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Procedia Technology 22 (2016) 478 – 485

Procedia Technology

9th International Conference Interdisciplinarity in Engineering, INTER-ENG 2015, 8-9 October 2015, Tirgu-Mures, Romania

Life Cycle Assessment of Diesel Fuel and Solar Pumps in Operation Stage for Rice Cultivation in Tanta, Nile Delta, Egypt

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Abstract

This paper aims at using life cycle assessment (LCA) to assess the environmental impacts of groundwater pumping systems diesel fuel and solar power for lifting irrigation water for one feddan (1.037 acre) of rice. The study area lies in Tanta semi-arid central Nile Delta, Egypt. LCA via SimaProv8.04.30 is used to study the environmental impacts of pumping water using two types of pumping systems. Environmental impacts of diesel pump and solar pump systems are compared for different hydraulic head and area of rice cultivation scenarios. Results indicated that the diesel-powered pumping systems are more harmful to the environment than solar power pumps. The contribution to midpoint environmental impacts of the diesel fuel pump impacts reach 70 % for natural resources, 18 % for human health, 10% for climate change and 2% for ecosystem quality. On the other hand, solar pumping system contributes to 3 % to climate change, 2% to human health and natural resources impacts, and 0.5 % to ecosystem quality. The results confirm that for groundwater pumping, diesel fuel energy has the highest environmental impacts on human health, the ecosystem quality, climate change and resources depletion. It is highlighted that the type of power source must be considered when ranking pumping systems based on environmental performance.

Peer-review under responsibility of the “Petru Maior” University of Tirgu Mures, Faculty of Engineering

Keywords: Diesel Fuel Pumps; Solar Pumps; Environmental impact; Life Cycle Assessment; SimaPro; Rice Cultivation; Nile Delta

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Peer-review under responsibility of the “Petru Maior” University of Tirgu Mures, Faculty of Engineering
doi:10.1016/j.protcy.2016.01.095

1. Introduction

LCA method was used in a wide range of applications to assess the environmental impacts of product or process [1, 2]. Especially in the irrigation and drainage system; LCA is used to compare between construction and maintenance costs of different groundwater pumping systems. LCA is a technique / tool to assess the potential environmental impacts and resources used throughout a product's life cycle [3]. The techniques of the solar powered water pumping system and what are the differences compared with other energy sources was explained [4]. Solar water pumping systems can provide water for irrigation without the need for any fuel, oil or maintenance required by diesel pumps. Solar water pumping system is easy to install and operate, highly reliable, durable and modular, which enables future expansion [5]. The life cycle thinking assessment method was applied to a small scale drip irrigation system in Bénin that used greywater [6]. The necessary steps and key components needed for designing and building a photovoltaic pump system were examined [7]. The development of different systems of solar power pumping systems was introduced. The Renewable Energy Sources (RESs) played "a vital role in reducing the consumption of conventional energy sources and its environmental impacts for water pumping applications" [8]. LCA was used to assess the environmental impacts of contrasted groundwater pumping systems in semi-arid central Tunisia. The results showed that the water depletion had a great importance in the "study, and ongoing LCA improvements should facilitate a more comprehensive picture of these site-specific impacts" [9]. The LCA method was used to assess the environmental impact of CO_2 emissions of a Photovoltaic Water Pumping (PVWP) System in China. The results indicated that the PVWP was a good choice for carbon emission reduction with carbon sequestration benefit much higher than the lifetime carbon emissions [10]. In Egypt, that total annual abstraction from groundwater in the Nile Delta due to pumped groundwater through irrigation and domestic pumping equaled 2123 Mm^3/year in 1993 [11]. Research Institute of Groundwater (RIGW) monitored the pumping activities at each governorate in the Nile Delta. According to the extraction well inventory in 1992, the total volume of extraction was estimated at 1.92 Mm^3/year. El Gharbia governorate recorded the maximum number of extraction wells that equals 3391 wells [12, 13]. Tanta lies in Gharbia governorate in the central Nile Delta. The total number of groundwater pumping wells in Gharbia Governorate is 3391 wells that depend mainly on diesel fuel for pumping water for irrigation. The main objective of this study is using LCA to assess the environmental impacts of groundwater pumping systems diesel fuel and solar power for irrigation of one feddan of rice by using SimaPro v 8.0.4.30.

