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ENERGETIC, HYDRAULIC AND ECONOMIC EFFICIENCY OF AXIAL FLOW AND CENTRIFUGAL PUMPS FOR SURFACE WATER IRRIGATION IN BANGLADESH†

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ABSTRACT

With conventional centrifugal (CEN) pumps, less than 50% of southern Bangladesh's farmers invest in irrigation, partly due to high diesel energy costs. New policies are prioritizing sustainable crop intensification in Bangladesh's delta. This objective is unlikely to be achieved without fundamental changes in the energetics and economics of irrigation. Where surface water is available, axial flow pumps (AFPs) may comprise part of the solution to this problem. Comparing the hydraulic, energetic and economic performance of prototype AFPs and CEN pumps, the latter produced less yet consistent rates of discharge than AFPs at all heads. AFP discharge was conversely larger than CEN pumps, but inversely related to increasing head. Discharge per unit of fuel was highest for AFPs (+51 and +21% at 1- and 2-m lifts), but declined with rising head until convergence with CEN pumps at 2.8 m. High AFP discharge reduced irrigation time requirements. On average, AFPs can save between US$70 and 38 ha^{-1} season^{-1} for *boro* rice at 1- and 3-m heads, respectively, and between US$15 and 8, and 26 and 14 ha^{-1} season^{-1} for wheat and maize. Fuel efficiency reductions above 2.8 m highlight the importance of improved prototyping and technology targeting to ensure AFP deployment in environments where the greatest efficiency gains are achievable. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: axial flow pump; energy efficiency; hydraulic performance; sustainable intensification; surface water irrigation; energy–water nexus

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RÉSUMÉ

Avec des pompes centrifuges classiques (CEN), moins de 50% des agriculteurs du sud du Bangladesh envisagent d'investir dans l'irrigation, en partie en raison des coûts élevés de l'énergie diesel. De nouvelles politiques donnent priorité à l'intensification agricole durable dans le delta du Bangladesh. Cet objectif est difficile à atteindre sans des changements fondamentaux dans l'énergétique et l'économie de l'irrigation. Lorsque les eaux superficielles sont disponibles, les pompes à écoulement axial (AFP) peuvent constituer une solution à ce problème, au moins pour partie. En comparant les performances hydraulique, énergique et économique de prototypes AFP et CEN, ces derniers ont fourni des débits moins cohérents que AFP pour toutes les charges. Le débit AFP était à l'inverse plus grand, mais inversement proportionnel à la charge. Le débit par unité de carburant était plus élevé pour les AFP (+51 et + 21% pour des hauteurs relevées de 1 et 2 m, respectivement), mais a diminué avec l'augmentation de la charge jusqu'à ce qu'au point de convergence avec CEN, situé à 2.8 m. Le haut débit AFP réduit les délais d'irrigation. En moyenne, les AFP peuvent économiser entre US$70 et 38 ha^{-1} par saison pour le riz *boro* pour 1 et 3 m de relevage, respectivement, et de US$15 à 8, et 26 à 14 ha^{-1} par saison de blé ou de maïs, respectivement. Les réductions de consommation de carburant en dessous de 2.8 m de relevage soulignent l'importance de l'amélioration des prototypes et du ciblage de la technologie pour assurer le déploiement AFP dans des environnements où les plus grands gains d'efficacité sont réalisables. Copyright © 2015 John Wiley & Sons, Ltd.

MOTS CLÉS: pompe à flux axial; efficacité énergétique; performances hydrauliques; intensification durable; irrigation de surface; nexus énergie–eau

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INTRODUCTION

Increasing incomes and population growth projections indicate that global food requirements will expand until they plateau around 2050. To meet future food demands with current dietary habits, staple crop production will have to double (Godfray *et al.*, 2010). Meeting future food requirements will also require more efficient agricultural practices that spare natural resources—particularly fresh water—and that make more effective use of inputs such as fuel and fertilizer. Irrigated agriculture uses about 70% of available freshwater resources globally (Cornish *et al.*, 2004). In South Asia, more than half of all agricultural area is irrigated, but water use efficiency remains low (Molden, 2007). Bangladesh in particular presents a useful case study for these issues. As South Asia's most densely populated nation with nearly 1000 people km^{-1}, urbanization and industrial growth have resulted in increased competition for water resources and a 10% decline in agricultural land availability over the last 30 years (Chowdhury, 2010; Hasan *et al.*, 2013). Today, 50% of Bangladesh's agricultural lands are irrigated, contributing greatly to food security (World Bank, 2006), although doubts have surfaced regarding the sustainability of groundwater extraction for agricultural production, especially in light of the anticipated impacts of climate change (Hossain, 2009).

Beginning in the late 1990s, the expansion of deep and shallow tube wells in northern Bangladesh enabled farmers to widely adopt dry season *boro* rice production, bringing the country to near rice self-sufficiency (Rahman and Parvin, 2009). However, this 'irrigation boom' (*sensu* Shah *et al.*, 2003) was dependent on large energy reserves. Use of fuel and electricity for ground as opposed to surface water pumping contributes proportionally more to greenhouse gas emissions (e.g. Shah *et al.*, 2009), and has resulted in the drawdown of aquifers. Though there is considerable seasonal and grographic variance, Shamsudduha *et al.* (2009) indicate that groundwater is declining by between 0.1 and 0.5 m yr^{-1} in areas of intensive dry season *boro* rice cultivation in northern Bangladesh, particularly near Rajshahi and the High Barind Tract. When combined with rising diesel and electricity costs, this has increased the price farmers must pay to lift water to their fields (Chowdhury, 2010). Estimates are that the Government of Bangladesh (GoB) spends approximately US$1.4 billion yr^{-1} on energy subsidies to fuel pumps and sustain irrigation (Bangladesh Institute for Development Studies (BIDS), 2012). These issues have resulted in widespread concern about the physical and financial sustainability of Bangladesh's groundwater irrigation economy, thereby focusing attention on the need for more resource use efficient production strategies. In response, the GoB recently implemented the 'Master Plan for Development in the Southern Region', which encourages foreign donor investment of over US$7 billion to increase cropping intensity on currently fallow and rainfed crop land and to expand the use of dry season surface water irrigation (SWI) in southern Bangladesh (Ministry of Agriculture (MOA) and Food and Agriculture Organization of the United Nations (FAO), 2012).

