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Stockholm Environment Institute, Working Paper - 2011

Carbon Footprint of Agricultural Development: the Potential Impact of Uptake of Small Electric and Diesel Pumps in Five Countries in Sub Saharan Africa

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Cover Photo: Farmer filling irrigation basin by small motorpump in Lome, Togo, West Africa © Eveline Klinkenberg

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EXECUTIVE SUMMARY

This pilot study aimed to compile a first estimate of the carbon footprint resulting from the current and potential operation of smallholder diesel/electric water irrigation pumps in the next 10-15 years for five Sub Saharan African countries: Burkina Faso, Ethiopia, Ghana, Tanzania and Zambia. The rationale behind this study was a statistic published by Shah (2009) which stated that four to six per cent of India's carbon dioxide emissions resulted from the use of these pumps. All agricultural development potentially has both positive and negative impacts. This study will contribute to the overall understanding of what impacts may be associated with the mechanisation of smallholder farming in the five Sub Saharan countries in terms of emissions.

This study followed the methodology used by Nelson and Robertson (2008) to estimate carbon dioxide equivalents of smallholder irrigation pump use in India. In this analysis however, all pumps are assumed to be diesel powered and below 10 horsepower. The results suggest that in contrast to India the emissions from water irrigation pumps are not and are not likely to become a significant proportion of carbon dioxide emissions in each of the five countries. The emissions from pumps in 2010 were significantly less than one per cent of each country's current agricultural sector emissions. Even with the development of a hypothetical scenario in which every smallholder uses a pump, the resulting carbon dioxide emissions are still less than one per cent of the current agricultural sector emissions. Although the impact on carbon dioxide emissions is small, cross checking the water abstraction rates for these pump numbers suggests that the limited amount of water resources (using the renewable national water resources as an indicator) is more likely to become a problem, especially at the local level. Further suggestions to improve these estimates are to ensure better monitoring of farmer adoption rates, and possibly consider ways of improving pump efficiency. This would benefit both the farmer and the environment. A shift to other energy sources (hydropower electricity and coal electricity) would also affect the estimated carbon dioxide emissions in this report.

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Acknowledgements

~~This report was developed during an internship at SEI, as a contribution to the AgWAter Solutions project coordinated by the International Water Management Institute (IWMI) in partnership with IFPRI, SEI, FAO, IDE and CH2MHill. The work was funded by the Bill & Melinda Gates Foundation. Support for supervision by Jennie Barron was also provided by FORMAS. We appreciate the contributions from individuals and organisations which helped by providing documentation for this synthesis. We would also like to thank the reviewers for their valuable comments.~~

1 INTRODUCTION

Smallholder farming systems are undergoing fast improvement in many developing countries. One identified pathway to improve these farming systems is the adoption of small-scale diesel or electrical pumps that enable farmers to grow more valuable crops such as vegetables and off season crops. In some cases renting the pumps to neighbouring farmers can generate extra income. The AgWater Solutions Project, led by the International Water Management Institute (IWMI), looks at different ways of improving agricultural water management (AWM) and the impacts of AWM technologies. As part of this project, national consultations were held in several countries in Sub Sahara Africa and South Asia that identified small pumps as a major AWM pathway to enhance smallholder production and income. However, some concerns have been raised that this adoption may also be associated with negative environmental impacts. Shah (2009) concludes in his work that around 4-6 per cent of India's total carbon emissions are a result of smallholder irrigation pumps.

This study aims to contribute to the discussions about the environmental impacts of diesel and electric pumps, focussing on the current and potential carbon emissions in five Sub Saharan African countries: Burkina Faso, Ethiopia, Ghana, Tanzania and Zambia. A current estimate of the carbon footprint was calculated, using a method applied by Nelson and Robertson (2008), and a potential estimate that takes into account an increased adoption of these pumps within the next 10-15 years.

There are approximately 33 million smallholder farmers in Africa (Nagayets, 2005) and historical trends suggest that this type of farming will continue to dominate the agricultural landscape in the developing world especially in Africa for at least the next two to three decades (Nagayets, 2005). Irrigation in smallholder farming in most Sub Saharan African countries is starting to shift towards motorised pumping (Baba, 1993). The large number of smallholder farmers and the potential large scale adoption of motorised pumping technologies can make the contribution of these pumps to Africa's total greenhouse gas emissions significant, as has been the case in India. Although this potentially can be a serious environmental impact, this is one of the first studies on this topic for Africa.

In this study smallholder farmers are defined as those farmers cultivating an area of five hectares or less. There are other definitions of smallholder farming that include variable land sizes. One example is the Tanzanian Government website that defines smallholder farmers as those cultivating an average farm size of between 0.9 ha and 3.0 ha each. Cornish (1998) refers to a land area of five hectares or less. Taking into consideration data constraints, the second definition is the most appropriate for this study. In order to include all pumps owned and rented both individually and communally by smallholder farmers (De Fraiture, 2010), the motorised pumps are defined as those pumps that are 10 horsepower or less. For the analysis of emissions, the carbon and carbon dioxide emissions resulting from the operation of the pumps are included. The results do not take into account other ensuing greenhouse gas emissions or carbon dioxide from processes related to the manufacturing of the pump or energy supply.

2 BACKGROUND INFORMATION

In India the adoption of motorised irrigation pumps began in the 1970s (Shah, 2009). Shah (2007) describes how motorised pumps revolutionised irrigation agriculture in India and even calls the period 1975-2000 the 'Golden Age' of smallholder irrigation in India. The adoption of these pumps peaked in 1986-87 (Scott, 2009). In Sub Saharan Africa, the adoption of motorised pumps began later. Baba (1993, p.47) writes that the adoption in Sub Saharan Africa started in the early 1990s. In some parts of Sub Saharan Africa, for instance in Zambia, the development from treadle pumps to motorised pumps did not happen until the early 21st Century (Kodamaya, 2008).

Unlike India, where electricity is increasingly available in rural areas and therefore electric pumps are increasingly used, electricity is rarely available in rural areas of Africa (Carter and Howsam, 1994). In comparison to electric pumps, the diesel pump is available for farmers in Africa and increasingly adopted. In many countries the adoption of diesel pumps has even been facilitated by the government. The Zambian Government, for example, removed taxes on agricultural equipment including water pumps in 2008/9 (FASAZ, 2009) and the Ethiopian Government has allowed the import of thousands of pumps free of custom duties, sur-tax, VAT and withholding tax (Tadesse, 2010, p.20). There is also evidence that the adoption of these technologies is desired by the farmers themselves. Interviews with farmers in Tanzania showed that many who currently use buckets and treadle pumps would like to use motor pumps. Almost all the farmers interviewed said that when they could afford a pump they would invest in one (Keraita *et al.*, 2010).

