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Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Banglades

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Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh

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DECLARATION

I, Md. Tawhidul Islam, hereby declares that I am the sole author of the thesis entitled **'Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh'**. This is written and submitted by me to the Institute of Bangladesh Studies, University of Rajshahi, to fulfill the requirements for acquiring the degree of Master of Philosophy. This work was done under the guidance of Prof. Dr. Md. Elias Hossain, Department of Economics, University of Rajshahi.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate proprietary rights, and any ideas, techniques, quotation, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

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SUPERVISOR'S CERTIFICATE

I have the pleasure to certify that the thesis titled '**Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh**' submitted by Md. Tawhidul Islam, for the Master of Philosophy award, is his original work. So far, I know, this is the researcher's achievement and is not a conjoint work. He has completed this thesis under my direct guidance and supervision.

I also certify that I have gone through the draft and final version of the thesis and found it satisfactory for submission to the Institute of Bangladesh Studies, University of Rajshahi, Bangladesh, to fulfill the requirement for the Degree of Master of Philosophy.

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Md. Tawhidul Islam

ABSTRACT

Bangladesh is heavily dependent on traditional energy sources and imported fossil fuel, which harms the environment and economy. Renewable energy technologies are promoted to satisfy the country's rural energy needs mainly as a form of solar home system and solar irrigation pump. As an agriculture-based country, irrigation is vital for ensuring the country's food security. The requirement for irrigation rises over the years, mainly due to the increase of High Yielding Variety (HYV) use, decline of the water table, reduction of surface water sources, increase of cropping areas, and volatility of climatic condition of the country. In recent years a sustainable source of irrigation becomes very important for Bangladesh. In this regard, solar irrigation will be a reliable source of irrigation. This study investigates the economic feasibility and environmental impact of the solar irrigation pump in Bangladesh's greater Rajshahi region. The study is mainly done based on primary data collected from the users and non-users of solar irrigation. The data have been collected from six unions of three Upazilas named Birganj under Dinajpur, Badarganj under Rangpur, and Nandigram under the Bogra district of Bangladesh. Fifty solar irrigation pumps (SIPs) with different capacities are selected randomly from the study areas after collecting a list of all solar irrigation pumps from Infrastructure Development Company Ltd (IDCOL). Then, five irrigation service takers from each solar irrigation pump have been selected by following multistage random sampling technique. The information was also collected from the 100 non-users of solar irrigation to accumulate the required data by personal interviews using standard questionnaires. In addition to primary data, some secondary data are also collected from IDCOL, PO, different government institutions, and published sources such as books, reports, and journal articles for this study. The aim was to conceive the economic feasibility and environmental impact of solar irrigation pumps in the Rajshahi region of Bangladesh. Several methods and techniques have been employed to attain the objectives of the study. The life cycle cost analysis of different energy options of irrigation, standard financial analysis of different solar pumps, two-sample t-test, a binary logistic regression model, and net environmental impact analysis of the solar pumps are mentionable.

According to the farmers, solar irrigation is a time-saving, pollution-free, and regular irrigation option than the diesel operated one. Furthermore, solar irrigation prevents the environment from air and sound pollution as well as water contamination with diesel. The calculated Annualized Life Cycle Cost (ALCC) for 3 HP solar, diesel, and electrified pumping systems were 38042 Tk, 94861 Tk, and 27740 Tk, respectively. ALCC of diesel operated pumping system has been found almost 2.5 fold greater than the ALCC of the solar PV pumping system. Thus, the farmers' irrigation cost would reduce substantially if solar pumps substitute the diesel pumps. In different solar irrigation pumps, the large solar irrigation pumps' economic feasibility was found moderately profitable. Furthermore, large pumps' profitability has been improved after the introduction of alternative use of it. Next, the financial indicators were found not viable in the case of medium solar irrigation pumps. On the other hand, small solar irrigation pumps have been the most profitable option for investment.

The Boro harvesting was increased significantly by more than 25 kg per bigha (50 decimal) land due to the introduction of solar irrigation. The availability and uninterrupted supply of irrigation water by the solar pump ensure Boro's significant increase. Then, from the binary logistic regression model, it is found that 'education', 'size of operational landholding', 'investment plan for renting', 'loan for agricultural investment' and 'view on solar irrigation pump' have a significant positive influence on the solar irrigation pump adoption decision. Lastly, the net environmental benefit of solar irrigation pump is found greater or equal to the given amount of subsidy to install it. Thus, the given subsidy has been justified for this investment. Besides, the net environmental benefit per kWp has been highest for the small solar irrigation pump. Therefore, government should continue to give subsidies in solar irrigation pump especially in small pump.

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CHAPTER ONE
INTRODUCTION

1.1 Background of the Study

Bangladesh is the most densely populated country (1099 persons / km^2 in 2010) in the world. A population of 162.20 million in 2011 requires constant food security to feed her vast population.[1] In this regard, the adaptation of irrigation systems plays a vital role in ensuring the efficient use of agricultural land and technology to safeguard our food security by enhancing food production. Hence, we need a massive number of pumps in our country's rural areas for irrigation in the upcoming years. However, nowadays, many rivers suffer from a scarcity of water, especially in dry seasons. As a result, underground water has become the primary source of irrigation. Thus, farmers mainly use diesel and grid-connected water pumps for irrigation. Over 1.57 million irrigation pumps are being used in the country, of which 80% are diesel engines operated, and 20% are electricity operated.[2] Thus, present pumps are mostly diesel engines operated, especially where electricity from the national grid is not available. For this reason, every year, Bangladesh imports about 1.06 million tons of diesel. The government usually provides subsidies in diesel prices to make it affordable for irrigation, which creates extra pressure on the country's economy. The World Bank also reported that over-dependency on costly imported diesel for irrigation puts pressure on our foreign currency reserve. For example, thirteen hundred solar irrigation pumps can save about $3.2 million every year by replacing diesel with clean and renewable solar energy.

On the other hand, the grid-connected irrigation pumps also have some problems in Bangladesh due to the low voltage and load shedding. Bangladesh faces an acute shortage of energy, especially in the peak irrigation period[3] due to 20.36% of total generated electricity is used for irrigation in peak hours.[4] Thus, during peak irrigation, the whole country faces an energy crisis of 1248 MW.[5] The total generation capacity of electricity in the country was about 15000 MW in 2018. However, the maximum generation was 10958

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[1] Ashwin Matabadal, *Country Report : Bangladesh* (Rabobank Netherland, 2011).
[2] Bangladesh Agricultural Development Corporation, "Organization Wise Summary of Irrigation Equipment Used, Area Irrigated and Benefited Farmers" http://www.badc.gov.bd (accessed 13 December 2017).
[3] *Biddut Sorborah Karjokrom, Sech Moushum (2017)*2017.
[4] *Ibid.*
[5] BBS, *National Accounts Statistics*2016. Vol. 19.

MW due to fuel supply constraints.[6] The primary source of electricity in Bangladesh is a fossil fuel. Contribution of the gas-based power generation is 61.37% (6725 MW), diesel and furnace oil is 24.72 % (2708 MW), the coal-based power plant is 2.70% (295 MW), and hydroelectric generation is 1.63 % (220 MW) of the total produced electricity of Bangladesh.[7] Thus the primary sources of electricity generation in Bangladesh are natural gas, diesel, and furnace oil-based power plants. Due to the reducing reserve of natural gas of the country and oil price volatility in the international market, these sources have become non-sustainable and vulnerable.