The logic for such intervention is clear. Surface water is perceived as being abundant in parts of the south where river and canal networks have perennial flow, and where salinity levels do not cross crop-damaging thresholds. Conversely, saline shallow aquifers are common and prohibit the easy installation of shallow tube wells. Compared to the investment required to sink deep tube wells and vertically pump water, of low-lift surface water pumps are comparatively less energy intensive (Shah, 2009). SWI therefore offers a means by which double cropping could be encouraged on southern Bangladesh's fallow or rainfed and water-stressed dry season land, which is estimated to range from 136 000 to 800000 ha, depending on the year and estimation technique (cf. Rawson, 2011; MOA and FAO, 2012). An estimated 50% of southern Bangladesh's farmers currently grow only one rainfed rice crop per year; GoB policy therefore focuses on increasing the cropping intensity of these marginal farmers, with emphasis on moving them to double-cropping using surface water resources for irrigation (MOA and FAO, 2012).

SWI initiatives, however, are not new in Bangladesh. Previous GoB SWI investments included the 72 000 ha Gangees–Kabadak scheme and the Barisal irrigation project, which was planned for 42000 ha but achieved only 10 000 ha (Brammer, 2002). Farmers were initially asked to rent low-lift water pumps from parastatal organizations that were responsible for the management of minor irrigation works (Bangladesh Agricultural Development Corporation (BADC), 2012), though farmers were usually unwilling to invest in irrigation under these conditions. Lack of pump ownership, management difficulties, and lack of autonomy over irrigation supervision and planning caused coordination problems (Brammer, 2004). As a result, while surface water irrigation pumps are available, they are not found in sufficient densities to encourage widespread uptake of SWI practices.

Where SWI or low-lift pumps are available, they are most commonly centrifugal in nature. Introduced in the 1970s, CEN pumps rely on the action of an internal spinning impeller located above the water surface, immediately below or horizontal with the point of discharge. CEN pumps are driven by an external engine to lift water through a flexible or rigid tube. This results from the negative pressure created by the centrifugal force made by the impeller. Water is then expelled through an outlet. Before use, it is necessary to 'prime' CEN pumps by adding water through the discharge point until the entire tube and interior pump system is completely filled to avoid efficiency losses resulting from air pockets in the suction system. Despite the availability

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of centrifugal pumps, they have not been widely adopted by farmers in southern Bangladesh.

To address these issues, this paper examines the potential impact of an alternative low-lift SWI technology, the axial flow pump (AFP). The AFP is widely used in the deltaic environments of Thailand and Vietnam, where irrigation head requirements are low, and where large volumes of water need to be lifted at low pressure (Kay and Hatcho, 1992; Biggs, 2011). A typical AFP consists of an impeller encased in and located at the base of a sealed and inflexible pipe. The impeller is driven by an internal or external shaft, which is in turn driven by pulley mechanisms or direct coupling to an engine. Unlike centrifugal pumps, AFPs do not need to be primed. In Asia, use of AFPs for SWI can be traced back to the 1970s in the Mekong Delta, where farmers innovated and reversed their boat propellers to lift water from rivers for rice cultivation (Biggs, 2011). Use of the AFP in Thailand enabled many farmers to move from single to double rice cropping (Chinsuwan and Cochran, 1986). Today, there exists a mature AFP manufacturing industry in Thailand and Vietnam, although in Bangladesh, AFPs remain relatively unknown, despite the country's similar deltaic geomorphology and potential for SWI.

In this paper, we assess the potential of AFPs for SWI in Bangladesh, by comparing different prototype AFPs to CEN pumps as a control. All pumps were assessed for their hydraulic and energetic performance. We hypothesized that the AFPs would show superior performance at low head, with declining performance as head increased. We implemented additional *ex-ante* economic comparisons to assess the potential economic performance of AFPs with respect to capital investment and variable costs, field irrigation time requirements, and fuel-use break-even scenarios. The latter analysis assessed the feasibility of investing in a prototype AFP to irrigate dry season *boro* rice (*Oryza sativa*), wheat (*Triticum aestivum*) or maize (*Zea mays*), the three primary cereals grown in Bangladesh that make substantial contributions to food and income security.

MATERIALS AND METHODS

Hydraulic and economic efficiency performance tests of axial flow and centrifugal pumps were conducted from April to May 2013 at the Bangladesh Agricultural Research Institute (BARI) in Gazipur, Bangladesh (23° 59' 13″; 90° 24' 51″). The experimental facilities consisted of a pond (620 m^2 surface area and 2.6 m depth), providing water for the tests. After pumping, water was deposited in a gauged concrete-lined test bed (6.1 m long, 0.72 m deep and 1.25 m wide) located parallel to, and 2 m from, the edge of the pond. The water level in the pond was controlled daily by replacing any water losses through pumping, seepage, or evaporation.

Pumps were placed perpendicular to the bank of the edge of the pond. The engines utilized to run the pumps were located 1.5 m from the pond bank, and perpendicular to the pumps. Power was transmitted to the pumps with 'V-shape' rubber belts connecting the engine and pump pulleys. In all cases, power transmission was arranged to assure maximal water discharge from each pump as measured over a period of 1 h during trial pre-test runs. Maximum discharge was an important objective in our tests, because most farmers interested in SWI in southern Bangladesh first consider cultivating water-intensive dry season *boro* rice above other crops, and thus seek to maximize flow for this flooded crop.