2. Study area and data availability

The study area lies in Tanta, El- Gharbia governorate, central Nile Delta, Egypt. Tanta lies in a semi-arid climate zone. Rice planting season in Tanta starts from mid-May to mid-November, almost 4-6 months, according to the policies of Ministry of Water Resources and Irrigation for rice cultivation [14]. No rainfall in Tanta in summer and fall seasons. The temperature in Tanta ranges from 21^{o}C in November to 30^{o}C in August, available on weather underground site [15].The characteristics of rice plant, lengths, crop coefficients, suitable soil and water properties are collected from [16] and [17]. From the field trip to the study area, the groundwater well covers an area of 6 feddan (6.23 acres), its depth is 30.0m, and the type of pump supported on is a diesel fuel pump. It was constructed in 2010. Distance between the study area and the nearest source of diesel oil is about 6.0 km. The study area is located between 30°51'26.02" and 30°51'29.60" in the North, 30°50'41.73" and 30°50'42.27" in the East. Location of the study area and photos are got from Google Earth site. It is about 6.23 acres, as shown in Fig. 1.

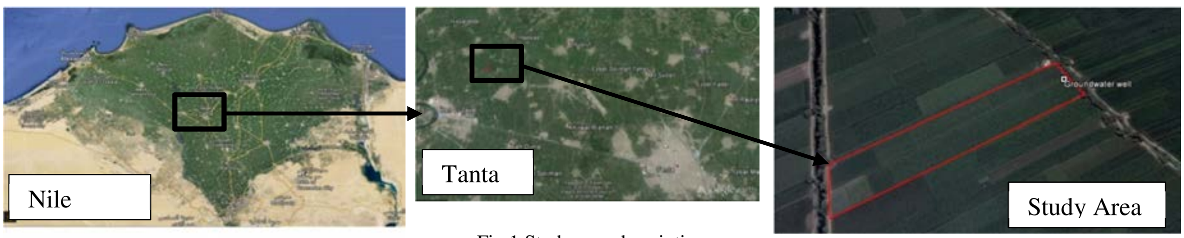

Fig.1 Study area description

3. Methodology

The use of LCA to compare the environmental impacts of the two pumping systems needs the power consumption of each pump to be known. Therefore, estimation of water requirements for irrigating the targeted area is essential. The methodology used to achieve the objectives of the present study consists of five main steps are Estimation of crop water requirements, Estimation of crop evapotranspiration, Estimation of leaching requirements, Estimation of power requirement of both solar PV system and diesel pump for Water Pumping and Using SimaPro to estimate the environmental impacts of each pump. The following sections/paragraphs describe each step of the methodology.

3.1. Crop water requirements calculation

The water requirement of rice varies with time and depends on the season and growth of plants. Rice season in Egypt takes about 150 days, almost from 4 to 6 months. It is essential to irrigate optimally during the stage of flowering to fruit maturity. Other factors that should be considered include the type of soil and the climatic parameters. However, in the present study the peak water requirement of the rice plant was evaluated to design the diesel fuel and solar pumping systems. The net irrigation requirement is derived from the following equation that was used. The field balance equation [16].

$$IR_n = ET_c - (P_e + G_e + W_b) + LR_{mm} \tag{1}$$

Where, IRn is the net irrigation requirement (mm), ET_c is the crop evapotranspiration (mm), P_e is the effective dependable rainfall (mm), G_e is the groundwater contribution from water table (mm) and W_b is the water stored in the soil at the beginning of each period (mm) and LR_{mm} is the leaching requirement (mm).

3.2. Crop evapotranspiration ETc

Rice evapotranspiration is a huge term that contributes to equation 1 to calculate the water requirements. Different equations and methods are available to calculate rice evapotranspiration. However, according to the available data about the study area, Blanny-Criddle equation [17] is suitable to be used that depends mainly on mean temperature and daily percentage of annual daytime hours, showed in equation 2. Crop evapotranspiration calculated from reference evapotranspiration by equations 3 depends mainly on temperature. The crop coefficient of rice equals 1.05 and 1.2 for intial and middle stage also ranges from 0.9 to 0.6 in the end stage [16]. The rice heights are 30 cm for initial, develop and late stage except middle stage length equals 60 cm [16].

$$ET_o = p(0.46T_{mean} + 8) \tag{2}$$

Where, ET_o is the reference crop evapotranspiration (mm/day), T_{mean} is the mean daily temperature (°C) and p is the mean daily percentage of annual daytime hours.

$$ET_c = k_c \times ET_o \tag{3}$$

Where, ET_C is the crop evapotranspiration (mm/day).