The country's energy demand has been growing remarkably due to the fast increasing population, rapid change in the economy, and industrialization. Increasing energy demand diminishes the reserve of fossil fuels, e.g., natural gas and coal, and adversely affect the environment. Therefore, to meet energy demand, reduce the adverse effect of price volatility, [8] many countries are looking for green energy resources, e. g. solar and wind energy to mitigate environmental problems.[9] Thus, the Bangladesh government has the vision to generate 10% of its total power by renewable sources within the year 2020.[10] Solar energy can play an essential role in fulfilling the vision because solar radiation is richly available in Bangladesh, with an average variation between 4 and 6.5 kW/m^2/day.[11] For example, Rajshahi's average solar insolation or radiation rate varies between 3.96 and 6.24 kW/m^2/day. The maximum solar insolation occurs during February–June, and the minimum occurs during October–February in Bangladesh.[12] The average bright sunshine hours vary from 6 to 9 h/day, which is one of the significant positive indications of solar irrigation pumps' viability. Bangladesh has already turned into a role model in using the solar home system (SHS). It has been acclaimed as the most extensive off-grid renewable energy program globally. Bangladesh now has more than five million units installed

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[6] *Ibid.*

[7] *Biddut Sorborah Karjokrom, Sech Moushum (2017)*.

[8] S. Mekhilef et al., "The Application of Solar Technologies for Sustainable Development of Agricultural Sector," *Renewable and Sustainable Energy Reviews* 18, (2013)

[9] Md Rabiul Islam, Youguang Guo, and Jianguo Zhu, "A Review of Offshore Wind Turbine Nacelle: Technical Challenges, and Research and Developmental Trends," *Renewable and Sustainable Energy Reviews* 33, (2014).

[10] BPDB, "Government of the Peoples Republic of the Bangladesh", Power Division http://www.powerdivision.gov.bd (accessed May 12 2017).

[11] MA Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh," *International Journal of Energy and Environmental Engineering* 6, no. 2 (2015).

[12] M. Islam, Md Rabiul Islam, and M. Beg, "Renewable Energy Resources and Technologies Practice in Bangladesh," *Renewable and Sustainable Energy Reviews*, (2008).

among seven million SHSs in operation worldwide. The information has been published in a recent report of the Paris-based energy think-tank, REN21. Thus SHS program has ensured the supply of solar electricity to 18 million people, i.e., 12 percent of the country's total population who previously used kerosene lamps for lighting purposes.[13]

Thus, Bangladesh has already utilized solar energy at the home level successfully through the solar home system. The economic, social, and environmental benefits of SHS have already been proved in several studies. Therefore, the system becomes acceptable to the root level and plays a significant role in improving poor people's socio-economic conditions. After getting this success in SHS, the government set a target to install 50000 solar irrigation pumps countrywide within 2025.

On the other hand, the CO_2 emission mainly due to the operation of diesel based irrigation pumps in Bangladesh's agriculture sector increases day by day. It has increased to 7814 thousand tons in 2012 from 705 thousand tons in 1983, which means about 11 folds increase in CO_2 emission from diesel and electricity run irrigation pumps within 30 years.[14] It can be checked by introducing solar irrigation pumps instead of conventional pumps. For these purposes, Infrastructure Development Company Limited (IDCOL) was established by Bangladesh's government in 1997. Its purpose was to bridge the financing gap for developing medium to large-scale infrastructure and renewable energy projects. Moreover, IDCOL already has a target to replace 18,700 diesel pumps with solar irrigation pumps within 2020.[15]Undoubtedly, installing solar irrigation pumps will reduce carbon emissions and have an almost negligible operation and maintenance cost.

Nevertheless, SIP's installation is not free from problems and the main problem is the high initial capital investment required to install it. Further, there is a lack of technically trained personnel and supply chains for components and parts of solar photovoltaic (PV) systems in rural areas. This leads to low maintenance and delays in repairs[16] and can affect system lifetime and economic viability. On the other hand, every SIP receives a 40% grant or

[13] Md Nazmul Islam Sarkar and Himanghshu Ranjan Ghosh, "Techno-Economic Analysis and Challenges of Solar Powered Pumps Dissemination in Bangladesh," *Sustainable Energy Technologies and Assessments* 20, (2017).

[14] R. F. Al-Masum, M. A. Ashraf, and M. T. Islam, "Environmental Contamination by Co2 Emission through Irrigation Pump " *Bangladesh Journal of Environmental Science* 32 (2017).

[15] Energy and Mineral Resources Ministry of Power, Government of the People's Republic of Bangladesh, "500 Mw Solar Programme" http://www.powerdivision.portal.gov.bd (accessed 23 October 2017).

[16] Sania Binte Mahtab and Abrar Morshed, "Achievements of a Pilot Solar Powered Irrigation Project in Bangladesh," *International Advanced Research Journal in Science, Engineering and Technology* 5, no. 9 (2018).

subsidy from development partners and the government. According to some studies, solar pumps become economically unviable for farmers without this subsidy compared to conventional electric and diesel-run pumps. Also, solar irrigation pumps are less efficient compared to diesel-operated pumps. A solar pump of 3 horsepower (hp) working for 8 hours a day gives the same water output as a standard 3 hp pump working on grid power or diesel engine for 5 hours a day.[17]

Then again, concerns are raised about the implications of using solar- pumps on the groundwater draft, as solar pump users are not confronted with the marginal costs of running their pumps. Thus groundwater might be overexploited as a negative externality.[18] Once a farmer switches over to a solar pump, he has no incentive to use water efficiently because the marginal cost of groundwater withdrawal comes to zero.

Finally, solar panels require 6 to 10 decimal land to install at the local level. In this regard, a study conducted by Nitin Bassi mentioned that cropping and irrigation intensity is very high in Eastern India, such as in West Bengal. So, no barren and un-cultivable land is available there to install a solar array.[19] The author then concluded that large-scale adoption of solar pumps in Eastern India looks like a remote possibility from a technical point of view. According to recent studies, the policy makers of GOs and NGOs of Bangladesh are very optimistic about SIP's large scale adoption. However, the agricultural and geographical scenario of Bangladesh and West Bengal is almost similar. Therefore, this study has tried to determine the real condition and possible solution to this problem from the field survey.

Therefore, this study tried to give a clear idea about the economic and environmental benefits and the real potentiality and impediment of SIP's mass adoption in Bangladesh. So, this study would help achieve the government's aim of generating 10% of total energy from renewable energy by 2025.[20]

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[17] Joydip Kumar Dev, "Assessment of Potential Environmental Benefits of Using Solar Power for Irrigation Pump in Bangladesh" (Bangladesh University of Engineering and Technology, 2014).

[18] M. Wakilur Rahman and Lovely Parvin, "Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades " *J. Water Resource and Protection* 3, (2009).

[19] Nitin Bassi, "Irrigation and Energy Nexus: Solar Pumps Are Not Viable," *Economic and political weekly* 50, no. 10 (2015).

[20] Energy and Mineral Resource Ministry of Power, Government of the Peoples Republic of Bangladesh, "Renewable Energy Policy of Bangladesh" http://pv-expo.net/BD/Renewable_Energy_Policy.pdf (accessed 6 Nov 2018).