Four locally manufactured prototype axial flow pumps (AFP1, AFP2, AFP3 and AFP4) were compared with two commonly used centrifugal pumps (CEN1 and CEN2) to test their hydraulic and energy performance.[1] Each prototype trial run was repeated three times with individual replicate prototype pumps. Parameters recorded during the tests included engine fuel consumption (l h^{-1}) and pump discharge (l s^{-1}). To measure fuel consumption, an external transparent 5 l plastic tank was placed on top of the engine and connected by fuel valves. After running the pump so that water output stabilized, the fuel input into the tank was measured volumetrically before and after each run of the pump.

Pump hydraulic performance and energy efficiency

Hydraulic performance was assessed using the standard head versus discharge ($H\,Q^{-1}$) relationship for each pump. As a measure of energy efficiency, the consumption of fuel compared to water discharge by all pumps was calculated using Equation 1:

$$F = \frac{Q(H)}{f(H)} \tag{1}$$

where F is fuel use (m^3 water discharged l fuel used^{-1}), $Q(H)$ is discharge (m^3 h^{-1}) at the lift height H (m), and $f(H)$ is fuel consumption (l h^{-1}) at a given head H. Water horsepower (WHP) is a measure of the power transferred to water by an irrigation pump. It was calculated according to Equation 2:

$$WHP = \frac{w \times Q \times h}{75} \tag{2}$$

[1]All prototype pumps were manufactured in Bangladesh. AFP1 was 3.7 m long, 150 mm diameter, with 5 mixed flow impeller blades. AFP2 was 4.45 m long, 150 mm diameter, with 5 mixed flow impeller blades. AFP3 was 5.46 long, 150 mm diameter, with mixed flow 5 impeller blades. AFP4 was 3.8 m long, 146 mm diameter, with 2 axial flow impeller blades. AFPs 1–3 were made by Rahman Engineering. AFP4 was manufactured by Hira Engineering. Both centrifugal pumps were manufactured by Milnars Pumps, Ltd. Both used a 4.35 m long flexible hose to draw water and were 102 and 127 mm diameter, respectively. CEN1 had 10 and CEN2 had 7 impeller blades. The engines used to power the pumps included a 12.5 HP model S195N (Changchai Co. Ltd, Changzou, Jiangsu, China) and 10 HP model EM190 (Sifeng Group, Shandong, China). AFPs 1–3 and CEN1 used the former engine, while the latter was used for AFP4 and CEN2.

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where *WHP* is water horse power (HP), *w* the unit weight of water $\left(\frac{1000\text{L}}{\text{m}^a}\right)$, *Q* is pump discharge (m^3 s^{-1}) and *h* is head (m). Pump efficiency (PE) was subsequently calculated to isolate the pump from the engine system, following Equation 3 as

$$PE = \frac{WHP}{PIHP} \tag{3}$$

where PIHP is pump input horsepower derived from break horsepower assuming a 10% power loss.

Economic performance analysis

Ex-ante economic analysis included both fixed and variable costs, the former encompassing capital outlays (e.g. costs of a full pump set, engine, V-belts). Costs were collected from the local market. The fixed cost per year was calculated from the sum of depreciation and interest on the investment. Machinery depreciation was calculated for pumps and engines according to Equation 4:

$$D = \frac{C - (C \times d)}{n} \tag{4}$$

where *D* is depreciation (US dollar, or US$),[2] *C* represents the total capital cost (US$), *d* the depreciation rate at 15% following the FAO (1992), and *n* the use life of the machine (years). *n* was assumed to be 5 years for well-maintained pumps. The interest rate on an average capital investment was considered to be 11% of the capital cost. Interest on investment was calculated following Equation 5:

$$I = \frac{C + (C \times d)}{2} \chi\, i \tag{5}$$

where *I* is interest on investment, *C* the capital cost, *d* the depreciation rate (15%) and *i* the bank interest rate (11%). The total fixed cost per year is simply the sum of *d* and *i* (US$ yr^{-1}). Variable input costs for dry season *boro* rice, wheat and maize were calculated using Equation 6:

$$V_C = \frac{V(f) \times I_c}{Q} \tag{6}$$

where V_C is the variable cost in question, $V(f)$ the variable cost of fuel (taken as US$0.78 l^{-1} according to our market research) consumed at each head level (US$ h^{-1}), I_c the measured irrigation rate for maize, wheat or *boro* rice (m^3 ha^{-1}) and *Q* is pump discharge *f* (m^3 h^{-1}) or the head level in question.

The physical properties of Bangladesh's soils (e.g. water-holding capacity, hydraulic conductivity, and porosity) vary widely. We therefore selected observations of high and low irrigation application rates for each crop grown near attainable yield and without water stress from peer-reviewed literature for Bangladesh. These values were used to model the outcomes of using AFPs and CEN pumps to irrigate *boro* rice, wheat and maize. In this sensitivity analysis, irrigation requirements were taken as 12800 m^3 ha^{-1} (high) (Sarkar and Ali, 2010) and 11700 m^3 ha^{-1} (low) (Rashid *et al.*, 1991) for *boro* rice, 3420 m^3 ha^{-1} (high) (Sarker *et al.*, 2010) and 2490 m^3 ha^{-1} (low) (Hossain *et al.*, 2008) for wheat, and 5600 m^3 ha^{-1} (high) and 3443 m^3 ha^{-1} (low) (Islam and Hossain, 2010) for maize. In all studies, only data for conventional water management and fully tilled, flat planting of crops were considered.