Another difference between India and Sub Saharan Africa is that the vast majority of pumps in Sub Saharan Africa are imported rather than manufactured locally. Pumps are most commonly imported from China, Japan and India (Keraita *et al.*, 2010; Perry 1997). The most common brands of pumps in Ghana for instance include Honda, Yamaha, Agromec and Maturs (Namara, 2009). Pumps in Sub Saharan Africa are especially used for high value crops such as okra, tomatoes, and fruits.

3 METHODS

The methodology used in this study closely mirrored that used by Nelson and Robertson (2008) and partially by Shah (2009) to calculate carbon emissions from the use of smallholder pumps. Nelson and Robertson's method involved first calculating the separate carbon emissions from a diesel and electric pump when pumping 1000 m^3 of water over one metre. This knowledge was subsequently applied to data regarding the total water abstraction and the depth over which the water was pumped which gave the total carbon emissions from water irrigation pumps. Finally, Nelson and Robertson (2008) compared their results to the total country carbon emissions. This gave an indication of the contribution from water irrigation pumps to, in their case, India's overall carbon footprint.

Carbon release when lifting 1000 m^3

The first step in this study in accordance with Nelson and Robertson's method was to calculate the carbon released by a pump lifting 1000 m^3 of water over one metre. Since the large majority of pumps in Sub Saharan Africa are diesel pumps the amount of carbon released by pumps is only calculated for diesel pumps. Nelson and Robertson calculated the carbon released as follows: If one litre of water weighs one kilogram and 1000 m^3 of water weighs 106 kg, the energy requirement to lift this mass is accordingly:

$$106 * 9.8\ m/s^2 * 1m = 9{,}800{,}000 \text{ or } 9.8*106\ J \qquad (1)$$

(9.8 m/s^2 is the acceleration due to gravity)

This is then converted into kilowatt hours (kWh). A watt measures the rate of energy usage and one watt is equal to one joule per second and therefore one kilowatt hour is:

$$1000 * 1J/s * 3600s/hour = 3{,}600{,}000 \text{ or } 3.6*106\ J/kWh \qquad (2)$$

Using the above information, the joules needed to lift 1000 m^3 of water one metre can be converted into kilowatt hours by dividing the answer from equation (2) by that of equation (1):

$$(9.8*106\ J)/(3.6*106\ J/kWh) = 2.722\ kWh \qquad (3)$$

Therefore, 2.722 kWh refers to the energy required to lift 1000 m^3 of water one metre if a pump operates at full efficiency. To convert the energy requirement to pump 1000 m^3 of water one metre into carbon emissions, Nelson and Robertson (2008) assume that a litre of standard diesel contains approximately 0.732 kgC and that it has an energy content of approximately 10.01 kWh. This data was confirmed by other sources; see appendix 1 for details. Equation (4) below shows the application of these figures to convert the energy requirement to carbon emissions using the result from equation (3):

$$(0.732\ kgC*2.722)/10.01 = 0.199\ kgC \qquad (4)$$

This result is for a pump lifting 1000m^3 over one meter at full efficiency. However, that is unlikely to be the case in reality. Nelson and Robertson (2008) chose to convert this figure to a pump operating at 30 per cent efficiency and at depths of 15 metres for a shallow well and 75 metres for a deep well and Shah (2009) chose to convert this figure to a pump operating at 40 per cent efficiency and over 10-15 metres. Due to the lack of a consensus on the operational efficiency of water irrigation pumps, this study calculated a range of figures for efficiencies from 30-60 per cent. With regards to pumping depths, it is unlikely that in Sub Saharan Africa pumps would lift from great depths. Evidence from the countries Situation Analyses (FASAZ, 2009; Namara, 2009; Kerita *et al.*, 2010; Tadesse, 2010) suggests that the maximum pump depths are eight metres, so a range of pumping depths were also used: 1 metre, 4 metres, and 8 metres.

Estimated pump numbers and water abstraction

The next step was to determine the number of pumps in each country and consequently the amount of water they lifted, but there was a severe lack of available data on the subject. Rough estimates for pump numbers in Ghana and Burkina Faso are in the range of 50,000-100,000 and 11,000-50,000 respectively (De Fraiture, 2010). Additionally, the number of smallholder farmers in each country were detailed in the country's Situation Analyses, with the exception of Burkina Faso whose smallholder numbers were not known (FASAZ, 2009; Namara, 2009; Kerita *et al.*, 2010; Tadesse, 2010). Using the available information, it was calculated that two to four per cent of smallholders in Ghana were pump users, assuming that one farmer owns/rents one pump. The assumption was then made that the same proportion of smallholders in each of the countries had access to a pump and an upper and lower boundary pump number was calculated for each country. This gave an approximate set of values for numbers of pumps in 2010.

The next stage was to calculate the total amount of water the pumps extracted per year. This was done on the basis of two statistics: one published by Shah *et al.* (2003) and the other by Kortatsi (1994). The first statistic stated that the average abstraction from pumps in India was 7,900 m^3/year and the second that pump abstraction in the Southern Volta Region of Ghana varied between 1.0-22.6 m^3/day with irrigation occurring every day by low powered pumps , giving a range of 365-8,249 m^3/year. The two figures are very similar, with 7,900 m^3/year falling within the range suggested by Kortatsi (1994), so this range was used to calculate an upper and lower bound for water abstraction by pumps. Multiplying the upper and lower bounds of water abstraction per pump by the upper and lower bounds of pump numbers gives four scenarios of water abstraction per country in millions of cubic metres:

- water lifted if abstraction was at its lowest and pump numbers were at their lowest,
- water lifted if abstraction was at its lowest and pump numbers were at their highest,
- water lifted if abstraction was at its highest and pump numbers were at their lowest,
- water lifted if abstraction was at its highest and pump numbers were at their highest.