1.2 Problem Statement

Bangladesh is primarily an agrarian country. The agriculture sector's total contribution to GDP is 15.33%, and the crop sector to GDP is 13.44%. Around 40% of the total workforce relies on the agriculture sector.[21] This agriculture sector has an enormous effect in generating employment, alleviate poverty, and provide food security to the country. The total cultivable land in Bangladesh is 8.52 million hectares, of which the total cropped area is 14.943 million hectares.[22] About 1.57 million irrigation pumps are used to cultivate this massive amount of land; 80% of total pumps are diesel engine-operated, and 20% are electricity operated.[23] Grid electricity-based irrigation pumps consume about 1300 MW of electricity, approximately 12% of its total production.[24] Electricity access to developing countries is a big challenge. It includes an ever-increasing demand-supply gap, crumbling electricity transmission, weak distribution infrastructure, and high diesel cost. At this moment, Bangladesh cannot supply the desired amount of electricity for irrigation as the country experiences an unmanageable gap between the supply and demand of electricity. Load shedding seems intolerable, especially in the summer season. There is a massive demand for electricity to irrigate the land. At present, the electricity generation capacity of Bangladesh is about 15000 MW.[25] Only about 68% of the total population of the country has access to grid electricity. This unavailability of electricity decreases the production of foods and also cut the growth of GDP. Besides grid electricity, a diesel generator is the other option to operate the irrigation pump. In Bangladesh, around 1 million tons of diesel is used per year to operate about 1.24 million diesel-run irrigation pumps.[26] The worth of this amount of imported diesel is about $280 million.[27] The transportation of this enormous amount of diesel to the fields is difficult, costly, and sometimes the supply can be inconsistent. Moreover, farmers are often dependent on intermediaries for fuel, who may charge higher diesel prices during peak irrigation period and drive farmers further

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[21] BBS.

[22] *Ibid.*

[23] M. A. Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh," *Int J Energy Environ Eng* 6, (2015).

[24] Allan Hoffman, "Water, Energy, and Environment", IWA Publishing http://www.oapen.org/download?type=document&docid=1004280.

[25] Alvar Closas and Edwin Rap, "Solar-Based Groundwater Pumping for Irrigation: Sustainability, Policies, and Limitations," *Energy policy* 104, (2017).

[26] M. R. Islam, M. R. Islam, and MRA Beg, "Renewable Energy Resources and Technologies Practice in Bangladesh," *Renewable and Sustainable Energy Reviews* 12, no. 2 (2008).

[27] M. S. H Lipu and T. Jamal, "Techno-Economic Analysis of Solar Concentrating Power (Csp) in Bangladesh," *International Journal of Advanced Renewable Energy Researches (IJARER)* 2, no. 5 (2013).

into financial difficulties. Diesel pumps also break down frequently, have high maintenance costs, and pollute the environment. So, to minimize the energy crisis and environmental pollution and reduce the dependency on petroleum fuel, it is a desperate need to explore alternative energy sources for irrigation purposes. In this regard, the solar power irrigation system brings a new era of irrigation in Bangladesh.

Solar energy is a safe alternative to fossil fuels like coal, oil, and gas for electricity generation. However, it also has some sort of disadvantages that are shown in Table 1.1.

Table 1.1: Pros and Cons of Solar Energy

Advantages of Solar Energy	Disadvantages of Solar Energy
Renewable and environmentally friendly energy	High initial cost
Reduces electricity bills or fuel cost	Weather dependency
Diverse applications	Solar energy storage is expensive
Low maintenance costs	Uses much space
Technology development	Associated with minimal pollution

Source: Greenmatch (2018) [28]

The first advantage of solar energy is that it is a renewable energy source. It can be excessed every day from any region of the world. Solar energy would be available to us for at least 5 billion years until the sun will die. The energy can reduce greenhouse gas emissions by replacing fossil fuels with renewable energy. The second advantage is, solar energy can replace grid-connected electricity or fossil fuel like diesel or gas by producing electricity. Thus it can save electricity bills as well as fossil fuel costs. The third advantage is its diverse application such as solar energy can produce electricity, distill water, withdraw water from underground, power satellites in space, etc. The fourth advantage is that this system generally does not require any maintenance costs; it has to be cleaned a couple of times per year. The cables and inverter need to change after 5-10 years. The fifth benefit is the constant advancement and improvement of the solar power industry. Thus, innovation in quantum physics and nanotechnology can potentially increase the effectiveness of solar panels.

On the other hand, the first disadvantage is the high initial cost of purchasing a solar system. It includes paying for solar panels, inverter, wiring, and installation. Nevertheless, solar technologies are continually developing, so the prices would go down in the future.

[28] Greenmatch, "Pros and Cons of Solar Energy" https://www.greenmatch.co.uk/blog/2014/08/5-advantages-and-5-disadvantages-of-solar-energy (accessed 25 Nov 2018).

The second disadvantage is weather dependency. Solar panels convert the sunlight into solar energy. Thus, a cloudy or rainy day can have a noticeable adverse effect on energy generation. The third weakness is the expensive solar energy storage process. Solar energy can use instantaneously, or it can store in large batteries. These batteries can be charged during the day so that the energy can be used at night; thus, it can be used all day long, but it is quite expensive. Nevertheless, it would be sufficient for the irrigation purpose to use the energy for withdrawing water at day time. The fourth limitation of solar energy is the space requirement. More solar panels are necessary to collect ample sunlight, and solar PV panels require open space to install. It would be one of the main concerns for a land-scarce country like Bangladesh to introduce the mass level's PV system. The fifth problem of solar energy is its association with minimal pollution. Transportation and installation of the solar system have been associated with the emission of some greenhouse gases. Moreover, some toxic materials and hazardous elements are used during the manufacturing process of solar photovoltaic panels, which can indirectly affect the environment. However, the pollution related to the solar energy system is far less than other sources of energy. These advantages and disadvantages of SIPs have been examined in the context of Bangladesh.

At present, there are more than 832 solar irrigation pumps already installed in the country, and there is also a plan to install 2278 solar irrigation pumps within the year 2020.[29] The system can be a sustainable source of irrigation if it will be economically feasible for farmers and beneficial for the environment. That is why the study tried to determine the economic feasibility and environmental benefit of SIPs in Bangladesh. Some relevant studies measured the economic feasibility in terms of NPV, IRR, BCR, and PBP but the financial indicators vary enormously from study to study. Also, the studies have considered only one type of solar irrigation pump with a respective panel capacity. However, several types of solar irrigation pumps with different panel capacities are being operated now in Bangladesh. The financial indicators should be measured more accurately for different solar irrigation pumps to realize this investment's actual feasibility. It would then also be worthy to compare the financial feasibility of all available energy sources

[29] Hoffman.

such as diesel, electricity, and solar to operate irrigation pumps. It will help to recognize the most sustainable and profitable source of energy for irrigation.

Also, the farmers' benefits from SIPs have not been calculated elaborately in the existing studies. That is why this study tried to measure the impact on the output of different crops due to solar irrigation. If it would positively affect the yield of crops, then the viability of solar irrigation pumps over the conventional pumps would be established further.

Besides, a logistic regression model is employed in this study, which identified the determinants of adopting the decision of SIPs instead of diesel-run pumps. The model's dependent variable is the adoption of a solar irrigation pump where 1 indicates adopting a solar irrigation pump, 0 otherwise. The independent variables used in the model are the age of farmer, education of farmers, size of landholding, land fragmentations, cropping intensity, an investment plan for renting, groundwater depth, satisfaction with present irrigation, loan for agricultural investment, view on solar irrigation pumps, and view on climate variations. This model is used to identify the influential factors that affect the adoption decision of solar irrigation pump.

Again, in Bangladesh, CO_2 emission from irrigation pumps was 1.43 million tons in 1990, and it was increased sharply to 6.73 million tons in 2012.[30] Within 22 years, CO_2 emission increased by 5 folds due to the increase in the number of irrigation pumps over these years. In 1990, the total number of irrigation pumps was 0.33 million, and they were increased to 1.81 million in 2012.[31] If these conventional irrigation pumps can be replaced with solar pumps, Bangladesh can mitigate massive CO_2 emissions each year. The mitigated amount of CO_2 has been considered as the environmental benefit of SIP.

