods between irrigations to avoid disease problems. Depending on how the trees are originally propagated, JC trees can produce seeds after 9 to 12 months and are considered established after 4 to 5 years and will produce to their full capacity (Simpson & Peer 2009a, 2009b; Nahar & Ozores-Hampton 2015).

EMA Step 4: The dry-season diurnally varying household consumption demands were kept constant for all modeling scenarios. To determine if JC cultivation for oil production was feasible, an additional demand for irrigation was associated with each system node. This irrigation demand was proportioned using both the same number of households assigned to each node determined previously and according to the number of trees each household could be expected to cultivate.

EMA Step 5: When the new irrigation base demands were entered into the network solver, the system produced pressures below the minimum value. To offset piping head loss in the distribution system, the upper set point of the tank water level for the pump to start was increased, since the model was set up so that the pump turned on and off based on tank water levels.

EMA Step 6: When the model produced system pressures that remained above the minimum acceptable value, the pump time was then analyzed over the course of a week to determine the pumping duration and, therefore, the fuel requirement. In the existing system, the pump would need to be on for an additional 4.3 hours per day.

This pumping value was then used to re-calculate the diesel required to run the system for this amount of time each day in order to supply water for the village and for JC irrigation. The calculated value was 13 liters of diesel per day. This value was then used in calculating the next required irrigation amount to produce enough trees to provide 13 liters of JC oil. For the irrigated plantations, a yield of 2,500 kg/ha/yr was used as achievable for semi-arid areas (Achten *et al.* 2008).

EMA Step 7: Additional irrigation demands and JC trees were added until the amount of JC oil was sufficient to meet the pump fuel demands for pumping domestic and irrigation water.

EMA Step 8: Next, greywater was used for irrigation. A value of greywater recovery of 70% of the total household use was used (Godfrey 2010), meaning that an average household can apply 140 liters a day (14 l/p/d with 10 people on average per household, based on the authors' experience) to JC tree seed production. For this region of Senegal, greywater usage consists of draining cooking and bathing wastewater through a ditch or pipe from the house to the JC field.

EMA Step 9: To calculate the amount of water required and JC oil produced, the fact that an MFP needs 1.8 kg of JC seeds to produce 1 liter of JC oil and that about 77% of the JC oil can be extracted from the seeds (Ofori-Boateng & Lee 2011) was employed. In addition, for every one liter of fuel used in the crushing process, 21 liters of JC oil was produced (Weingart 2003).

EMA Step 10: A timeline of PP can be calculated that includes the purchase price of an MFP, if required, diesel costs, diesel savings, and surplus JC oil profit. Since the JC oil production starts low and gradually increases to maximum production after 5 years (Figure 3), a timeline is necessary.

ALGORITHM DEMONSTRATION RESULTS AND DISCUSSION

EMA Steps 1 through 7

Modeling revealed an annual amount of 2,190 liters of diesel is required to fuel the WDS. It was found that without greywater and a mechanical press, the water system pumps and piping needed to be upgraded to maintain acceptable pressure

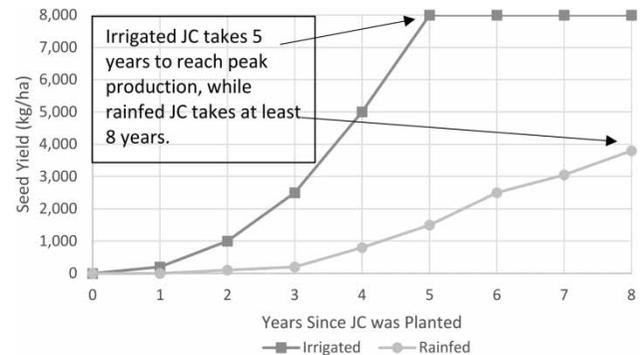


Figure 3 | Seed yield of rain fed and irrigated JC seeds from establishment to 8 years of age.

values throughout the system in such a way that the cost was prohibitive (Figure 3). With the addition of more JC, the irrigation demands became such that more JC was needed. Since only 23% of the JC oil could be extracted by a hand press, enough JC oil could never be extracted for that many JC trees without significantly larger tanks and pipes.

EMA Step 8: Greywater calculations

Using the irrigation requirement previously calculated of 9.5 liters/plant/day, each house would be able to irrigate 14.7 trees. Combining tree productions, the overall oil produced by the 2,881 trees is 659 liters annually. This could run the pump for 170.8 days (Figure 4). Incorporating recycled greywater into the required irrigation calculations for meeting the diesel needs reduces the diesel requirement from 2,190 liters to 1,025 liters (since 1,165 liters is provided by JC) to provide 20 liters of continuous water supply to each person per day for the population of approximately 1,000. The yield from rain-fed JC cultivation will remain the same as the previously calculated dry seed yields; however, the oil extraction efficiency increases. Therefore, the total JC oil produced was recalculated.