Once the figures for the cumulative annual pump abstraction per country for 2010 were estimated, the figures were compared with information regarding the current total water withdrawal for the agricultural sector, the total water withdrawal and the total renewable water resource for each country according to the FAO's AQUASTAT. The calculated figures were converted into cubic kilometres to allow for this comparison to confirm whether the estimates appeared sensible.

Scenarios for carbon dioxide release

The next step was to calculate water abstraction from 2010 until 2025. However, there was no information in the literature regarding current estimates of adoption of water pumping technologies. Therefore, to do this, a pump adoption rate of a factor of two every five years was assumed, allowing the water abstraction to be estimated until 2025 by doubling the amount of water lifted every five years. These figures were then multiplied by the various carbon release values according to pumping efficiency and depth. This gave the carbon emissions in kilograms of carbon for each scenario of pumping depth, efficiency and year.

Once this had been calculated the results were compared to the county's total carbon dioxide emissions and agricultural sector carbon dioxide emissions. In order for a comparison to be made between these results, the results must first be converted into metric tonnes by multiplying by 0.001, and then converted into carbon dioxide by multiplying by the fraction 44/12 i.e. 44 the molecular weight of carbon dioxide divided by 12 the molecular weight of carbon (Carbon Trust, 2008).

The emissions values used in the comparison were taken from the World Resources Institute's Earth Trends Website (2005) and referred to the emissions released in 2001. This site detailed each country's total carbon dioxide emissions and the percentage of the total carbon dioxide emissions which were accounted for by the agricultural sector. From this the actual carbon dioxide emissions from agriculture were calculated in metric tonnes. Table 1 details the emissions values used in these comparisons.

Carbon dioxide emissions assuming every smallholder farmer was a pump user

The final step of the methodology, going beyond Nelson and Robertson's method, was to calculate the carbon dioxide emissions of a scenario in which every smallholder farmer in the country owned one diesel pump. This was done for all countries with the exception of Burkina Faso for which there was no data regarding the number of smallholder farmers. The number of smallholder farmers was multiplied by the upper and lower bound of possible water abstraction to give the range of water abstraction that this number of pumps would generate. The total water abstraction in millions of cubic metres was then multiplied by the carbon release values according to pumping depth and efficiency. This resulted in a carbon release in kilograms of carbon. For an effective comparison with the country's total emissions these figures were converted into metric tonnes of carbon dioxide using the method detailed above. This stage gave an indication of what might be expected if the largest possible adoption of diesel pumps in each country would occur and the corresponding maximum carbon dioxide emissions.

Table 1: Country's total and agricultural sector carbon dioxide emissions taken from the World Resources Institute's Earth Trends Website (2005)

Country	Country's total CO_2 emissions (millions metric tonnes)	Percentage of CO_2 emissions by agricultural sector *	Calculated emissions resulting from agriculture (metric tonnes)
Burkina Faso	-	-	-
Ethiopia	3.3	0.0	0.0
Ghana	6.2	9.9	613,800
Tanzania	2.8	3.3	92,400
Zambia	1.9	6.9	131,100

*This includes the sum of emissions from fuel combustion used in agriculture, forestry, fishing and commercial activities.

4 RESULTS

This section details the main results generated at each stage of the study. Four scenarios for each country were developed (as listed in Section 3.2) and within each scenario emissions were calculated according to various efficiencies and pumping depths, giving a range of 12 different results per scenario.

Carbon release when lifting 1000 m³

The first set of results generated was a range of carbon emissions resulting from a diesel pump lifting 1000 m^3 of water over various depths and at varying efficiencies (see figure 1). The graph clearly shows that as the efficiency of a pump increases the carbon emissions as a result of its operation decrease. Additionally, as the depth over which the pump lifts increases the carbon emissions increase. This increase is linear.

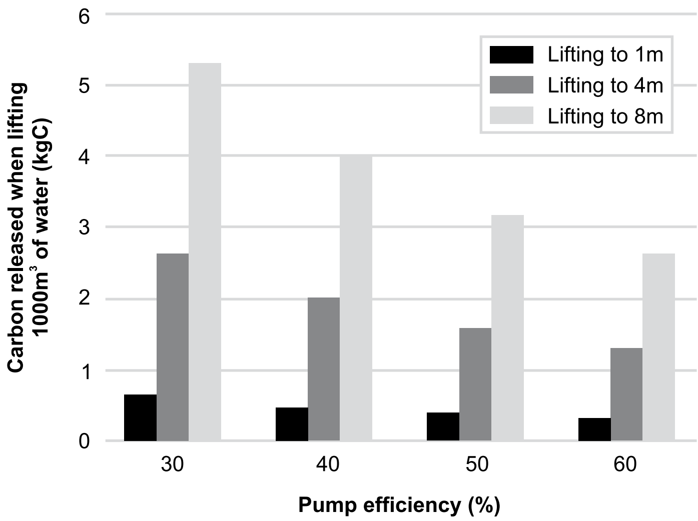

Figure 1: Graph showing the varying amounts of carbon released when a diesel pump lifts 1000 m^3 of water operating at various efficiencies and depths

Estimated pump numbers and water abstraction

The results generated for Section 3.2 were the 2010 (starting values) of number of pumps. These were generated using the number of smallholder farmers and information on the number of pumps in Ghana. The results are displayed in table 2.

Table 2: The estimated number of pumps for each country to the nearest thousand in 2010

Country	Number of Small-holders*	Calculated number of pumps (lower boundary)	Calculated number of pumps (upper boundary)
Burkina Faso	-	11,000*[1]	50,000*[1]
Ethiopia	9,374,455	187,000	375,000
Ghana	2,740,000	50,000*[1]	100,000*[1]
Tanzania	2,904,241	58,000	116,000
Zambia	1,056,000	21,000	42,000

*Number of smallholders according to the situation analyses for each country

*[1] based on rough estimates for pump numbers (De Fraiture, 2010)

The number of pumps listed above is graphically displayed in figure 2. From this it is apparent that the estimated pump numbers for Ethiopia are far greater than for the other four countries.