The SIP's economic feasibility from the perspective of the installers (OPs) has been found in a few existing studies. However, the real benefit of farmers from solar irrigation pumps is not yet examined. In this study, to realize the real impact of solar irrigation, information has been collected from both service providers (POs) and receivers (farmers).

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[30] Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh."
[31] *Ibid.*

Based on the above-stated problems, some research questions have arisen regarding the use of solar irrigation pumps in the context of Bangladesh. The questions are as follows:

i. What is the present scenario of energy and irrigation in Bangladesh?
ii. Is solar irrigation an economically feasible option for irrigation in the Rajshahi region of Bangladesh?
iii. Furthermore, what factors are affecting the adoption decision of solar irrigation?
iv. What is the impact of solar irrigation pumps on the environment?

These relevant questions regarding the current status of SIP in agriculture need to be analyzed in the context of Bangladesh. The answer to the first question is given based on secondary data and information. The second and third questions are investigated mainly based on field survey data collected from farmers and solar pumps' installers.

The data collected from the service receivers (farmers) about SIP's service is crucial because it helps realize the actual impact of solar irrigation on the crops' productivity and yields. Moreover, the information collected from the installers (POs) is also essential to understand the difficulties of installing and running a SIP in a remote village. Thus, the primary data collected from field surveys and the secondary data collected from different sources have been used to measure the economic and environmental benefits of SIPs.

1.3 Objectives of the Study

The study's primary purpose is to identify the solar irrigation pumps' overall economic and environmental viability in the Rajshahi region of Bangladesh. Some specific objectives have been set to achieve the primary objective. These are mentioned below:

i. To portray a scenario of energy and its use in irrigation in Bangladesh;
ii. To measure the economic feasibility of solar irrigation pumps in the greater Rajshahi region of Bangladesh;
iii. To find out the factors affecting the adoption decision of solar irrigation by farmers;
iv. To estimate the environmental impact of solar irrigation pumps.

This study applied the descriptive statistical techniques, cost-benefit analysis, and a binary logistic model to achieve the above-stated objectives. Its first objective has been achieved by analyzing secondary data collected from some earlier publications such as journal articles, reports, and information from IDCOL and BBS. The second objective has been achieved by the cost-benefit analysis, scientific comparisons among the different energy options of irrigation pumps, and logistic regression model analysis with the data collected from the field survey. The last objective, the environmental impact of SIP, has been reached by calculating CO_2 emission reduction due to diesel substitution by solar irrigation pump.

1.4 Justification of the Study

It is crucial to ensure the food security of 162.20 million people in Bangladesh by increasing the agricultural sector's productivity. That is why the necessity and demand for surface and groundwater irrigation increases day by day in Bangladesh. It is also true for the global context means the demand for irrigation gradually increases globally. That is why conventional irrigation pumps' harmful impact on the environment and its sustainability becomes a concern worldwide. Therefore, different countries' policymakers support new policies to replace the conventional pumps with renewable energy run pumps like solar and wind pumps to ensure sustainable water supply for irrigation. It is an economically and environmentally viable option for irrigation. It helps to ensure food security by increasing the yield of crops in the long run. It would also help achieve the SDGs' 7^{th} goal to ensure access to affordable, reliable, sustainable, and modern energy for all within 2030. That is why it would be vital to formulate appropriate policies to accept the new renewable energy technology widely at the root level. In this perspective, this research will significantly contribute to the literature related to the economic and environmental impact of solar irrigation pump in Bangladesh. The objective, methodological approach, results, findings, and policy suggestions of this study would expand the knowledge about the present scenario, economic feasibility, environmental impact and the key factors that influence the adoption decision of solar irrigation pumps in Bangladesh.

1.5 Thesis Structure

This present study on the solar irrigation pump's economic and environmental feasibility in the greater Rajshahi region contains six chapters. The chapters are organized as follows: The first chapter, the present chapter, starts with the study's background and ends up with this section. Chapter two, titled literature review, contains a brief review of the earlier literature regarding the solar irrigation pump's economic feasibility and environmental impact. The gaps in the previous research have also been mentioned here. Chapter three describes the research methodology followed in this study, including the data collection procedure, the sample selection, description of the data, estimation procedure, and the empirical results' presentation. Chapter four provides the overviews of the energy and irrigation of Bangladesh. This chapter also illustrates the present scenario of SIPs in the country. Chapter five provides a detailed result and discussion about the cost-benefit analysis of the investment to install a solar irrigation pump and a comparison of SIPs with other conventional irrigation pumps. Besides, the environmental impacts of SIPs and a logistic model also have been employed in this chapter. Finally, chapter six, the final chapter, summarizes the significant findings of this study and policy implications. Besides main chapters, declaration, acknowledgment, abstract, contents, list of tables, list of figures, list of abbreviations, references, and appendices are also provided as part of this thesis's organization.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Renewable energy is energy produced from sources that do not deplete or can be replenished within a human's lifetime. The most common examples of renewable energy are wind, solar, geothermal, biomass, and hydropower.[32] Renewable energy is the opposite of non-renewable sources such as fossil fuels. The use of renewable energy, especially in the agriculture sector, becomes a vital matter for being a sustainable energy source and impacts the environment. Solar energy has already been introduced in Bangladesh's agriculture and other countries as solar photovoltaic pumps for irrigation. Hence this study has been conducted under the title of 'Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh.' Economic feasibility, also known as cost-benefit analysis, is the most commonly used method for determining a new project's efficiency. It helps in identifying profit against investment expected from a project.[33] Environmental impact indicates the environmental consequences (positive and negative) of a project.

Moreover, irrigation is an artificial water supply process for dry agricultural land using dams, barrages, channels, or other devices such as pumps.[34] Therefore, a solar irrigation pump runs on electricity generated from collected sunlight by photovoltaic panels instead of grid electricity or diesel run irrigation pumps.[35] Several researchers have examined the economic feasibility of solar irrigation pumps. Some of them give their attention to the environmental impact of this pump. This chapter is a critical and in-depth analysis of earlier studies related to the solar irrigation pump's economic feasibility and environmental impacts. The main intention of reviewing earlier literature is to establish the grounds for conducting this study. Importance was given to the issues related to the economic feasibility and the environmental consequences of solar irrigation pumps that have already

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[32] "Renewable Energy " https://www.studentenergy.org/topics/renewable-energy#reference-1 (accessed 12 March 2020).

[33] Annual Report of Dhaka Electric Supply Authority (DESA), 2012.

[34] A. Mérida García et al., "Comparing the Environmental and Economic Impacts of on- or Off-Grid Solar Photovoltaics with Traditional Energy Sources for Rural Irrigation Systems," *Renewable Energy* 140, (2019).

[35] Maura McDermott and James E. Horne, "The Next Green Revolution : Essential Steps to a Healthy, Sustainable Agriculture," *Food Products Press, New York* (2001).

been investigated in other countries. Thus, this chapter helps to find the gaps in the earlier literature and enables the researcher to carry out a new study about the sustainability and environmental impact of renewable energy for irrigation in the country's agriculture.

This chapter is divided into four sections. Section 2.1, the present section, introduces the literature review; Section 2.2 provides the review of earlier literature in the context of solar pumps' economic feasibility. Section 2.3 describes the environmental impacts of solar PV pumps; finally, gaps in the existing literature mentioned in section 2.4.