The use of a manual oil expeller decreases the efficiency of oil retrieved from the seeds; therefore, more trees must be cultivated to provide the same amount of oil that a mechanical oil expeller can provide. In order to make a recommendation that is cost-effective for the users of the WDS, two optional solutions are further investigated: (1) the use of greywater to irrigate the trees and (2) the incorporation of an MFP to increase the percentage of usable oil

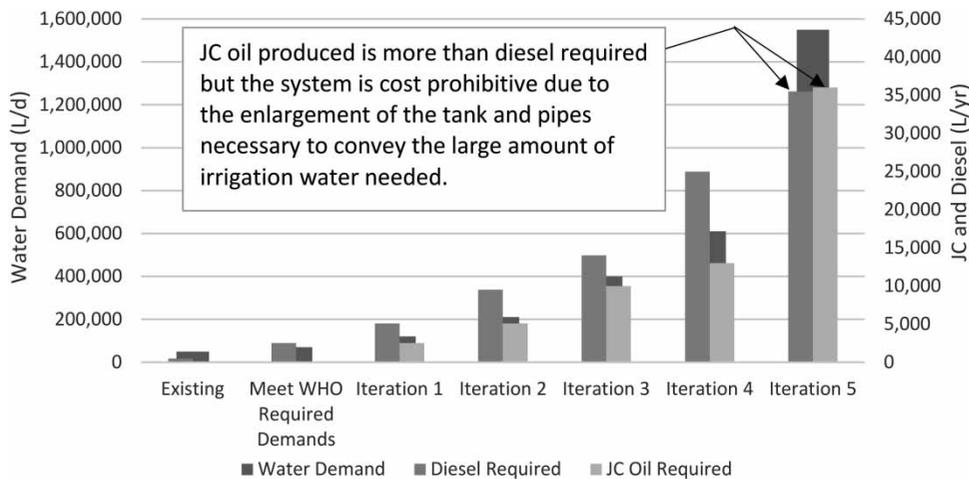


Figure 4 | Water, diesel, and JC oil required for EMA Steps 2 through 7.

recovered from each tree from 23% to 55%. Both of these solutions would decrease the demand for water from the WDS, therefore decreasing the amount of diesel/JC oil required to run the system.

EMA Step 9: Combining greywater with a mechanical press

Combining MFP extraction with recycled greywater would provide 1,599 liters of JC oil from the assumed total 1.15 ha of greywater-irrigated home gardens for the entire community. Using a value of 70% to represent water available to be applied as greywater for irrigation (Godfrey 2010), an average household can apply 140 liters per day (14 l/p/d with 10 people on average per household) to JC tree seed production. Using the irrigation requirement previously calculated of 9.5 liters/plant/day, each house would be able to irrigate 14.7 trees. Combining tree productions for all three communities, the overall oil produced by the 2,881 trees is 659 liters annually. This could run the pump for 170.8 days. Combining recycled greywater with irrigation to meet diesel requirements for basic, continuous access water supply to communities yields a total area of 1.79 ha, 2,500 plants per ha, a yield of 2,500 kg dry seed per ha, a seed yield of 4,475 kg, and 1,025 liters of JC oil produced.

This brings the total JC oil produced up to 2,828 liters annually. The WDS requires 2,190 liters, leaving 638 liters to fuel the MFP. A value of 2.2 kg, or 1.7 liters, of JC oil consumption per hour for an MFP powered by a 10 HP liter

engine was used (Sanga & Meena 2008; Grimsby *et al.* 2012), although other values have been reported (Rordorf 2011). The greywater-irrigated JC trees could produce enough oil to run the MFP for approximately 375 hours or approximately an hour a day. Using these values, JC trees could fuel the MFP for 491 hours or approximately 1.3 hours a day. When new irrigation demands were entered into EPANET for JC production with a mechanical oil extractor, pumping time to provide supply and fill up the reservoir tank increased from 2 to 2.7 hours to meet irrigation and basic use water demands. However, there was still an increase of 782 liters of diesel required to run the system. Since 21 liters of JC oil was produced for every liter of fuel used in the crushing process (Weingart 2015), the 638 liters of JC oil would provide enough fuel to process 13,395 liters of additional JC oil, thereby rendering the system energy self-sufficient (Figure 5).

EMA Step 10: PP

In addition, the possibility of selling extra JC oil for profit exists (Archer 2015). The use of a mechanical press provides the best financial returns to a community, but it is important to investigate how the initial purchase of an MFP would financially impact the community. The Senegalese government and outside donors are willing to subsidize this cost to help communities that show interest and are willing to financially commit to the project (Treister 2007). If a community purchased an MFP, they are expected to pay