The variables $V(f)$, I_c and *Q* (m^3 ha^{-1}) were calculated on a yearly basis. $V(f)$ was calculated using Equation 7:

$$V(f) = F(h) \times f \tag{7}$$

where $V(f)$ is the variable cost of fuel (US$ h^{-1}), $F(h)$ is fuel consumption (l h^{-1}) and *f* is fuel price (US$ l^{-1}). We then calculated the break-even point considering the value of fuel savings per unit of land that could be achieved through use of the AFP compared to the CEN pump for each crop and head lift requirement, using the mean of field-collected data for each pump, following the first year of fixed cost investment and accumulation of variable costs by a hypothetical farmer irrigating with a prototype AFP. This break-even point for average AFP and CEN pump performance is calculated following Equation 8:

$$\text{BP} = \frac{\Delta C_i}{\Delta V(h)} \tag{8}$$

where BP is the break-even point (ha), ΔC_i is the difference in costs for the *i*th US$, and $\Delta V(h)$ is the variable cost savings (US $ ha^{-1}) per head level. Finally, we also analysed the potential command area performance of the pumps by measuring the time typically needed to irrigate 1 ha of *boro* rice, wheat and maize for high and low irrigation requirements assuming initial soil saturation, using the pump discharge at each lift. This was accomplished using Equation 9:

$$t = \frac{I_C}{Q(H)} \tag{9}$$

where *t* is the time required to irrigate (hours (h) ha^{-1}), I_C the irrigation requirement of a particular crop (m^3 ha^{-1}) and $Q(H)$ is pump water discharge in relation to each head level (m^3 h^{-1}).

Data for water discharge, fuel consumption and fuel use were also analysed using JMP software 8.0.2 (SAS Institute Inc., San Francisco), and were subjected to analysis of variance (ANOVA) between groups of pumps (AFP and CEN pump) at each head level, and within pumps (AFPs 1–4 and CEN pumps 1–2), also at each head level. Where significant effects were found, means were separated using Tukey's Honestly Significant Different test at α = 0.05. Least square means contrast statements were employed to

[2]Throughout this study, 1 US dollar = 77.7 BD taka in May of 2013 (Exchange Rates, 2013).

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separate the treatment means of each pump type. Where significant differences were detected, means were separated using the Student's *t*-test (α = 0.05).

RESULTS AND DISCUSSION

Hydraulic performance

Water discharge from prototype axial flow pumps was higher than centrifugal pumps at all lift heights (Table I), with significant differences detected at all head levels, although a negative relationship between lift height and discharge was also observed for the AFPs. For example, at 1-m head, average discharge of AFPs was 72% higher than CEN pumps, whereas at 2-m and 3-m heads, discharge of AFPs was 55 and 28% higher than CEN pumps, respectively. At 1-m head, maximum discharge obtained by AFPs was 215 $m^3 h^{-1}$, compared to 125 $m^3 h^{-1}$ for the centrifugal pumps. This clearly shows that the hydraulic performance of AFPs is significantly higher than CEN pumps at lower heads. For all pumps, significant differences ($P < 0.01$ for AFPs, and $P < 0.05$ for CEN pumps) were found between lift heights and discharge.

The average discharge of the AFPs decreased by 15% between 1- and 2-m lifts, whereas the decrease was only 25% between 2 and 3 m. In contrast, the reduction in discharge between 2- to 3-m lift was only 0.03% for CEN pumps. The hydraulic performance of AFPs was higher at low lifts (i.e. 1–2 m), although it dropped significantly as head increases. Conversely, CEN pump hydraulic performance was low at all heads, with a significant but slight decline as head increased. Although the water discharge obtained by the AFPs at 3-m lifts was significantly lower than 1-m lifts, they were still comparable with the CEN pump discharge at all heights. This indicates that the hydraulic efficiency of AFPs is higher than CEN pump in all respects. Karthival (2000) found similar results while comparing the performance of AFPs at different heads in India, obtaining maximum volumetric discharge of 226, 187 and 144 $m^3 h^{-1}$ at 1-m, 2-m and 3-m heads, respectively.

Table I. Water discharge ($m^3 h^{-1}$) at different head levels by pump model, horsepower and pump type.

Factor effects		Water discharge ($m^3 h^{-1}$) 1 m head	2 m head	3 m head	*F*-values
Pump model	AFP1[a]	215 A b	205 B a	168 C b	811**
	AFP2	245 A a	202 B a	172 C a	102**
	AFP3	216 A b	190 B b	145 C c	344**
	AFP4	186 A c	149 B c	111 C e	339**
	CEN1[b]	104 A e	100 B e	98 C f	67*
	CEN2	148 A d	141 B d	135 C d	44*
	F-values	1528**	333**	684**	
LS means contrast: pump type					
	AFP	215 a	187 a	149.3 a	
	CEN	125 b	120 b	116.3 b	
	F-values	1428**	1124**	1107**	

[a]Indicates prototype axial flow pump.
[b]Indicates centrifugal pump.
*Indicates significance at $P \leq 0.05$, and **indicates significance at $P \leq 0.001$.Values in columns not separated by blank rows sharing the same lowercase letter are not significantly different according to Tukey's Honestly Significant Different test at α = 0.05. Values in rows sharing the same upper-case letter are significantly different according to the same test. Values in columns for the least squares (LS) planned means contrasts for horsepower and pump type are significantly different at α = 0.05 according to the Student's *t*-test.

Fuel consumption

Comparing AFPs to CEN pumps, the former exhibited an asymptotic and declining trend in WHP as head increased, while the latter showed a linear and increasing trend. Despite this, WHP was greater for three of the four tested AFPs at 3-m lift, with the exception of AFP 4, which was 20% lower than CEN 2 (Figure 1).