2.2 Economic Feasibility of Solar Irrigation Pumps

Economic feasibility mainly depends on the life cycle costs and benefits of an investment. From the existing literature in the context of all over the world, three factors have been found those broadly influence the economic feasibility of solar irrigation pumps. These factors are (1) Costs and benefits of solar irrigation pumps, (2) Cost of alternative irrigation solutions, and (3) Impact on revenues due to the use of solar irrigation pump. These three determinants influence the economic feasibility of solar irrigation pump in the following way:

2.2.1 Costs and Benefits of Solar Irrigation Pumps

Costs and benefits of solar irrigation pumps are the main factors of the pump's economic feasibility analysis. Several studies have tried to find out the costs and benefits of solar irrigation pumps in the following ways:

Leah C. Kelley et al. found from lifecycle cost analysis that solar-powered irrigation is economically viable in Saudi Arabia. However, the PV panels' high costs involve a high initial cash outlay, which will likely need financing. So, the lifecycle costs of the PV systems may be lower. Still, the ability to fund the initial capital costs may create a barrier to implementing a solar-powered irrigation system even in Saudi Arabia.[36] In Bangladesh's case, the initial cost of SIP would also make a barrier for the poor, middle, and even wealthy farmers to adopt this technology. García et al. estimated that the economic payback time was 8.6 years for the off-grid PV installation.[37] It seems quite a high payback period in Spain. However, in Bangladesh's context, PBPs of different SIPs have

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[36] Leah C. Kelley et al., "On the Feasibility of Solar-Powered Irrigation," *Renewable and Sustainable Energy Reviews* 14, no. 9 (2010).

[37] Mérida García et al., "Comparing the Environmental and Economic Impacts of on- or Off-Grid Solar Photovoltaics with Traditional Energy Sources for Rural Irrigation Systems."

not been measured precisely in existing studies.

In the developing nations, the capital cost is still the main hindrances to the widespread use of SIPs.[38] In Bangladesh's context, the capital cost also would be the main barrier to the widespread installation of SIPs. Burney et al. concluded that when fuel prices are higher (without subsidy), PV irrigation became cost-competitive, even with the very high array prices associated with the pilot project.[39] Thus the current price of diesel and electricity can affect the demand for solar irrigation pumps.

In Sudan's case, Bakir Ali found that solar energy in the form of solar photovoltaic irrigation pumps would contribute significantly to the sustainable development of the agricultural sector in Sudan.[40] As a developing country, Bangladesh also has a reasonable opportunity to get a sustainable irrigation source from solar energy.

In another study in Sudan, A. M. Omer investigated the solar PV water pumping system's technical and economic feasibility. He found that SPV pumps were the most feasible solution to meet water requirements for drinking, livestock feeding, and irrigation purposes considering Sudan's meteorological conditions.[41] Bangladesh's meteorological conditions might also be suitable for the operation of solar irrigation pumps, especially in the study areas.

In Algeria, Hamidat et al. found that SIPs can efficiently pump sufficient water for small-scale irrigation with an area smaller than 2 ha.[42] Nevertheless, in Bangladesh's case, the average holding is less than 1 ha. Thus, the owner can quickly sell water for irrigation to his neighbor farmers and get additional benefits from this investment.

Hammad and Ebaid conducted a study in South Jordan about the energy source for the large scale water extraction from wells for mass household use. The life cycle costs of producing 1 kWh energy for water extraction from the lowest to highest alternative were

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[38] Kala Meah, Sadrul Ula, and Steven Barrett, "Solar Photovoltaic Water Pumping Opportunities and Challenges," *RSER Renewable and Sustainable Energy Reviews* 12, no. 4 (2008).
[39] Jennifer Burney et al., "Solar-Powered Drip Irrigation Enhances Food Security in the Sudano-Sahel," *procnatiacadscie Proceedings of the National Academy of Sciences of the United States of America* 107, no. 5 (2010).
[40] Bakir Ali, "Comparative Assessment of the Feasibility for Solar Irrigation Pumps in Sudan," *Renewable and Sustainable Energy Reviews* 81, (2018).
[41] Abdeen Mustafa Omer, "Solar Water Pumping Clean Water for Sudan Rural Areas," *Renewable Energy* 24, no. 2 (2001).
[42] A. Hamidat, B. Benyoucef, and T. Hartani, "Small-Scale Irrigation with Photovoltaic Water Pumping System in Sahara Regions," *RENE</cja:jid> Renewable Energy* 28, no. 7 (2003).

the only PV (US$0.136/kWh), PV-grid (US$0.140/kWh), only grid (US$0.144/kWh), PV-generator (US$0.185/kWh), and only generator (US$0.239/kWh), respectively. The analysis proved that the PV solar system is a more cost-effective and suitable option over other conventional energy types for even an extensive power system.[43]

Foster et al. surveyed 46 water pumping systems installed under Mexican Renewable Energy Program (MREP) – a collaborative program sponsored by the United States. The results show that most systems were functioning after 10 years. They have proven to be an excellent option to meet water pumping needs in rural Mexico, where electrical grid services are not available. The average investment payback period for the PV water pumping systems found to be 5–6 years.[44] Thus SIP's economic viability has increased in distant rural areas where electricity connection is not available. Mekhilef et al. also mentioned in favor of this matter. They found that globally solar energy applications would be a suitable option in the agricultural sector, especially for the distant rural area. The solar system offers maintenance-free and locally available, environmentally friendly energy.[45]

In India, Pande et al. found that supply water through the solar pump for drip irrigation to an orchard farm is economically feasible, and the calculated payback period was 6 years.[46] However, in Bangladesh, for paddy cultivation, mainly flood irrigation is practiced. Thus the feasibility test for flood irrigation by SIP would be crucial for this region. Surendra et al. presented the economic analysis and life cycle cost-analysis of solar pumps developed for small farmers in India. They found that small capacity pumps are most suitable for countries like India.[47] However, in Bangladesh's case, the solar irrigation pump's suitable size has not yet been measured.

Purohit and Kandpal presented a financial performance evaluation of a PV water pump in India. They found that PV pumping systems are a viable option when the government

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[43] Mahmoud Hammad and Munzer S. Y. Ebaid, "Comparative Economic Viability and Environmental Impact of Pv, Diesel and Grid Systems for Large Underground Water Pumping Application (55 Wells) in Jordan," *Renewables: Wind, Water, and Solar* 2, no. 1 (2015).
[44] RE Foster et al., "Ten-Year Reliability Assessment of Photovoltaic Water Pumping Systems in Mexico," *American Solar Energy Society*, no. 1 (2004).
[45] Mekhilef et al., "The Application of Solar Technologies for Sustainable Development of Agricultural Sector."
[46] P. C. Pande et al., "Design Development and Testing of a Solar Pv Pump Based Drip System for Orchards," *Renewable energy.* 28, no. 3 (2003).
[47] TS Surendra and SVV Subbaraman, "Solar Pv Water Pumping Comes of Age in India," in *The twenty-ninth IEE photovoltaic specialists conference* (2002).

provides sufficient incentives.[48] Thus, it would be challenging for the investor to manage the capital cost of SIP without subsidy. In the case of Bangladesh, Najmul Hoque et al. also support the findings of Purohit and Kandpal. For the current financial scheme for SIPs (20% equity investment, 40% credit support, and the remaining 40% grant from IDCOL), the payback period's average value was 5.43 years. NPV was 13,756 Tk at a 15% discounting factor, and IRR was 18%. However, without any support, these projects were not economically attractive. The payback period for this case was about 18 years.[49]

In Bangladesh, Sarkar and Ghosh also calculated the financial indicators for an investment to install a 1 kW solar irrigation pump. They found that the internal rate of return (IRR) was 12.95%. The simple payback period was 9.33 years, and the benefit-cost ratio was 1.08 for the investment.[50] This finding does not seem very impressive. Thus, further investigation for SIPs with different capacities would help produce more effective policies and recommendations to increase the SIP's acceptance.