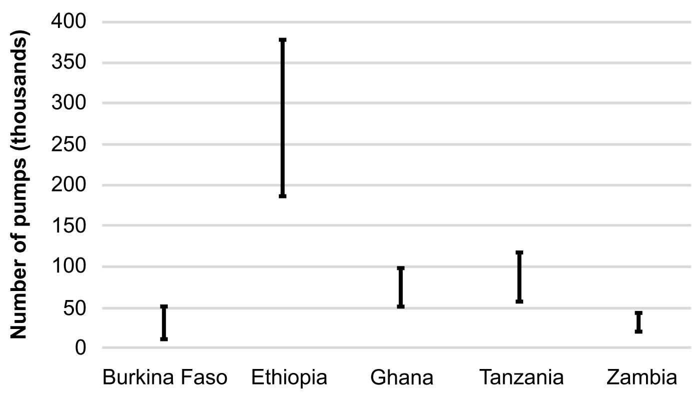

Figure 2: Graph showing the estimated range of pump numbers for each of the five Sub Saharan African countries

Once pump numbers were estimated the total amount of water abstracted was calculated, and these estimates are detailed in table 3. According to this table it appears that the estimates are sensible because with the exception of Ghana's highest estimate of 0.82, the estimates are below the total water withdrawal for the agricultural sector and fall considerably below the country's individual total renewable water resource. Table 3 also shows that the estimated amount of water abstracted is the greatest for Ethiopia and smallest for Burkina Faso.

Table 3: The estimated amount of water lifted by pumps in each country in km^3, compared with the water withdrawal for the agricultural sector, the total water withdrawal and the total renewable water resource for each country

Country	Estimated amount of water abstracted by pumps in 2010 (km^3/year)	Total water withdrawal by the agricultural sector (km^3/year)*	Total water abstraction per country (km^3/year)*	Total Renewable water resource (km^3/year)*
Burkina Faso	0.004 - 0.04	0.69	0.8	12.5
Ethiopia	0.06 - 3.01	5.204	5.558	122
Ghana	0.02 - 0.82	0.652	0.982	53.2
Tanzania	0.21 - 0.96	4.632	5.184	99.27
Zambia	0.01 - 0.35	1.32	1.74	105.2

*Statistics taken from AQUASTAT country factsheets (2000/2002)

Figure 3 displays the current amount of water abstracted by pumps in each country as a percentage of the country's total renewable water resource. From this it can be inferred that pumping in Burkina Faso uses the largest proportion of total renewable water resources and Zambia the smallest.

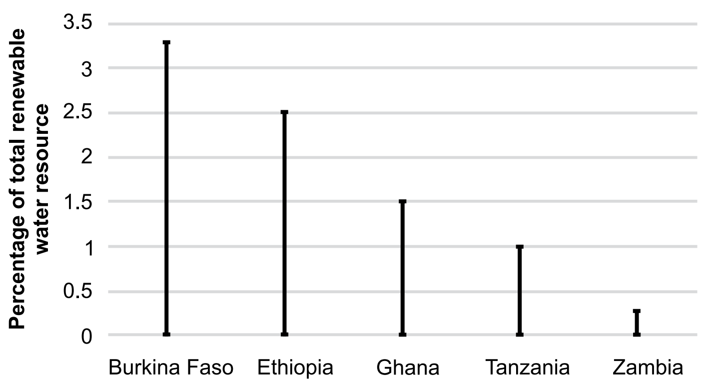

Figure 3: Graph showing the estimated range of water abstraction by diesel irrigation pumps in each county in 2010 as a percentage each country's total renewable water resource

Scenarios for carbon dioxide release

The data generated in section 3.1 and 3.2 was then used to generate scenarios for carbon dioxide emissions resulting from the operation of water irrigation pumps. Figures 4-8 below detail the carbon dioxide emissions for the four scenarios mentioned in section 3.2 assuming they lift at a depth of four metres and at a 30 per cent efficiency.

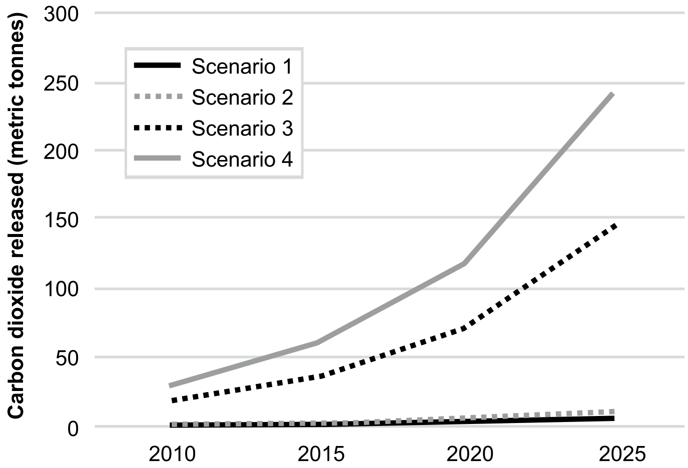

Figure 4: Graph detailing the carbon dioxide emissions for scenarios 1-4 for Burkina Faso assuming pumps operate at a 30% efficiency over 4 m

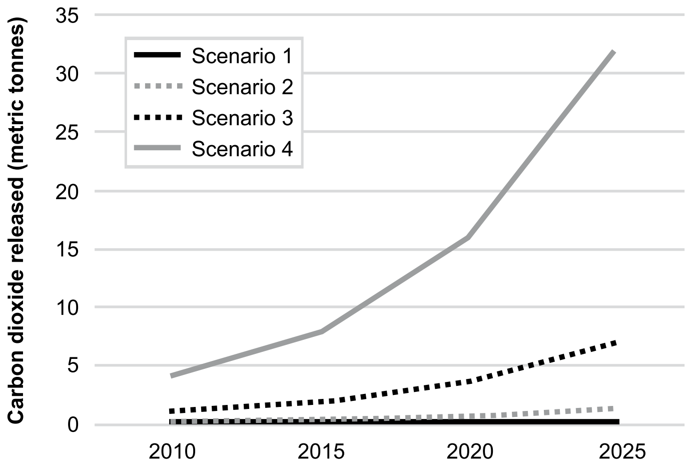

Figure 5: Graph detailing the carbon dioxide emissions from scenarios 1- 4 for Ethiopia assuming pumps operate at a 30% efficiency over 4 m