Fuel consumption by AFPs was always higher and significantly different ($P < 0.001$) than for CEN pumps when compared within and across pump types (Table II). As for WHP, CEN pumps consumed relatively the same amount of fuel when measured across the two pumps at all

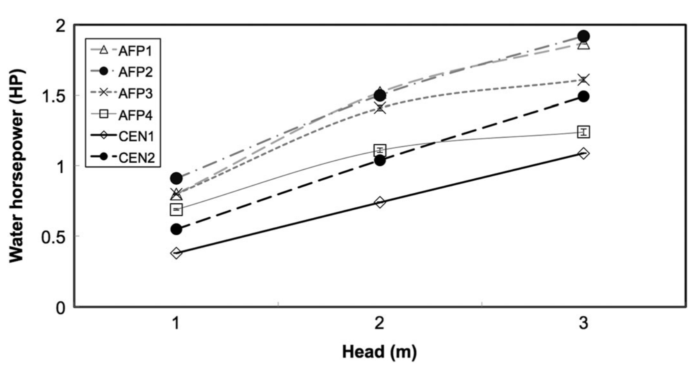

Figure 1. Water horsepower (HP) for prototype axial flow (AFP) and centrifugal (CEN) pumps at 1-, 2- and 3-m head. Bars indicate the standard error of the mean

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Table II. Fuel consumption (l h^{-1}) at different head levels by pump model, horsepower and pump type.

Factor effects		Fuel consumption (l h^{-1})			
		1 m head	2 m head	3 m head	*F*-values
Pump model	AFP1[a]	2.1 C b	2.2 B b	2.3 A b	152**
	AFP2	2.3 C a	2.4 B a	2.5 A a	7*
	AFP3	1.8 C c	2.1 B b	2.3 A b	228**
	AFP4	1.6 d	1.6 d	1.6 d	3 ns
	CEN1[b]	1.5 A d	1.4 B e	1.4 B e	17.*
	CEN2	1.8 c	1.8 c	1.8 c	3 ns
	F-values	189**	654**	333**	
LS means contrast: pump type					
	AFP	1.9 a	2.1 a	2.2 a	
	CEN	1.7 b	1.6 b	1.8 b	
	F-values	187**	1346**	806**	

[a]Indicates prototype axial flow pump.
[b]Indicates centrifugal pump.
*Indicates significance at $P \leq 0.05$, and **indicates significance at $P \leq 0.001$.Values in columns not separated by blank rows sharing the same lower-case letter are not significantly different according to Tukey's Honestly Significant Different test at α = 0.05. Values in rows sharing the same upper-case letter are significantly different according to the same test. Values in columns for the least squares (LS) planned means contrasts for horsepower and pump type not sharing the same lower-case letter are significantly different at α = 0.05 according to the Student's *t*-test.

lifts (1.7, 1.6 and 1.8 l h^{-1} at 1-, 2- and 3-m lifts), while AFPs consumed relatively more fuel (1.9, 2.1 and 2.2 l h^{-1} at 1-, 2- and 3-m lifts) at the same head levels. The differences in fuel consumption within AFPs were related to differences in the pumps' structural and impeller designs (mixed flow for AFPs 1-3, and axial for AFP 4), and in length and diameter, as well as the number of impeller blades.

Prototype axial flow pump efficiency

Integrating total dynamic head, volumetric water discharge and pump efficiency (the ratio of WHP to pump input HP, see Equation 3), AFP 2 performed relatively better than the other AFPs (Figure 2). Pump efficiency (without consideration of the engine) was 7.67 and 16.2% at 1- and 3-m head, with discharge of 245 and 172 m^3 h^{-1} for AFP 2, with significant differences between each head level ($P < 0.01$). Conversely, AFP 4 performed poorly, with low discharge at these heads (111 and 186 m^3 h^{-1}), with respective pump efficiencies of 5.8 and 10.4%. The pump efficiencies of AFPs 2 and 3 fell between these extremes. The higher efficiency of AFP 2 was most likely due to increased impeller number and design (five blades and mixed flow), compared to AFP 4 (with axial flow design blades). Despite the superior performance of AFP 2, the generally low pump efficiencies encountered indicate a substantial opportunity for Bangladeshi AFP manufacturers to improve pump design and production processes, with the ultimate objective of improving pump efficiency alongside fuel use efficiency.

Water delivery per unit of fuel use

Considering both fuel use and water delivery, AFPs delivered more water per unit of fuel use (m^3 l^{-1}) at 1- and 2-m lifts ($P < 0.01$ for both lifts), but not at the 3-m head level ($P < 0.001$; Table III). When measured across pumps, AFPs were 51 and 21% more efficient at converting fuel to water discharge at 1- and 2-m lifts in this regard, though at 1-m lift, 5% more fuel (4 m^3 l^{-1} on average) was required to deliver the same volume of water as the centrifugal pumps. Comparing pumps at each lift, significant differences were also found at 1-, 2- and 3-m heads ($P < 0.01$ for each level). Shah (2009) examined the relationship between irrigation pump type, fuel consumption and CO_2 emissions in India, and found SWI low-lift pumps to typically be low-emission. Our data indicate the potential to reduce the greenhouse gas (GHG) footprint of SWI where farmers make use of AFPs rather than CEN pumps for low lifts in Bangladesh's delta, though additional research is necessary to confirm this hypothesis. Additional policy action to support the use of fuel-efficient and thus potentially lower GHG-emitting

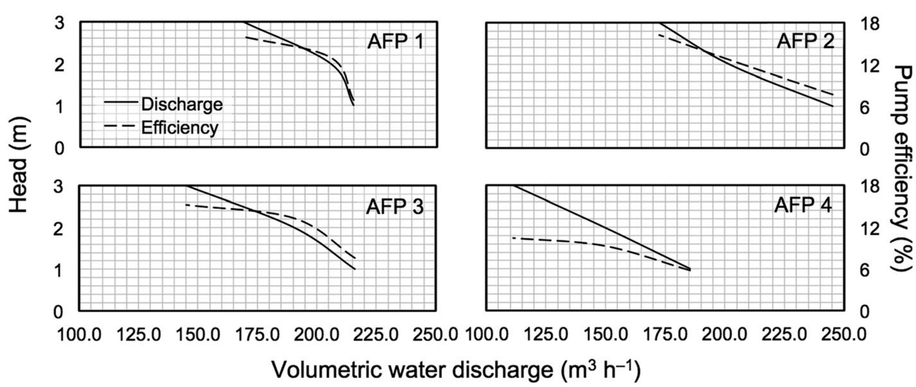

Figure 2. Integration of total dynamic head, volumetric water discharge, and pump efficiency for four prototype axial flow pumps (AFPs) tested in Bangladesh