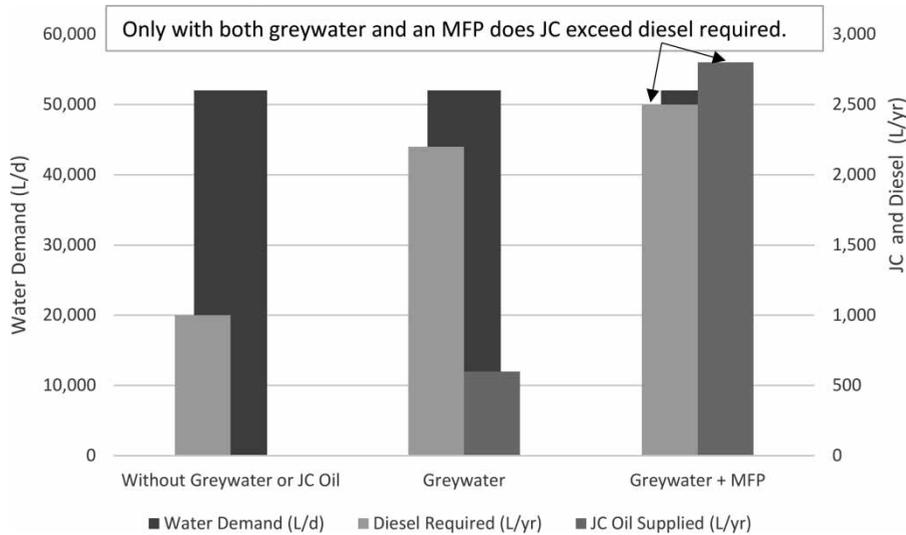


Figure 5 | Calculated water demand on WDS including user and irrigation requirements, the required diesel to fuel the system, and JC oil produced by the EMA Steps 8 through 11.

anywhere from 20–50% of the total cost, approximately \$4,000, which includes the engine, battery charger, platform housing, rice de-huller, and mill (Weingart 2015). The possibilities exist for government assistance in obtaining an MFP for suitable communities (United Nations 2015). For this study, an initial investment of \$1,000 on the communities' part will be considered (Ofori-Boateng & Lee 2011).

Since JC production increases over the first 5 years (Figure 3), for the initial 2 years, the communities can expect to have to purchase 100% of the diesel required to run the WDS. However, using the yield prediction calculations from above, the communities can expect an increasing production of JC oil with which they can begin to replace diesel to run the MFP and WDS generator. To recover the initial \$1,000 investment of an MFP and pay for diesel in the initial 5 years until full JC oil production is realized, the calculated PP was 9 years (Table 1), and only 8 years if the MFP is donated. After this PP is realized, the system was energy self-sufficient and produced extra JC oil for profit thenceforth. It was assumed that other costs such as maintenance on the MFP were minimal or were performed by the users.

CONCLUSIONS

The newly introduced, simple, easily implemented EMA performs well on the demonstration system used here from

a typical developing-nation WDS. The algorithm was able to show that it is possible to run a water system with no electricity or diesel. This is important, since it will allow the more sustainable design of water systems and give the residents a more reliable water supply.

DISCUSSION

While the results estimate that JC can make this WDS energy self-sufficient, there is a byproduct, phorbol esters, of JC that is carcinogenic. Although not suggested here, means of removal should be employed (Masten *et al.* 2015) if JC is to be used as feedstock.

Other renewable energy sources exist such as solar, wind, and biogas. Although these are beyond the scope of this work, the designer should consider these as well. One advantage of using JC over solar and wind is that energy could be produced on cloudy, windless days. Solar and wind, however, may not need any pressing equipment or as much labor.

The configuration suggested here, that of growing JC trees, harvesting the seeds, pressing them in an MFP, and using the JC oil for running the MFP and the water pump(s), is a self-contained system that does not depend on any other infrastructure services, such as electricity, roads, etc. Labor is required, but often labor is inexpensive or free in rural communities in developing countries. The incentive for performing the labor is

Table 1 | Timeline for PP calculation for a combined MFP and recycled greywater showing a PP of 9 years (bold)

Yr	Seed yield kg	Expenses			Savings		Annual net	Cumulative
		Purchase price	Annual diesel purchase	MFP fuel cost	Diesel	Surplus oil production		
0	0	-\$1,000	\$0	\$0	\$0	\$0	-\$1,000	-\$1,000
1	10	\$0	-\$3,828	\$0	\$0	\$0	-\$3,828	-\$4,826
2	125	\$0	-\$3,721	-\$9	\$107	\$0	-\$3,624	-\$8,452
3	649	\$0	-\$3,276	-\$47	\$552	\$0	-\$2,772	-\$11,224
4	1,581	\$0	-\$2,484	-\$115	\$1,344	\$0	-\$1,255	-\$12,480
5	2,921	\$0	-\$1,345	-\$212	\$2,483	\$0	\$926	-\$11,554
6	4,670	\$0	\$0	-\$340	\$3,828	\$142	\$3,629	-\$7,924
7	4,670	\$0	\$0	-\$340	\$3,828	\$142	\$3,629	-\$4,295
8	4,670	\$0	\$0	-\$340	\$3,828	\$142	\$3,629	-\$666
9	4,670	\$0	\$0	-\$340	\$3,828	\$142	\$3,629	\$2,964
10	4,670	\$0	\$0	-\$340	\$3,828	\$142	\$3,629	\$6,593

present in the fact that excess JC oil can be sold as an income producing activity. This excess income can be used to improve the community's life in other ways. This makes it ideal for rural communities in developing countries.

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