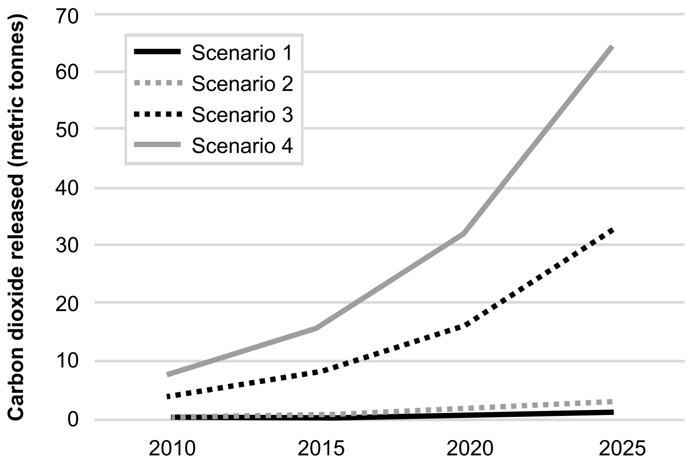

Figure 6: Graph detailing the carbon dioxide emissions from scenarios 1 - 4 for Ghana assuming pumps operate at a 30% efficiency over 4 m

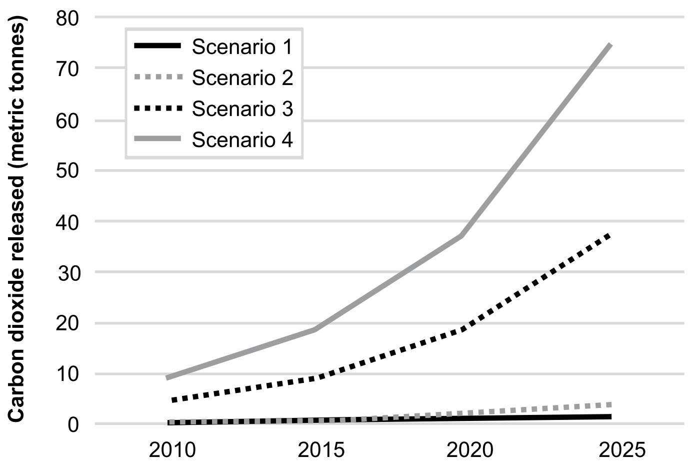

Figure 7: Graph detailing the carbon dioxide emissions from scenarios 1- 4 for Tanzania assuming pumps operate at a 30% efficiency over 4 m

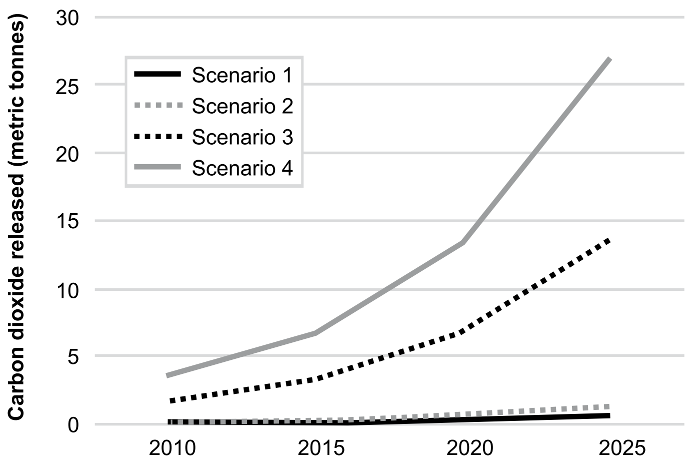

Figure 8: Graph detailing the carbon dioxide emissions from scenarios 1 - 4 for Zambia assuming pumps operate at a 30% efficiency over 4 m

Figures 4-8 show that the carbon dioxide emissions increase over time as expected. Furthermore, emissions also increase according to the scenario, with scenario 1 generating the lowest possible emissions and scenario 4 the highest. Due to the same pump adoption rate being applied in every country each graph displays the same pattern regarding emissions, but with different quantities of emissions. The difference in emissions between scenarios 1 and two is much smaller compared to the difference between scenarios 3 and 4. Scenarios 1 and 2 refer to the application of the lower abstraction rate (365 m^3/year/pump), whereas scenarios 3 and 4 refer to the application of the higher abstraction rate (8,249 m^3/year/pump). When comparing the graphs, Ethiopia has the potential to emit the greatest total emissions as a result of diesel pump irrigation. Data on the carbon release for each country can be found in appendices 2 to 6.

Table 4 below shows the upper and lower bounds of carbon dioxide emissions for each country in 2010 and 2025. Additionally it details the carbon dioxide emissions in 2010 as a percentage of current agricultural sector emissions. In the case of Ghana, Tanzania and Zambia emissions from pumps accounts for a miniscule amount of the total agricultural emissions. For Burkina Faso and Ethiopia there is no result from the percentage of agricultural emissions. In the instance of Burkina Faso this is due to there being no record of emissions (see table 1). However for Ethiopia, as can be seen from table 1 in chapter 3, the emissions from agriculture are zero. In these two cases the emissions from smallholder pumps account for the entirety of the country's carbon dioxide emissions from agriculture. It is important to note when analysing these results that the current agricultural sector emissions used as a comparison were as of 2001, being the most up to date values that could be found from the available literature.

Table 4: The range of carbon dioxide emissions for each country in 2010 and 2025 and the percentage of current agricultural sector emissions this represents for a pump lifting at 30% efficiency over 4 m

Country	**Carbon dioxide emissions 2010 (metric tonnes)**	**Percentage of current agricultural sector emissions**	**Carbon dioxide emissions 2025 (metric tonnes)**
Burkina Faso	0.04 - 4.0	-	0.3 - 32.1
Ethiopia	0.8 - 30.1	-	6.4 - 240.8
Ghana	0.2 - 8.0	0.00003 - 0.001	1.4 - 64.2
Tanzania	0.2 - 9.3	0.0004 - 0.01	1.7 - 74.5
Zambia	0.1 - 3.4	0.00008 - 0.003	0.6 - 27.0

Carbon dioxide emissions assuming every smallholder farmer was a pump user

The scenarios developed in the section above indicate that carbon dioxide emissions from water irrigation pumps are small. Therefore a hypothetical scenario was generated, in which every smallholder farmer will use a diesel pump. Figure 9 shows the results.