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Table III. Water delivery per unit of fuel consumed ($m^3\ l^{-1}$) at different head levels by pump model, horsepower and pump type

Factor effects		Water delivery per unit of fuel consumed ($m^3\ l^{-1}$)			
		1 m head	2 m head	3 m head	*F*-values
Pump model	AFP1[a]	104 A b	95 B a	73 C ab	1240**
	AFP2	106 A b	84 B bc	70 C bc	250**
	AFP3	120 A a	90 B ab	66 C d	485**
	AFP4	120 A a	93 B a	68 C cd	301**
	CEN1[b]	67 B d	71 A d	70 AB bc	9*
	CEN2	82 A c	79 B c	75 C a	33*
	F-values	333**	49**	19**	
LS means contrast: pump type					
	AFP	112.4 a	90.7 a	69.0 a	
	CEN AV	74.5 b	75.0 b	72.7 b	
	F-values	1422**	192**	30**	

[a]Indicates prototype axial flow pump.
[b]Indicates centrifugal pump.
*Indicates significance at $P \leq 0.05$, and **indicates significance at $P \leq 0.001$.Values in columns not separated by blank rows sharing the same lower-case letter are not significantly different according to Tukey's Honestly Significant Different test at α = 0.05. Values in rows sharing the same upper-case letter are significantly different according to the same test. Values in columns for the least squares (LS) planned means contrasts for horsepower and pump type are significantly different at α = 0.05 according to the Student's *t*-test.

pumps should be encouraged as efforts to develop SWI resources in South Asia increase (cf. Molden, 2007; Shah, 2009).

Fitting second-order polynomial equations to the average performance of the different pump types across all lifts, we determined that the break-even point between AFP and CEN pump types for energy efficiency (as measured by the fuel consumption to discharge ratio) is 2.8-m head (Figure 3). In other words, up to a lift of 2.8-m height, the prototype AFPs used proportionally less fuel per unit of water delivered compared to CEN pumps. When exceeding 2.8-m, this efficiency is lost—while the tested AFPs continued to deliver more water (up to 33 $m^3\ h^{-1}$ at 3 m, Table I) than CEN pumps, fuel consumption becomes higher (+0.5 $l\ h^{-1}$ at 3 m, Table II) (Figure 3).

This trade-off offers important information for examining the potential performance of each AFP prototype when used for low-lift SWI in deltaic environments like Bangladesh, where water can be lifted from rivers and canals and then directed to farmers' fields for irrigation. Spatial analyses that assist in the targeting of technologies (e.g. Schulthess *et al.*, 2014; Chandna *et al.*, 2012) to particular, and ideally suited locations based on georeferenced landscape and temporal information pertaining to tidal freshwater availability, could assist in the deployment of AFPs for efficient use in the field.

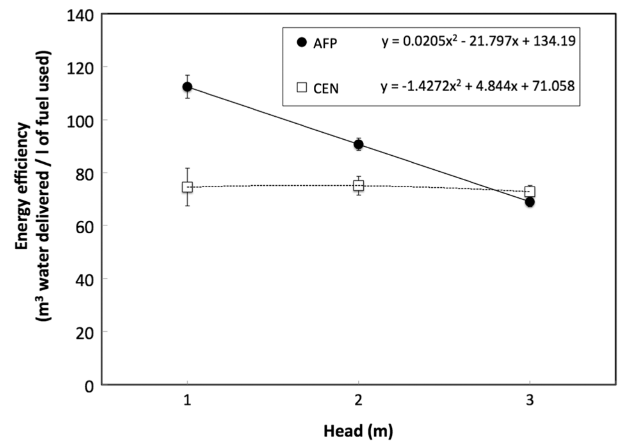

Figure 3. Energy efficiency break-even point for prototype axial flow (AFP) and centrifugal (CEN) pumps as determined by the best-fit second order polynomial equations fitted to the fuel consumption to water discharge ratio (m3 water delivered per meter of fuel consumed at 1 to 3-m head). Bars indicate the standard error of the mean

Ex-ante economic performance

Until the late 1980s, the Bangladeshi government was responsible all irrigation management and deployment of pump sets to farmers. After this period, restrictions on private sector imports of small engines and irrigation equipment were removed, which ushered in the growth of an independently operated irrigation water economy (Hossain, 2009). Today, irrigation is supplied to farmers primarily by private service providers, who as local entrepreneurs invest in pump sets and supply water on a fee-for-use basis, although in some cases groundwater and to a lesser extent surface water pumping equipment is owned by farmers' groups collectively (Palmer-Jones, 2001). In the current study, the average fixed costs for a hypothetical service provider investing in an AFP was 21% higher than those of centrifugal pumps (Table IV). Costs ranged from US \$195 to 165 yr^{-1} for AFPs and US\$160 to 130 yr^{-1} for centrifugal pumps. In all cases, engine depreciation made up the largest proportion of the fixed costs, followed by repair and maintenance. Importantly, the unit costs of the prototype AFPs used in this study may be slightly higher than the market price. This is because the AFP market is not yet widely developed, and prototype pumps have high manufacturing and transaction costs. However, costs are likely to decrease over time if farmer adoption of AFPs is widespread and manufacturers react with increased supplies.

We next explored the consequences of investment and irrigation via the average of the prototype AFPs for three key irrigated dry season cereal crops in Bangladesh—*boro* rice, wheat and maize—all of which typically have different irrigation water requirements, and which can be grown using surface water lifted from canals and rivers. The GoB

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Table IV. Capital and fixed costs (US$[a]) for the prototype axial flow (AFP) and centrifugal (CEN) pumps.