Moreover, the following factors would also have substantial impacts on the costs and benefits of solar irrigation pump:

Closas and Rap were concerned about access to solar irrigation services. They mentioned that the access could be limited to specific farmers. Its benefits can escape small farmers like Bangladesh, mostly if they do not own their farms.[51] To solve the problem, non-government organizations (NGOs) of Bangladesh introduced fees for the service model for a solar irrigation pump. However, the pros and cons of this model have not yet been examined in the existing literature.

Theft of agricultural equipment is also an additional risk that farmers would have to face if they installed this system in remote areas. This stolen technology can be re-sold.[52] It might also affect the economic feasibility of the solar irrigation pump in Bangladesh by bringing additional costs to ensure the pump's security.

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[48] P Purohit and TC Kandpal, "Solar Photovoltaic Water Pumping in India: A Financial Evaluation " *Int J Ambient Energy* 26, (2011).
[49] Najmul Hoque et al., "Techno-Economic Evaluation of Solar Irrigation Plants Installed in Bangladesh," *Int. Journal of Renewable Energy Development* 5 no. 1 (2016).
[50] Sarkar and Ghosh, "Techno-Economic Analysis and Challenges of Solar Powered Pumps Dissemination in Bangladesh."
[51] Closas and Rap, "Solar-Based Groundwater Pumping for Irrigation: Sustainability, Policies, and Limitations."
[52] *Ibid.*

Verena Radulovic and Nitin Bassi mentioned that viable PV markets need successful entrepreneurial projects with sales and service delivery in India. Access to SIPs is still limited in many countries due to a lack of local manufacturers and technical expertise.[53,54] Bangladesh also may suffer from the shortage of local PV panel manufacturers and technical expertise in solar irrigation. Thus it would reduce the benefit and increase the cost of SIPs. That is why personal consumption of solar irrigation pump may not enhance here. In this regard, Williams et al. tested low-cost solar photovoltaic pumps in Ghana. They also concluded that about a 60% reduction in cost is possible if the pump is manufactured locally.[55] That is why the manufacture and after-sale service of SIP would also be vital in Bangladesh.

Widespread adoption of new technology would help get available after-sale services and manufacture the technology locally. In this regard, A. Jain and T. Shahidi have deployed a binary logistic regression model to realize the effect of relevant variables on the intent to adopt a solar irrigation pump in the context of Northern India. According to the outcome of the study, the interest variables such as 'agriculture as a primary activity', 'investment plan for renting', 'total current irrigation cost', 'view on solar irrigation' and 'education' have a significant favorable influence on the decision of adoption a solar irrigation pump.[56] This model would also help realize the most important factors that influence the widespread adoption decision of solar irrigation pumps in Bangladesh. However, such a model is not yet implemented in the context of Bangladesh.

2.2.2 Cost of Alternative Irrigation Solutions

The cost of alternative solutions, such as diesel and electric pumps, is also an essential determinant of solar pumps' economic attractiveness. The leading alternative of the solar irrigation pump is the diesel and electricity operated irrigation pumps. Several studies show that solar-based irrigation is more economical than diesel operated irrigation pumps on a life cycle basis. At first, the discussions about the solar and diesel operated irrigation pumps' cost have been given below:

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[53] Bassi, "Irrigation and Energy Nexus: Solar Pumps Are Not Viable."

[54] Verena Radulovic, "Are New Institutional Economics Enough? Promoting Photovoltaics in India's Agricultural Sector," *Energy Policy* 33, (2005).

[55] Daniel E Williams et al., "Tests on Photovoltaic Radial Centrifugal Pump Systems," *Renewable Energy Transforming Business*, (2008).

[56] Abhishek Jain and Tauseef Shahidi, *Adopting Solar for Irrigation: Farmers' Perspectives from Uttar Pradesh* (Council on Energy, Environment and Water (CEEW), India, 2018).

According to Niajalili et al., the initial outlay of the solar pumping system is about 9 times the conventional system in Iran's .context. The total lifecycle cost of the solar pumping system is about 66% conventional pumping system's cost.[57] According to Nikzad et al., for rice cultivation in north Iran, the initial cost of a solar irrigation pump (SIP) in the off-grid area is 2.14 times higher than the conventional irrigation pump (CIP). Nevertheless, its operating and maintenance costs are 8.7 times lower, and total life cycle cost (LCC) is 29.9% lower than the CIP's costs.[58]

Mahmoud and Nather have conducted an economic feasibility test for SIPs in Egypt. They found that SIP is the most efficient source of water for irrigation.[59] Their operating cost is low compared to the diesel operated pumping system, especially in the sprinkler and drip irrigation method. Surface irrigation is the most practiced irrigation procedure in Bangladesh; thus, the comparison needs to be performed for surface irrigation. Odeh et al. investigated and compared the solar water pump and diesel water pump's economic viability in Jordan. They found that the solar water pump was more efficient and cost-effective to fulfill water requirements than the diesel water pump.[60]

In Sub-Sahara Africa, Wazed et al. concluded that the development of solar-powered irrigation technologies (especially the efficacy of Photovoltaic solar panels) has elapsed diesel-powered irrigation systems in terms of the payback period and reduction in greenhouse gasses.[61]

Now the comparisons in the context of the Indian subcontinent are given below:

In India Shinde et al. mentioned in their study that photovoltaic pumps are economical compared to diesel pumps up to approximately 3 kWp for village water supply and around 1 kWp for irrigation.[62] In Bangladesh, the size of the solar irrigation pump installed by partner organizations varies from 3 to 30 kWp. Thus; solar pumps' economic feasibilities

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[57] Mehdi Niajalili et al., "Techno-Economic Feasibility of Off-Grid Solar Irrigation for a Rice Paddy in Guilan Province in Iran: A Case Study," *Solar Energy* 150, (2017).
[58] Amirhossein Nikzad, Mahmood Chahartaghi, and Mohammad Hossein Ahmadi, "Technical, Economic, and Environmental Modeling of Solar Water Pump for Irrigation of Rice in Mazandaran Province in Iran: A Case Study," *Journal of Cleaner Production* 239, (2019).
[59] Elham Mahmoud and Hoseen el Nather, "Renewable Energy and Sustainable Developments in Egypt: Photovoltaic Water Pumping in Remote Areas," *APEN</cja:jid> Applied Energy* 74, no. 1 (2003).
[60] I. Odeh, Y. G. Yohanis, and B. Norton, "Economic Viability of Photovoltaic Water Pumping Systems," *SE Solar Energy* 80, no. 7 (2006).
[61] Saeed Mohammed Wazed et al., "Solar Driven Irrigation Systems for Remote Rural Farms," *Energy Procedia* 142, (2017).
[62] V. B. Shinde and S. S. Wandre, "Solar Photovoltaic Water Pumping System for Irrigation: A Review," *Afr. J. Agric. Res. African Journal of Agricultural Research* 10, no. 22 (2015).

with different capacities have been measured in this study to examine the above proclamation in Bangladesh's context.

In India, P.D. Narale et al. depicted that for horticulture crops PV water pumping system is more economical than the diesel water pumping system because the PV system's life cycle cost (LCC) was 132924.12/- while the diesel engine's LCC was 759069.0/-.[63] Parajuli et al. investigated the solar water pump's techno-economic feasibility and compared it with diesel and biodiesel operated water pump and found that the solar pump is the most viable energy source for pumping water in Doti, Nepal.[64]

M. A. Hossain et al. compared the same capacity solar and diesel operated pumps in Bangladesh. The solar pump became more profitable than diesel engine-operated pumps after 5 years of installment. The benefit-cost ratio of the solar pump (1.91) was higher than the diesel-operated pump (1.31). The solar pump's net present value was higher than the diesel engine-operated pump. The solar pump's internal rate of return (80 %) was also higher than the diesel operated irrigation pump (71 %). It indicates that investing in solar pumps is more profitable than diesel pumps.[65] Therefore in Bangladesh, some studies have compared the economic viability of solar and diesel irrigation pumps. Still, exact comparisons among all available alternatives of irrigation are not observed in the existing literature.