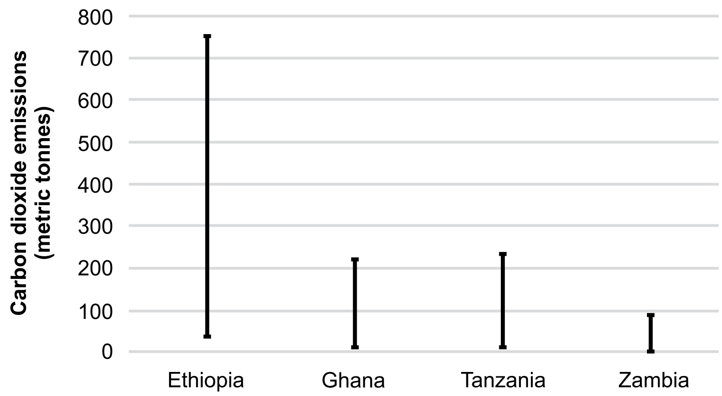

Figure 9: Graph showing the range of carbon dioxide emissions for a hypothetical scenario in which every smallholder is a pump user

Ethiopia again, displays the highest potential carbon dioxide emissions, with the other three Sub Saharan countries displaying very similar levels of carbon dioxide emissions. There is no estimate of emissions for Burkina Faso as numbers of smallholder farmers are unknown for this country.

Table 5 below displays the hypothetical carbon dioxide emissions as a percentage of the current agricultural sector emissions. It shows that even with every smallholder farmer having access to a pump the carbon emissions are still very small in comparison to the current emissions from agriculture.

Table 5: Carbon dioxide emissions from a scenario that assumes every smallholder is a pump user as a percentage of the current agricultural sector carbon dioxide emissions: (1) Referring to the lower emissions estimate and (2) referring to the upper estimate

Country	Percentage of current agricultural sector emissions (1)	Percentage of current agricultural sector emissions (2)
Ethiopia	-	-
Ghana	0.002	0.034
Tanzania	0.001	0.025
Zambia	0.003	0.065

5 DISCUSSION

The first step in this study calculated carbon emissions from a pump lifting at various efficiencies and from a variety of depths and as it would be expected the emissions rose as the lifting depth increased and the emissions decreased as the efficiency rose. Emissions from diesel pumps calculated in this study were significantly smaller than the emissions calculated for diesel pumps by both Nelson and Robertson (2008) and Shah (2009) in India. The major difference between the calculations at this first step was pumping depth. According to the two studies, pumps in India pump at a greater depth than those operating in Sub Saharan African countries. Nelson and Robertson (2008) stated that pumps lifted at depths of 15 metres for a shallow well and 75 metres for a deep well and Shah (2009) stated that pumps lifted over 10-15 metres. From the individual country's Situation Analyses it was determined that pumps in Sub Saharan Africa generally did not lift below 8 metres (FASAZ, 2009; Namara, 2009; Kerita *et al.*, 2010; Tadesse, 2010).

The next step of the study involved making estimates of number of pumps and pump water extraction. For the five Sub Saharan countries the estimated number of pumps were small in comparison to India's 19 million (Purohit and Michaelowa, 2005). Ethiopia appeared to have the largest number of pumps and Zambia had the smallest. These numbers were proportionate to the number of smallholder farmers. The water abstraction values in comparison to India were very small, most likely as a result of the much smaller number of pumps operating in these countries. In Burkina Faso the abstraction from pumps was the greatest proportion of the country's total renewable water resource, despite being low with 3.5 per cent. Table 3 showed that Burkina Faso had the smallest total renewable water resource at 12.5 km^3/year. This explains why pumps in this country utilised a greater proportion of the resource than pumps in other countries.

Despite this falling outside the remit of this study, it is important to note that whilst abstraction was not calculated to be a large proportion of Burkina Faso's total renewable water resource this may not be the case in the future; especially if the assumed adoption rate for pumps in this country is accurate. The highest estimate of abstraction for Burkina Faso was just under 3.5 per cent of the country's total renewable water resource, yet if abstraction doubled every five years by 2025 the amount of water lifted could be approximately 28 per cent. This would be a very large proportion of the country's total renewable water resource. As the value of the national renewable water resource is an average of a country, water can be in abundance in some places and deficit in others. Evidently local water resources and water stress may emerge as the adoption of small pumps grows beyond a certain level. These landscape boundaries must be determined at a local scale. The comparison of water resource withdrawal used here is only a first estimate to cross check potential impacts.

The generation of the multiple emissions scenarios for each country revealed large differences in absolute carbon dioxide. Figures 4-8 showed as expected that emissions displayed an increasing pattern over time. This pattern was in contrast to the estimates by Nelson and Robertson (2008) in India where emissions from both shallow electric and diesel wells decreased over time up to 2050. This was the case in India because they assumed that there would be no growth in the availability of water from these sources. Again Ethiopia had the potential for the largest carbon dioxide emissions, up to 250 million metric tonnes in 2025, and Zambia contributed to the smallest emissions just over 25 metric tonnes by 2025. This was proportionate to the country's number of smallholder farmers. It should be noted that these scenarios do not account for a growing smallholder farmers population, but only a growing adoption rate among the current population.

A 'worst-case' and very unrealistic scenario regarding emissions from pumps assumed every smallholder to become a user of an irrigation pump was also estimated. Interestingly it indicated that the carbon dioxide emissions even with such a large number of pumps were unlikely to be a large proportion of the countries emissions. This is a very positive outcome, but I s in great contrast with the calculations for India. This is possibly due to the smaller total number of smallholder farmers in India or the method of energy generation most commonly used.

There were some weaknesses in the data underlying the estimated current and potential carbon dioxide release. The first weakness was the lack of relevant, available and up-to-date data, in particular on existing pump numbers, their efficiency and possible adoption rates. This study was not alone in experiencing difficulties regarding agricultural data in this region, for instance Awulachew *et al.* (2005: p.46) stated that there was very little knowledge of modern irrigation like the motor pump and that it was one of the main knowledge gaps in Ethiopian agriculture. Additionally, Turner (1994) stated that the reliability of data on small-scale irrigation was generally lacking, with many governments in developing countries keeping only records of large-scale systems. However, these data issues were also noted by Shah (2009) for the carbon footprint of Indian pumps where data is more widely available.

The shortage of appropriate data for this study led to a large number of assumptions being made. These were made to the best of available knowledge and data and in consultation with local expertise in the AgWater Solution Project. However, the data used is still associated with high levels of uncertainty. One issue was the numbers of electric pumps used in each country. The assumption of poor rural electrification in many Sub Saharan African countries led to the exclusion of electric pumps from the carbon release calculations. Contact with researchers in Africa suggested that for Ghana in particular this may not be the case. Namara (2010) stated that electric pumps were extensively used in the east coast part of the Volta Region. It is also possible that smallholder farmers in semi urban settings can access electricity in various countries in Sub Saharan Africa. Nonetheless, as no quantitative information about use or current adoption of electrical pumps is available for the countries in this study, only calculations were done for diesel pumps.