Cost variable	Axial flow pumps					Centrifugal pumps		
	AFP 1	AFP 2	AFP 3	AFP 4	AFP mean	CEN 1	CEN 2	CEN mean
Capital cost (US$)								
Pump	142	136	128	94	125	41	61	51
Engine	415 [b]	415 [b]	341 [c]	415 [b]	397	341 [c]	415 [b]	225
V-belt	6	6	6	6	6	6	6	6
Total capital costs (US$)	563	557	476	515	528	388	482	435
Annual costs (US$ yr^{-1})								
Depreciation of engine quality	70	70	58	70	67	58	70	64
Depreciation of pump quality	24	23	22	16	21	3	5	4
Interest on average capital investment (15%)	44	44	37	40	41	29	37	33
Repair and maintenance (10% of capital)	56	56	48	52	53	39	48	44
Total annual fixed costs	195	193	165	178	183	129	160	145
Total capital and fixed costs in the first year of investment (US$)	758	750	641	693	711	517	642	580

[a]The value of the 2013 US dollar was employed using the 16 September 2013 Bangladesh taka (BDT) exchange rate of 1 US$ = 77.77 BDT (Exchange Rates, 2013).
[b]Indicates use of a 16 HP engine.
[c]Indicates use of a 12 HP engine.

has for decades placed attention on *boro* rice because of its contribution to food security and consequent political stability (see Hossain, 2009; MoA and FAO, 2012). Wheat is the country's second most widely grown field crop, while maize production is now increasing more rapidly than any other cereal in response to the burgeoning poultry and fish feed sectors (Timsina *et al*., 2010; Rawson, 2011). *Boro* grown in Bangladesh requires about 3000 l of water per kg of grain produced, often applied through over 20 irrigations per season. In comparison, wheat requires 1–3 irrigations and 1000 l water kg grain^{-1}, while maize requires 850 l kg grain^{-1} and between 2 and 4 irrigations (Ali *et al*., 2009). Because AFPs require 22% more investment than CEN pumps on average, we investigated the potential to break even both in terms of the number of hectares of land of *boro* rice, wheat and maize that would need to be irrigated to reap the benefits of fuel savings from AFPs at 1- and 2-m lifts (and the trade-offs at 3-m lifts) relative to the lower investment costs in CEN pumps, and also in terms of irrigation time savings accrued from use of AFPs. The latter analysis is important because the reduction in time requirements for irrigation could release irrigation service providers who sell water to farmers on a fee-for-service basis, as is common througout Bangladesh, from extended irrigation time commitments in a particular command area, allowing them to move pumps to new locations and serve larger groups of farmer-clients in different irrigated areas.

Considering a fuel cost of US$0.78 l^{-1}, and each crop's irrigation water requirement under high and low water use scenarios, fuel savings for *boro* rice resulting from the use of an AFP were US$40, 20 and −7 season^{-1} for the high requirement scenario at 1-, 2- and 3-m lifts (Table V). This compares to US$70, 59 and 38 under the low water use scenario. As such, an irrigation pump owner servicing *boro* rice farmers would need to supply water to a minimum of 3 or 5 ha at 1-m lift to break even on variable costs in the low and high scenarios, respectively, in the first year of AFP investment, according to data from the prototypes. By comparison, 9 and 3 ha would be required at 2-m lifts for low and high water requirements. The increase in land area required is representative of the decrease in fuel use to water delivery ratio as head increases. At 3-m lifts and under the high water use scenario, our analysis indicates that it would be impossible to break even on the investment by irrigating *boro* rice in the first season after purchase because of the reduced efficiency of the prototype AFPs at lifts in excess of 2.8 m, although higher-efficiency AFPs with improved manufacturing may not have this constraint. Under the low water use scenario, 5 ha would be required to break even using the prototypes. Because much of southern Bangladesh's delta is tidal in nature (MoA and FAO, 2012), service providers are likely to benefit the most when AFPs are used at high tide, so as to make use of lower head levels not in excess of 2.8 m.

For wheat, the area requirement to break even at 1-m head was 17 and 12 ha under the high and low scenarios. At 3-m head, 31 or 22 ha would be required, respectively. Use of AFPs on surface areas smaller than these would result in the pump owner's inability to break even on the prototypes in the initial season following investment, unless he or she differentiated crops by seeking to service farmers growing more high-water-demanding crops (e.g. by mixing *boro* and wheat farmer clients within a command area). For maize, which requires 2180 and 953 m^3 ha^{-1} more water

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Table V. Required irrigated land surface area (ha) and value of fuel-saving requirements from prototype axial flow pumps (AFP) relative to centrifugal (CEN) pumps (US\$ season^{-1}) for *boro* rice, wheat and maize, to break even on the first-year variable investment costs investment following the purchase of an AFP[a]

Crop	Head (m)	Irrigation rate sensitivity analysis					
		High			Low		
		Variable cost (US\$ season^{-1})	Value of fuel savings (US\$ season^{-1})	Required irrigated area to break even (ha)	Variable cost (US\$ season^{-1})	Fuel savings relative to CEN (US\$ season^{-1})	Required irrigated area to break even (ha)
Boro rice	1	82.2	39.8	4.6	97.2	70.3	2.6
	2	101.3	20.0	9.1	107.3	59.0	3.1
	3	132.5	−7.1	−25.7	133.7	38.0	4.8
Wheat	1	5.1	10.9	16.7	20.7	15.0	12.2
	2	16.6	9.2	19.9	22.9	12.6	14.5
	3	20.7	5.9	30.9	28.5	8.1	22.5
Maize	1	20.9	15.1	12.1	36.4	26.4	6.9
	2	23.0	12.7	14.4	40.2	22.0	8.3
	3	28.7	8.2	22.3	50.0	14.3	12.8

[a]The value of the 2013 US dollar was employed using the 16 September 2013 Bangladesh taka (BDT) exchange rate of 1 US\$ = 77.77 BDT (Exchange Rates, 2013).

than wheat under the high and low scenarios, 12, 14 and 22 ha would be required to break even for the high water requirement at 1-, 2- and 3-m lifts, compared to 7, 8 and 13 ha under the low scenario. This indicates that the prototype AFPs would be most immediately useful for irrigation pump owners who provide irrigation services to farmers growing more water-demanding crops, though primarily at low water lift heights. Similarly, AFP owners could also find viable markets in freshwater aquaculture, where large volumes of water must be moved at low lifts from pond to pond, or to fishponds, at low lifts. Conversely, this situation could also facilitate new irrigation service provider business models that favour lower irrigation pricing due to the fuel savings accrued from use of AFPs at low lifts, especially where reduced irrigation time requirements enable service providers to move pumps to new command areas and service larger numbers of farmer-clients.