3.3. Leaching Requirements (LR)

Leaching requirements of rice depend on the irrigation; the common type of rice irrigation in Tanta is surface irrigation. For surface irrigation method, the following equations 4, 5 and 6 were used to calculate the leaching requirements, [16]. Fraction water for rice was calculated from equation 4, [16]. Leaching requirements of rice calculated from equation 5 and depend on crop evapotranspiration and fraction water.

$$LR_{fr} = \frac{EC_w}{5EC_e - EC_w} \times \frac{1}{L_e} \quad (4)$$

Where, LR_{fr} is the fraction of the water to be applied that passes through the entire root zone depth and percolates below, EC_w is the electrical conductivity of irrigation water (dS/m) and EC_e is the electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction (dS/m) and Le is Leaching efficiency (in decimals), EC_w and EC_S equal 5.1 and 3.4 at 75 % yield potential respectively, [18].

$$LR_{fr} = \frac{LR_{mm}}{ET_C - LR_{mm}} \quad (5)$$

If we assume that G_e and W_b equal zero, equation 1 to calculate water requirements become

$$IR_n = ET_c + LR_{mm} \quad (6)$$

3.4. Design of Solar PV system and diesel pump for Water Pumping

3.4.1. Energy requirements for diesel fuel and solar pump systems

Energy requirements for lifting groundwater for rice irrigation depend mainly on volume of requirements water for irrigation. The volume of water calculated from equation 7, taking in account the efficiency of surface irrigation 70%, the actual volume of water requirements calculated from equation 8.

Q=Area of rice× water requirements (mm/day) (7)

Actual volume of water requirements=V/efficiency of irrigation (8)

Energy requirements for the two pumping systems calculated from equation 9, by substitute properties of water and gravity acceleration, equation 9 taken the shape of equation 10.

$$E = \frac{\rho g H Q}{3.6 \times 10^6} \quad (9)$$

Where, E is the hydraulic gradient required (kwh/day), ρ is the density of water (1000 kg/m^3), G = the gravitational acceleration (9.81 m/sec^2), H is the total hydraulic head equals 30 (m) and Q is the volume of water required per time unit (m^3/day).

E=0.002725HQ (kwh/day) (10)

3.4.2. Design of solar pump requirements

The design of solar pump depends on water requirements for rice cultivation to determine the needed number of solar aluminum panels. The size of a PV array was calculated by using the following equation.

Total voltage of PV panel=E/actual sunshine hours (11)

Considering system losses, actual total voltage of PV panels were calculated from equations

$$Actual\ Total\ voltage\ of\ PV\ panel = \frac{Wattage\ of\ panel}{system\ efficiency \times Minmatch\ factor} \quad (12)$$

By assuming that the system efficiency=30% and Minmatch factor=85%. The type of PV panel used in the calculation has 75 w as a voltage capacity. Number of PV panels calculated from equation 13.

Number of solar panels required=total voltage of pv panel/75 W of each panel (13)

$$Total\ weight\ of\ aluminium\ panel=number\ of\ panels\times weight\ of\ each\ panel \quad (14)$$

By assuming the life time of solar pump=15 year, the weight of aluminium for operation stage for one day of cultivation calculated from equation 15, that was used as an input to SimaPro software.

$$Weight\ of\ aluminium\ for\ solar\ pump\ per\ one\ day=total\ weight\ of\ aluminium\ panels/[365\times 15] \quad (15)$$

3.4.3. Design requirements of diesel fuel pump

The design of diesel fuel pump depends on water requirements for rice cultivation to determine the needed oil and diesel consumption. The used type of diesel pump has a diesel consumption ranges from 197.1 to 286 gm, and 5-litre oil consumption for each 1 KWh required. The total volume of diesel and oil consumptions that were used as an input to SimaPro calculated from equations 16 and 17 respectively.

$$Diesel\ consumption=\ diesel\ consumption\ rate\ (Litre/1KWh)\times number\ of\ KWh\ required \quad (16)$$

$$Oil\ consumption\ =oil\ consumption\ rate\ (litre/1KWh)\times number\ of\ KWh\ required \quad (17)$$