It may also be useful to develop other methods of calculating the operational carbon footprint of these pumps to compare with the estimates of this study. Just as the different studies for India produced differing results, this may also be the case in Africa. The amount of diesel used to irrigate land in Ghana and Burkina Faso is known: 250 and 1000 litres per hectare per year respectively (De Fraiture, 2010). These figures could be applied to a different methodology to estimate emissions using the known carbon content of a standard litre of diesel. Nonetheless, these figures could not be utilised in this study due to a lack of information regarding the areas irrigated in the other countries.

There are several improvements that could be made to increase the reliability of the methodology used in this study. The first improvement would be to include electric pumps in the analysis. This could either increase or decrease the carbon emissions depending on the type of power generation for the electricity. Table 6 details the emissions from electricity generation and the emissions factors, given in kilograms of carbon. These could be used as a replacement for the diesel emissions values if numbers of electric pumps and energy sources were known. This table is based on information regarding energy generation from Yale's Environmental Performance Index 2010 Website. The estimates included a 5 per cent transmission loss as adopted by Nelson and Robertson (2008) and a 25 per cent transmission loss as adopted by Shah (2009) in their estimates for India. See appendix 7-9 for further details on how this data was calculated.

Table 6 shows the emissions generated when an electric pump lifts 1000 m^3 of water over one metre at 30 per cent efficiency. Diesel pumps operating at this efficiency emit 0.66 kgC. In the majority of cases diesel pumps appear to release less carbon than electric pumps. This was also found by Shah (2009) in India, and the reasoning behind this in Shah's study was the transmissions losses.

Table 6: Carbon dioxide emissions associated with electricity generation in the various countries and the emissions resulting from one electric pump operating at 30% efficiency lifting 1000 m^3 of water 1 m with a 5% and a 25% transmission loss

Country	Emissions from electricity generation (gCO_2 per kWh)*	Emissions with a 5% transmission loss lifting 1000 m^3 of water over 1m (kgC)	Emissions with a 25% transmission loss lifting 1000 m^3 of water over 1m (kgC)
Burkina Faso	729.441	1.895	2.255
Ethiopia	36.265	0.094	0.112
Ghana	359.634	0.908	1.112
Tanzania	247.603	0.643	0.776
Zambia	6.6688	0.017	0.021

*Statistics taken from Yale's Environmental Performance Index Website

The emissions data in table 6 only refer to electricity generated from fossil fuels, not hydropower. Yet, any change in emissions is dependent on the source of energy responsible for electricity generation i.e. coal fired or hydropower. Table 7 gives an indication of the proportion of electricity generated

Table 7: The proportion of power in each country generated by either fossil fuels or hydropower

Country		Percentage from fossil fuels	Percentage from hydropower
Burkina Faso	2000	68.92	31.08
	Present	82.33	17.52
Ethiopia	2000	1.2	96.44
	Present	2.17	96.49
Ghana	2000	7.76	88.57
	Present	11.51	83.98
Tanzania	2000	10.1	85.35
	Present	6.99	87.85
Zambia	2000	0.29	98.83
	Present	0.26	98.96

from each source according to CARMA (Carbon Monitoring for Action Website). The table suggests that in the majority of the countries, with the exception of Burkina Faso, hydropower is the dominant energy source. Electrically driven pumps could be a cleaner option in Sub Saharan Africa, but further investigation is needed to ascertain this.

Another possibility is that energy for irrigation pumps in the future may come from renewable sources such as biofuels. Roseblum (2000) in a study regarding irrigation in India stated that the use of biodiesel (a type of biofuel) would reduce carbon dioxide emissions. Therefore any shift in their favour should decrease the carbon dioxide estimates. Additionally, biodiesel could have the added advantage of increasing economic activity through its production and utilisation, and would increase energy independence. The switch from petroleum-based diesel to biodiesel could be a smooth one, with no engine modifications needed for this transition (Roseblum, 2000).

The analysis could also be improved by taking into account the change in operational efficiency of diesel engines due to wear and tear. In a study by Reidhead (2001) in India, even after rectification measures to improve efficiency, within several months efficiency had fallen by an average of 5 per cent. This study also suggested that the operational efficiency of these pumps may be lower than assumed in this study. Reidhead (2001, p.138) stated that if diesel pumps operated perfectly i.e. per design specifications, the maximum achievable efficiency in the field was approximately 20 per cent and observed efficiencies could be as low as 5 per cent. It would be good to improve the operational efficiency of diesel pumps which would decrease the already low emissions. This would reduce the environmental impact in terms of carbon emissions and would also benefit farmers by having less pump running costs. Efficiency is defined as the ratio of work being done by the pump to the power or energy being supplied, and an appropriate pump size is vital to increase efficiency (Smajstria, n.d.). Other ways to improve efficiency would be to use a pump suitable for the local conditions and have good maintenance in place to decrease wear and tear.

Finally, this study could be extended to include emissions from all stages of the life cycle of these pumps. Current emissions estimates only include carbon dioxide from the operation of these pumps, yet the definition of carbon footprint is as follows: a measure of the exclusive total amount of carbon dioxide that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann and Minx, 2007). The inclusion of all associated carbon dioxide emissions would give a truer picture of the carbon footprint of the pumps.

6 CONCLUSIONS

From the calculations in this study it can be concluded that carbon dioxide emissions as a consequence of the use of water irrigation pumps in the five Sub Saharan African countries are currently only a very small proportion of the overall carbon dioxide emissions of the countries. In the next 10-15 years these carbon dioxide emissions are likely to increase but will remain only a small proportion of the country's total emissions according to the optimistic emissions scenarios that were used in this study. More energy efficient small scale pumps could keep carbon dioxide emissions at a low rate even if adoption quadruples in the future. A higher efficiency will also benefit farmers by having less pump running costs. However, a more pressing environmental issue with increased adoption will be the stress on available surface and groundwater resources at the local scale.

This study was based on a range of assumptions and highly uncertain data and is therefore only intended as a pilot for future research. More research is essential especially into exact numbers of pumps in use. This data will help improve the carbon footprint calculations of diesel pumps for irrigation in the five Sub Saharan African countries.