The above business model could potentially be feasible because AFPs require less time to irrigate 1 ha of land as compared to centrifugal pumps (Table VI), though modular and lightweight pump designs would aid in improving pump mobility. The maximum time required to irrigate 1 ha of *boro* rice for the duration of the season under the high water requirement scenario by the mean of the prototype AFPs was 86 h compared to 110 h for CEN at 3-m lift height. At 1- and 2-m heads, 43 or 38 less h of pumping would be required under the high scenario, while 39 and 34 h less would be required for the low irrigation rate scenario for

Table VI. Projected total irrigation time (h ha^{-1}) required under high and low irrigation rate scenarios for *boro* rice, wheat and maize at 1, 2 and 3 m head lifts considering the mean performance axial flow and centrifugal pumps

Head lift (m)	Crop species											
	Boro rice (h ha^{-1})[a]				Wheat (h ha^{-1})[b]				Maize (h ha^{-1})[c]			
	High scenario		Low scenario		High scenario		Low scenario		High scenario		Low scenario	
	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN
1	59.4	102.2	54.3	93.4	15.9	27.3	11.6	19.9	26.0	44.7	16.0	27.5
2	68.5	106.2	62.7	97.1	18.3	28.4	13.3	20.7	30.0	46.5	18.4	28.6
3	85.7	110.1	78.3	100.6	22.9	29.4	16.7	21.4	37.5	48.2	23.1	29.6

[a]High scenario is 12 800 m^3 ha^{-1} (Sarkar and Ali, 2010). Low scenario is 11 700 m^3 ha^{-1} (Rashid *et al.*, 1991).
[b]High scenario is 3420 m^3 ha^{-1} (Sarker *et al.*, 2010). Low scenario is 2490 m^3 ha^{-1} (Hossain *et al.*, 2008).
[c]High scenario is 5600 m^3 ha^{-1}. Low scenario is 3443 m^3 ha^{-1} (Islam and Hossain, 2010).

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the same crop species. When compared to centrifugal pumps, our data indicate that use of the prototype AFPs would save about US\$70 season^{-1} at 1-m head for low water requirements for *boro*, compared to US\$38 season^{-1} at 3 m. Similar trends were observed for wheat and maize, though projected time savings are higher for the latter due to greater water requirements resulting from increased biomass yield (and hence evapotranspiration) under both high and low irrigation scenarios. This implies that pump operators could potentially charge less for irrigation in cases where the number of hours a pump is running is the variable that determines pumping cost, though irrigation service providers would have to make efforts to move pumps to serve more farmer-clients to recuperate investment costs in the first year of use.

CONCLUSIONS

Compared to CEN pumps, the hydraulic performance of the prototype AFPs was higher at low lifts although it dropped significantly with increasing head and converged with CEN pumps at 2.8 m. The CEN pumps produced lower and more consistent (though slightly declining) discharge than AFPs at all head levels. At 1-m head, the average discharge of the AFPs was 72% higher than centrifugal pumps, whereas at 2- and 3-m heads, discharge was 55 and 28% higher, respectively. Although the discharges obtained by the AFPs at 3-m lifts were significantly lower than 1-m lifts, they remained comparable to CEN discharge at all lift heights. This clearly indicates that the hydraulic efficiency of AFPs is higher than CEN in all respects at low lift levels.

WHP showed a linear and increasing trend as head increased for CEN pumps, whereas AFPs exhibited an asymptotic and declining trend. Water delivery per unit of fuel was highest in AFPs at 1-m head, although this variable was inversely proportional to increasing head. This was not the case for CEN pumps where water delivery per unit of fuel use remained almost constant. The volume of water delivered per unit of fuel consumed by the prototype AFPs was on average +51% higher than centrifugal pumps at 1- and 2-m head (+21%), but declined to –0.05% at 3-m heads, respectively. The tested AFPs used proportionally less fuel per unit of water delivered up to a head of 2.8 m compared to CEN pumps. Further research is needed to investigate the potential contribution of AFP use in the mitigation of greenhouse gases resulting from fuel use in irrigated agriculture. After 2.8 m of head, the tested AFPs continued to deliver more water than CEN pumps, though fuel use became proportionally higher. Due to high discharge, AFPs reduce the time required to irrigate *boro* rice, wheat and maize, with the greatest time-saving benefits resulting when more water-consumptive crops are irrigated.

Compared to CEN pumps and where irrigation volume requirements are low, AFPs can save between US\$70 and 38 ha^{-1} season^{-1} for *boro* rice when water is lifted at 1- and 3-m heads, respectively, and US\$15–8 and 26–14 ha^{-1} season^{-1} for wheat and maize at the same lifts. In conclusion, the prototype AFPs showed potential for considerable fuel savings; opportunities may exist for irrigation service providers to modify their business models to reduce irrigation costs and thus the cost of production for farmers, provided that they are able to recuperate the number of farmer-clients by moving pumps and/or by diversifying with water supply to more water-demanding crops. In summary, the use of more resource use efficient yet niche technologies such as the AFP can be an effective tool to mitigate the increasing energy costs derived from irrigation, and to encourage the wise use of SWI for sustainable intensification in deltaic environments like southern Bangladesh.

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