3.5. SimaPro application

SimaPro software version 8.0.4.30 was used to assess the environmental impacts of two pumping systems diesel fuel and solar for the cultivation of one feddan of rice and total dynamic head 30 m. The total volume of water requirements equals 44.46 m^3/day based on the maximum water requirements 7.41 mm/day in August. Two assemblies are assigned to the program diesel fuel pump and solar pump. The inputs to SimaPro for the current situation of diesel fuel pump include 1.093 kg/day as diesel consumption and 15.26 kg/day as oil consumption. For the solar pump the inputs is 0.18 kg/day from aluminium consumption and the number of aluminium panel required is 6 panels. The distance from nearest city to the site is 6.0 km and type of vehicle for transport is 3.5-5.5 ton lorry.

4. Results and discussion

4.1. Crop water requirements results

The last equations mentioned in sections 3.1, 3.2 and 3.4 were used to calculate the water requirements for rice irrigation. Table 1 shows the values of reference evapotranspiration, crop evapotranspiration, fraction water, leaching water and water requirements from May to November. Minimum value of water requirements is observed in November (6.04 mm/day).The required energy and design of the two pumping system is according to the maximum water requirements observed in August equal 7.41 mm/day.

Table 1: Reference evapotranspiration, crop evapotranspiration, leaching fraction and irrigation water requirements

month	T °c	ET_o	ET_o	Et_c	LR_{fr}	LR_{mm}	IR_n	month	T °c	ET_o	ET_o	Et_c	LR_{fr}	LR_{mm}	IR_n
May	26	5.78	6.07	0.22	1.04	7.18	26	Sep.	28	6.05	4.53	0.22	1.09	7.14	28
June	28	6.05	6.35	0.22	1.09	7.14	28	Oct.	24	5.52	4.14	0.22	0.99	6.51	24
July	29	6.18	7.42	0.22	1.11	7.29	29	Nov.	21	5.12	3.84	0.22	0.92	6.04	21
Aug.	30	6.32	4.74	0.22	1.14	7.41	30								

4.2. LCA Results

4.2.1. Comparison of LCA results/environmental impacts of water pumping systems

According to IMPACT 2002+, Fig. 2 presents the LCA results for the diesel fuel and solar pumping systems in the baseline situation. This computation was based on the functional unit, i.e. irrigation of one feddan of rice. In LCA, results from different environmental impact categories have different units, e.g. 'kg of CO_2 equivalent' for climate change or 'kg of chlorofluorocarbon CFC11 equivalent' for ozone depletion, [9]. For more visualization of the impact categories, the standard unit for each impact categories category units must be defined. After comparing different systems, the greatest impact in each category is set to the maximal value (100%). Each environmental impact system is then showed relative to this maximum 100% value, [9]. Each impact contribution has a number, as shown in Fig.2. The first 4 impact categories relates to human health damage. They are carcinogens, non-carcinogens, respiratory in organics and ionizing radiation. The next 4 and 3 impact categories relate to ecosystem impacts and climate change respectively. They are ozone depletion, respiratory organics, aquatic Eco toxicity, terrestrial Eco toxicity, terrestrial acid, land occupation, aquatic acidification, aquatic eutrophication, and Global warming. Non-renewable energy and mineral extraction are linked to resource depletion. The pumping system hierarchy is identical over all categories of impacts except mineral extraction, i.e. the diesel-fuel pump system is the most harmful system for the environment compared with the solar water pumping system. The use of diesel fuel to pump water for irrigation usually has hazardous impacts to the environment. According to the human health impacts, diesel fuel pump have a negative impacts to human health. Also have the same for global warming and ecosystem-environmental impacts. On the other hand the story is changed for mineral extraction impacts; solar pump has negative impacts to the mineral extraction higher than the diesel pumping system, as shown in Fig. 2.