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APPENDICES

Appendix 1: Sources and stated carbon emissions per litre of diesel

Carbon content per litre of diesel	Source	Date Accessed
0.732 kgC (2,778 grams/USgallon)	www.epa.gov/oms/climate/420f05001.htm (2005)	07/07/2010
0.731 kg (2.77 kg/USgallon)	http://bioenergy.ornl/gov/papers/misc/energy_conv.html	07/07/2010
0.739 kgC (12.2 kgCO_2/gallon)	http://timeforchange.org/what-is-a-carbon-footprint-definition	07/07/2010

Appendix 2: The carbon release in metric tonnes of pumps lifting over 8 m in Burkina Faso

Year	30% efficiency	40% efficiency	50% efficiency	60% efficiency
2010	0.08 - 8.03	0.06 - 6.02	0.05 - 4.82	0.04 - 4.01
2015	0.16 - 16.06	0.12 - 12.04	0.09 - 9.63	0.08 - 8.03
2020	0.31 - 32.11	0.23 - 24.08	0.19 - 19.27	0.16 - 16.06
2025	0.63 - 64.22	0.47 - 48.17	0.38 - 38.53	0.31 - 32.11

Appendix 3: The carbon release in metric tonnes of pumps lifting over 8 m in Ethiopia

Year	30% efficiency	40% efficiency	50% efficiency	60% efficiency
2010	1.33 - 60.21	1.00 - 45.16	0.80 - 36.13	0.66 - 30.11
2015	2.66 - 120.42	1.99 - 90.32	1.59 - 72.25	1.33 - 60.21
2020	5.31 - 240.84	3.99 - 180.63	3.19 - 144.51	2.66 - 120.42
2025	10.63 - 481.69	7.97 - 361.26	6.38 - 289.01	5.31 - 240.84

Appendix 4: The carbon release in metric tonnes of pumps lifting over 8 m in Ghana

Year	30% efficiency	40% efficiency	50% efficiency	60% efficiency
2010	0.36 - 16.06	0.27 - 12.04	0.21 - 9.63	0.18 - 8.03
2015	0.71 - 32.11	0.53 - 24.08	0.43 - 19.27	0.36 - 16.06
2020	1.42 - 64.22	1.07 - 48.17	0.85 - 38.53	0.71 - 32.11
2025	2.84 - 128.45	2.13 - 96.34	1.71 - 77.07	1.42 - 64.22

Appendix 5: The carbon release in metric tonnes of pumps lifting over 8 m in Tanzania

Year	30% efficiency	40% efficiency	50% efficiency	60% efficiency
2010	0.41 - 18.63	0.31 - 13.97	0.25 - 11.18	0.21 - 9.31
2015	0.82 - 37.25	0.62 - 27.94	0.49 - 22.35	0.41 - 18.63
2020	1.65 - 74.50	1.24 - 55.88	0.99 - 44.70	0.82 - 37.25
2025	3.30 - 149.00	2.47 - 111.75	1.98 - 89.40	1.65 - 74.50

Appendix 6: The carbon release in metric tonnes of pumps lifting over 8 m in Zambia

Year	30% efficiency	40% efficiency	50% efficiency	60% efficiency
2010	0.15 - 6.74	0.11 - 5.06	0.09 - 4.05	0.07 - 3.37
2015	0.30 - 13.49	0.22 - 10.12	0.18 - 8.09	0.15 - 6.74
2020	0.60 - 26.97	0.45 - 20.23	0.36 - 16.18	0.30 - 13.49
2025	1.19 - 53.95	0.90 - 40.46	0.72 - 32.37	0.60 - 26.97

Appendix 7: The methodology used to calculated the emissions factors for electric pumps

- The carbon dioxide emissions from each country for electricity generation according to the Yale Environmental Performance Website are given in grams of carbon per kilowatt hour.

- From the previous calculations for diesel pumps it was known that a pump lifting 1000 m^3 of water over one metre at full efficiency would require 2.73 kWh of energy and at 30 per cent efficiency it would require 9.07 kWh of energy.

- In electricity generation there are additional efficiency losses known as transmissions losses. Therefore if a pump operates at a 30 per cent efficiency with a five per cent transmissions loss it would require 9.5235 kWh of energy, and a pump that operates at a 30 per cent efficiency with a 25 per cent transmission loss would require 11.3375 kWh of energy.

- The carbon dioxide emissions to pump 1000 m^3 of water over one metre was calculated by multiplying the energy requirements calculated in Step 3 by the figures for carbon dioxide released per kilowatt hour. This gave figures in grams of carbon dioxide which could then be converted to kilograms of carbon dioxide.

- Finally, these values were then converted from carbon dioxide to carbon to give emissions values. This was done by dividing the result by 44/12, i.e. 44 the molecular weight of carbon dioxide divided by 12 the molecular weight of carbon.

Appendix 8: The emissions values in both carbon dioxide and carbon for an electric pump lifting 1000 m^3 of water 1 m operating at a 30% efficiency with a 5% transmission loss

Country	Emissions from electricity generation (gCO_2 per kWh)*	Emissions from pumping 1000 m^3 of water over 1 m with a 5% transmission loss ($kgCO_2$)	Emissions from pumping 1000 m^3 of water over 1 m with a 5% transmission loss (kgC)
Burkina Faso	729.441	6.947	1.895
Ethiopia	36.265	0.345	0.094
Ghana	349.634	3.330	0.908
Tanzania	247.603	2.358	0.643
Zambia	6.6688	0.064	0.017

*Statistics from Yale's Environmental Performance Index Website

Appendix 9: The emissions values in both carbon dioxide and carbon for an electric pump lifting 1000 m^3 of water 1 m operating at a 30% efficiency with a 25% transmission loss

Country	Emissions from electricity generation (gCO_2 per kWh)*	Emissions from pumping 1000 m^3 of water over 1 m with a 25% transmission loss ($kgCO_2$)	Emissions from pumping 1000 m^3 of water over 1 m with a 25% transmission loss (kgC)
Burkina Faso	729.441	8.270	2.255
Ethiopia	36.265	0.411	0.112
Ghana	359.634	4.077	1.112
Tanzania	247.603	2.807	0.766
Zambia	6.6688	0.076	0.021

*Statistics from Yale's Environmental Performance Index Website

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