Besides, some studies also presented comparisons among all the available alternative costs to run irrigation pumps as follows:

In Spain García et al. found that solar PV pump represented 37% of the (Life cycle cost) LCC of the diesel generator. It represented 64% of the LCC of the grid electricity option over 30 years.[66] In Bangladesh's case, the LCC of all available sources for irrigation is not well measured yet. Meah et al. have made a comparison (shown in Table 2.1) among PV, electric, and gasoline source of water pumping mechanism in the context of America. They

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[63] PD Narale, NS Rathore, and S Kothari, "Study of Solar Pv Water Pumping System for Irrigation of Horticulture Crops," *International Journal of Engineering Science Invention* 2, no. 12 (2013).
[64] Ranjan Parajuli, Govind Raj Pokharel, and Poul Alberg Østergaard, "A Comparison of Diesel, Biodiesel and Solar Pv-Based Water Pumping Systems in the Context of Rural Nepal," *International Journal of Sustainable Energy* 33, no. 3 (2014).
[65] Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh."
[66] Mérida García et al., "Comparing the Environmental and Economic Impacts of on- or Off-Grid Solar Photovoltaics with Traditional Energy Sources for Rural Irrigation Systems."

found that the PV system had a higher fixed cost than the gasoline generator. Still, the PV system's operating and maintenance cost is lower than the gasoline generator because a diesel generator's efficiency goes down with time. In contrast, the PV system produces the same power throughout its lifespan.

Table 2.1: Comparison of Energy Options for Remote Water Pumping

Energy source	Estimated capital cost ($/W)	Operation cost ($/kWh)	Maintenance	Life span (year)
PV system	6.8	None	Low	10–15
Electric utility	22	0.05–0.13	Low	N/A
Gasoline Generator	2.5	0.60	High	5–10

Source: Meah et al. (2008) [67]

Fossil fuel and electricity subsidies are very high in Iran. Rizi et al. found that 4.5 to 5.5 kW photovoltaic water pumps (PWPs) were more cost-effective than the electric system. Still, by increasing the power required, the current PV pumps are not viable financially. Furthermore, the diesel fuel pump is cheaper than the photovoltaic and electric system. If subsidy provides to the new energy source, the cost of solar pumps will be competitive with diesel and electric pumps.[68] In Bangladesh, electricity and diesel are also highly subsidized. Thus, the economic comparison with and without subsidy among solar, diesel, and electricity run pumps would help policymakers to take steps for the widespread use of solar irrigation.

Shuba et al. compared the costs of different energy sources of 5 HP pumps for irrigation in India. They found the life cycle cost was 516300 INR for the solar pump, 927400 INR for diesel operated pump, and 560000 INR for the grid-connected pump.[69] That is why the most cost-effective irrigation pump would be a solar irrigation pump. In Bangladesh, the primary sources of irrigation are now diesel and electricity run pumps. Thus the precise comparison among all sources of irrigation in monetary terms would help take the initiative for the widespread promotion of SIPs in the country.

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[67] K. Meah, S. Fletcher, and S. Ula, "Solar Photovoltaic Water Pumping for Remote Locations," *Renewable and Sustainable Energy Reviews* 12, no. 2 (2008).
[68] Atefeh Parvaresh Rizi, Afshin Ashrafzadeh, and Azita Ramezani, "A Financial Comparative Study of Solar and Regular Irrigation Pumps: Case Studies in Eastern and Southern Iran," *Renewable Energy* 138, (2019).
[69] V.R. Shuba et al., "Harnessing Solar Energy: Options for India, " Center for Study of Science, Technology and Policy, Bangalore http://shaktifoundation.in/wp-content/uploads/2014/02/cstep-harnessing%20solar%20energy%20-%20final%20report.pdf (accessed 20th February 2018).

Last but not least, Kumar et al. also made a comparison among the all available renewable sources of energy for irrigation in India as follow:

In India, out of all available renewable energy technologies (solar, wind, biogas) used for water pumping, a solar water pump's estimated utilization potential is highest.[70] Solar energy would also be the most viable renewable energy source for irrigation in Bangladesh because of its available insolation rate.

2.2.3 Impact on Revenue due to the Use of Solar Irrigation Pump

'Impact on revenue for using solar irrigation pump' is the third important factor in determining the pump's economic feasibility. At first, according to some studies, the revenue can be affected by increasing or decreasing crop production for solar irrigation in the following ways:

In the context of Benin, Burney et al. found that solar-powered drip irrigation significantly augments both household income and nutritional intake, particularly during the dry season.[71] It is still a subject to measure solar irrigation's impact on crop yield in Bangladesh's context.

Niajalili et al. also found that for a 0.5 ha paddy area, the required PV panel area is 2.7 m^2. Indeed, covering just 0.05% of paddy's total area with PV panels cannot have tangible effects on rice production.[72] So, the land requirement for installing SIPs would not have a considerable adverse effect on output. In Maharashtra, India, SIP's replacement of diesel pumps helped to improve the on-farm economic benefits. These were attributed to micro-irrigation practices integrated with SIP, reducing input costs, increasing productivity, and generating higher income from higher yields.[73] Therefore, SIP increases productivity. Thus higher yield leads to higher income. in Maharashtra, India. In this study, especially the change in rice productivity due to solar irrigation has been investigated in Rajshahi region of Bangladesh.

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[70] A. Kumar and T. Kandpal, "Renewable Energy Technologies for Irrigation Water Pumping in India: A Preliminary Attempt Towards Potential Estimation," *Energy Energy* 32, no. 5 (2007).
[71] Burney et al., "Solar-Powered Drip Irrigation Enhances Food Security in the Sudano-Sahel."
[72] Niajalili et al., "Techno-Economic Feasibility of Off-Grid Solar Irrigation for a Rice Paddy in Guilan Province in Iran: A Case Study."
[73] PM Honrao, "Economic Viability of Solar Irrigation Pumps for Sustainable Agriculture in Maharashtra: Adoption Response by Farmers. ," *Global Journal for Research Analysis* 4, no. 8 (2015).

In the Sudano-Sahel area of Northern Benin, SIP (with low-pressure drip irrigation) was installed in vegetable gardens where formerly watered with cans and hauled water. This installation allowed the women farmers to become net producers of vegetables, generate income from market sales, and substantially increase their household nutrition intake and food security.[74] Thus SIP is not only an economically and environmentally viable option for investment but also it could help ensure food security, especially in developing countries.

The revenue also can be increased from the alternative uses of solar irrigation pumps. These impacts on the gains are highlighted in the following studies:

Some farmers in northern West Bengal (India) need irrigation for an average of 8 hrs/day for 30 days in a year. Such farmers' SIPs would lie idle for most of the year, potentially making it economically unviable.[75] Thus the alternative use of SIP when it is not used for irrigation purposes would make this investment more economically viable. In this regard, Agrawal and Jain proposed that the farmers of the area with good groundwater availability could grow multiple irrigated crops in a year, particularly those with a high price and requiring frequent irrigation, like vegetables.[76] Additionally, farmers can use their solar pumps to sell water to the neighboring farms. In Bangladesh, especially the Rangpur and Dinajpur region, with a satisfactory water table, it would be a suitable place to accumulate this opportunity and increasing income from the adoption of SIP. The SIP owner can also utilize surplus electricity from solar panels for husking, grinding, lighting activities. However, further innovation needs to facilitate this opportunity.