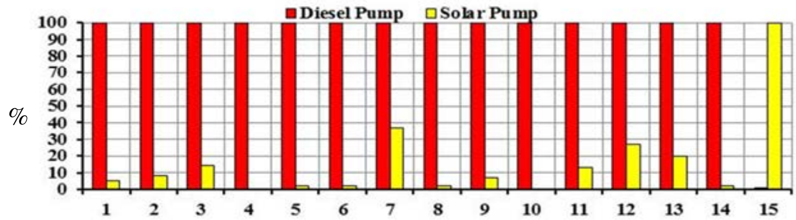

Fig. 2. Midpoint LCA results for the irrigation one feddan of rice using various pumping systems sets, powered either with diesel or with the solar energy, IMPACT 2002+

The midpoint indicators are very useful for ecosystem design purposes in the life cycle assessment method taken in account the four areas of protection, [9]. The four areas of protection that considered in LCA are human health, ecosystem quality, climate change and finally resources, as shown in Fig. 3. Diesel fuel water pumping system has higher negative impacts than the solar pumping system. The diesel fuel impact share is relatively steady over the three endpoints compared with the solar system. For ecosystem quality, human health and climate change impact solar power system about 10%, 12% and 25% respectively compared with 100% for diesel fuel pump, while 2 % for natural resources impact.

4.2.2. Contribution of the different pumping system components to environmental impacts

The main contributors to each environmental impact category were identified by performing contribution analysis. The contribution analysis performed to identify the room for-environmentally friendly-improvements, [9]. Fig.4 displays the contribution to midpoint impacts of each of the two pumping system diesel fuel and solar power systems. Diesel Fuel Pump impacts reach 70% for natural resources, 18% for human health, 10% for climate change and 2% for ecosystem quality. On the other hand, solar pumping system contributes to 3 % to climate change, 2% to human health and natural resources impacts, 0.5 % to ecosystem quality.

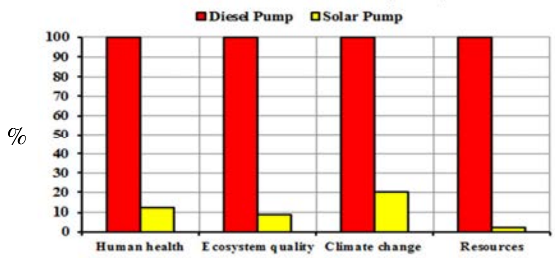

Fig. 3. Endpoint LCA results for the water pumping for irrigation one feddan of rice for the baseline situation (Tanta, Egypt, depth 30 m)

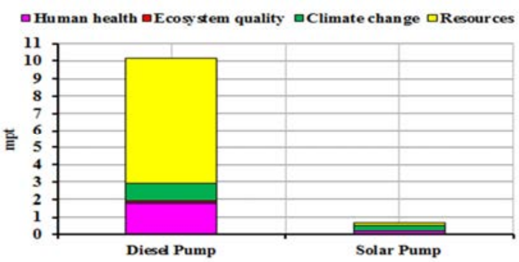

Fig. 4. Contribution analyses to endpoint impact categories of the pumping system

4.3. Sensitivity analysis

4.3.1. Sensitivity of head variation

In order to visualize the effect of variation of the dynamic hydraulic head the problem run by SimaPro for different values of dynamic head H equals 10, 20, 30, 40, 50 and 60m. Table 2 shows the design requirements for diesel fuel pump and solar pump for different hydraulic head and area cultivation scenarios.

Table 2: Requirements of diesel fuel and solar pump systems for different hydraulic head and area cultivation scenarios

Pump type	Diesel Fuel Pump		Solar Pump		Pump type	Diesel Fuel Pump		Solar Pump	
Head H (m)	Diesel fuel consumption Kg/day	Oil Consumption Kg/day	Number of solar panels	Weight of aluminium Kg/day	Area of planting feddan	Diesel fuel consumption Kg/day	Oil Consumption Kg/day	Number of solar panels	Weight of aluminium
10	0.35	5.09	7	0.06	1	1.04	15.26	20	0.18
20	0.69	10.17	13	0.12	2	2.08	30.52	40	0.36
30	1.04	15.26	20	0.18	3	3.12	45.78	60	0.54
40	1.39	20.35	27	0.24	4	4.16	61.04	80	0.72
50	1.73	25.43	34	0.30					

For the first scenario of a total dynamic head set at 10 m, i.e. the diesel fuel and oil consumption decreased by about 66% than at H=30m. The diesel pump still contribute to human resources, human health, climate change and quality ecosystem and by 70.58%, 17.64%, 11.76%, and 1.5% compared with 1.5, 1.5%, 3.0% and 0.75% respectively for solar pump. The most common contribution of solar energy is to climate change more than 20%, as shown in Fig. 5. The results of the second scenarios indicated the increase of contribution to environmental categories more than the first scenarios. SimaPro software made several calculations and transformed different units of emissions to one scale – milliEcopoints (mPt). Hence, the level of every impact category is presented on the bar chart. The contribution to human resources, human health, and climate change increased to4.5mPt, 1.25mPt and 0.75mPt respectively for a diesel fuel pumping system. In the fourth and fifth scenarios, the dynamic head of the pump increased to 40 and 50m respectively. For the fourth scenarios, the contribution to human resources from diesel fuel pump still the common environmental impacts contribution about 70.0% compared with 11.11 % to climate change impact and 18.51 to human health impact. The last scenarios indicated that the diesel fuel pump still contributes to the environment negatively than the solar pump system. Fig. 6 shows the contribution analysis to endpoint impact categories of the pumping system at H=40m for the two power pumping system diesel fuel and solar energy. It can be observed that the total contribution of the four environmental impacts categories increased by 17mPt and 1.0mPt for diesel fuel and solar energy pumps respectively.

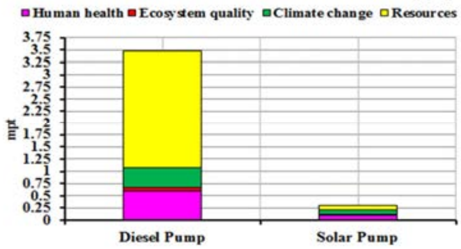

Fig. 5. Contribution analyses to endpoint impact categories of the pumping system at H=10m

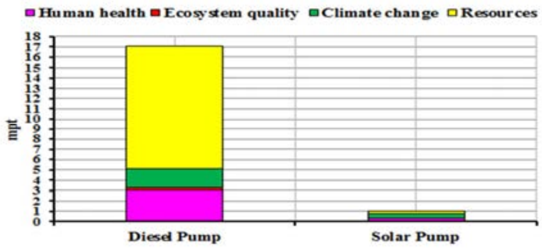

Fig. 6. Contribution analyses to endpoint impact categories of the pumping system at H=40m

4.3.2. Sensitivity of area of planting

In order to visualize the effect of variations of the area of rice cultivation, the problem run by SimaPro for different values of area equal 1, 2, 3 and 4 feddan. The contribution to the environmental impacts human resources, climate change, ecosystem quality and human resources are calculated for different areas scenarios 1, 2, 3 and 4 feddan. The results indicated that the increase of area cultivation would increase the pump requirements, so diesel fuel and oil consumption increased and also a number of solar panel increase for the solar pump system. As a result of that, the contribution to different environmental impacts increased. It increased from 8 mPt at 1 feddan to 12 mPt, 24mPt, 30mPt at 2, 3 and 4 feddan respectively for diesel fuel pump. On the other hand, the contribution to environmental impacts from solar pump increased by about 5%, 6.6% and 7.5% more than the contribution at 1 feddan for the solar pump system. The results show that the climate changes environmental impact is the most common environmental impact contribution for solar pump. It is about 20% followed by human health12%, ecosystem quality 10% and finally natural resources 3%.

5. Conclusions

LCA is performed by using SimaPro version 8.0.4.30 to assess the potential environmental impacts of diesel fuel and solar pumping systems also to evaluate the relative contribution of impact categories. Two power sources are taken into account in order to perform an accurate environmental assessment. The environmental impacts of pumping water using diesel pump and solar pump systems were reconducted for different hydraulic head and area of rice cultivation scenarios. The diesel-powered pumping systems are more harmful to the environment than solar power pumps. The contribution to midpoint environmental impacts of the diesel fuel pump impacts reach 70 % for natural resources, 18 % for human health, 10% for climate change and 2% for ecosystem quality. On the other hand, solar pumping system contributes to 3 % to climate change, 2% to human health and natural resources impacts, and 0.5 % to ecosystem quality. The sensitivity of hydraulic head and area of rice cultivation indicated that climate change impact is the most common category impact for solar pump, and the using of the solar pump system is more friendlily than diesel fuel pump.

Acknowledgements

The first author would like to thank the Egyptian Ministry of Higher Education (MoHE) for providing him the financial support (PhD scholarship) for this research as well as the Egypt Japan University of Science and Technology (E-JUST) for offering the facility and tools needed to conduct this work.

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