Besides, FAO mentioned in their report that irrigated land is 2.7 times more productive than rain-fed land.[77] Tahir and Habib mentioned that the adequacy and reliability of irrigation water significantly influence crop yield.[78] Sometimes the high cost of diesel forces the marginal farmers to under-irrigate their farms to save money, thereby affecting the yields. If designed and maintained correctly, SIP could provide reliable irrigation

[74] Burney et al., "Solar-Powered Drip Irrigation Enhances Food Security in the Sudano-Sahel."
[75] Shalu Agrawal and Abhishek Jain, "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies," *WENE Wiley Interdisciplinary Reviews: Energy and Environment* 8, no. 2 (2019).
[76] *Ibid.*
[77] Food and Agriculture Organization (FAO), *The State of the World's Land and Water Resources for Food and Agriculture—Managing Systems at Risk* (Rome, Italy, 2011).
[78] Z. Tahir and Z. Habib, "Land and Water Productivity: Trends across Punjab Canal Commands", International Water Management Institute
http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR14.pdf (accessed 5th June 2019).

service and increase the yields and revenues.[79] However, adequate irrigation depends on the availability of complementary inputs, such as fertilizers, improved seeds, and extension services.[80] Moreover, in many developing countries, farmers generally lack access to high-quality inputs, market information about crop prices, and demand. Access to market and extension services are found essential determinants of the adoption of lift-irrigation technologies.[81] Thus, it is essential to coordinate between solar irrigation programs and other market linking and extension programs to ensure additional revenue from SIP adoption. In this context, suppliers like Sun Culture in Kenya and partner organizations in Bangladesh play vital roles. Because they provide extension services and market information to their customers for adopting better cropping practices.[82]

SIPs have already been promoted in different areas via different business models. Agrawal and Jain have compiled the business models in the following way.

Table 2.2: Different Types of Business Models for Solar Irrigation

Business models	Examples of deployment
Individual ownership models	
Retail and pay-as-you-go (PAYG): Suppliers provide individual SIPs to farmers, along with provisions of service warranty for 2–5 years.	In Kenya, suppliers such as Future Pump and Sun Culture provide customized SIPs to farmers, retail, and recently on a PAYG basis.
Equity cum subsidy model: Suppliers provide SIPs at benchmarked costs to farmers. A share is borne by the government/donors as a capital subsidy. Suppliers have to meet prescribed technical standards and provide a multi-year service warranty.	More than 140,000 SIPs have been deployed under this model in India, with generous subsidy support from national and state governments.
Rent-to-own: Suppliers provide SIPs on loans to farmers, with the SIP acting as collateral. Farmers have to pay a fixed monthly fee, and interest is charged on the declining principal balance. After the balance is paid in full, the customer owns the equipment.	In Nepal, Sunfarmer provides SIPs on a rent-to-own basis. Farmers have to pay a small down payment, and the remaining amount can be paid in installments over 3 years. Farmer cooperatives identify the interested farmers and collect monthly payments on behalf of the supplier.
Shared models	
Group sharing: A group of farmers jointly owns and shares a SIP to meet their	In India, GIZ, along with SIP suppliers, enables the farmers to form joint liability

[79] Agrawal and Jain, "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies."
[80] Liangzhi You et al., "What Is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach," *Food Policy* 36, no. 6 (2011).
[81] Mekonnen B. Wakeyo and Cornelis Gardebroek, "Share of Irrigated Land and Farm Size in Rainwater Harvesting Irrigation in Ethiopia," *Journal of arid environments* 139, (2017).
[82] Agrawal and Jain, "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies."

irrigation needs.	groups (JLGs) and secure collateral-free bank loans to purchase SIPs.
Renting: A provider owns, maintains, and rents the SIPs to interested farmers. The provider could be a SIP supplier, any private entity, or a farmers' association.	Claro energy in Bihar (India) has this model at several locations. A portable trolley-mounted SIP is offered on a fixed hourly rent to small farmers within a local area.
Water-as-a-service: a SIP is used to pump and sell water for a fee to a group of farmers. The system can be owned, operated, and maintained by a SIP supplier, farmers association, or any other third party.	In Bangladesh, more than 600 SIPs have been deployed under this model. With the help of low-cost finance and partial grants, NGOs and MFIs own and operate SIPs to sell water for irrigation to farmers. Some Indian farmers' associations, such as Vaishali Area Small Farmers Association (VASFA) in Bihar, own and operate multiple solar pumps to provide irrigation water for a fixed fee to their members.

Source: Agrawal and Jain (2019) [83]

Almost all business models show that an individual farmer or 'group of farmers' are the owner of SIPs. However, in Bangladesh, 'water as a service model' (shown in Table 2.2) has been deployed. Under this model (shown in Table 2.2), the NGOs and MFIs are the installers, owners, and caretakers of the solar irrigation pumps for their whole lifespan (20-25 years). They provide irrigation services to the farmers and collect irrigation fees from them. It makes it difficult for the framers to get maximum benefits from the given subsidy and loans. As a result, the acceptability of the pumps is not increasing rapidly at the field level.

2.3 Environmental Viability

SIPs have some direct potential to reduce greenhouse gas (GHG) emissions from irrigation activities by replacing fossil fuels with solar energy. This potentiality of SIPs to minimize environmental pollution has been investigated in some studies. Some of the findings of the studies have given below:

According to the finding of Gesellschaft für Internationale Zusammenarbeit (GIZ), Life cycle assessments (LCA) of CO_2 emission of SIPs indicates a potential reduction in GHG emissions per unit of energy used for water pumping (CO_2-eq/kWh) of 95 to 97 percent as compared to pumps operated with grid electricity (global average energy mix) and 97 to

[83] *Ibid.*

98 percent as compared to diesel-pumps.[84] Thus solar photovoltaic (SPV) pump is almost pollution-free compare to the diesel and electricity operated pump. This finding with the other two results has been given in the following table.

Table 2.3: GHG Emissions for Different Power Generation Technologies

	Unit	Solar PV	Grid electricity	Diesel
GIZ 2016[85]	g CO_2-eq/kWh	16-32	600	1000
POST 2011[86]	g CO_2-eq/kWh	75-116	488-990	-
Ould-Amrouche et al. 2010[87]	g CO_2/m^3	0	-	480-2230

Source: GIZ (2018), POST (2019) & Ould-Amrouche et al. (2010)

Here, per unit of power generated and per volume of water pumped measured in terms of CO_2-equivalent per kilowatt-hour (gCO_2-eq/kWh) and (gCO_2/m^3), respectively. GIZ (2016) and POST (2011) describe values from life cycle assessment, whereas values in Ould-Amrouche et al. (2010) refer to the operation of 1kW pumps in Algeria with pumping heads ranging between 10 to 60 m.

According to GIZ's report in 2016, solar PV panels, grid electricity, and diesel machines generate 16 to 32 gCO_2, 600g CO_2, and 1000 gCO_2 gas, respectively, to produce 1 kWh power. It is illustrated in the first row of Table 2.3. Thus, it is clear that the solar PV system is the most environmentally friendly option to generate power among the three available alternatives. According to the Parliamentary Office of Science and Technology (POST) report, the UK- solar PV system and grid-connected machine generate 75-116 and 488-990 gCO_2 to produce 1 kWh power. Therefore, according to this report, the solar irrigation system is a more environmentally friendly option than a grid-connected irrigation system. At last, Ould-Amrouche et al. found that to withdraw 1 m^3 or 1000 liter, additional water from the underground solar PV pump generates almost 0 gCO_2. On the other hand, diesel operated machine generates almost 480-2230 gCO_2 (from Table 2.3). Thus from the research, it is clear that to mitigate CO_2 emission, a solar PV pump is a far better option for irrigation than the diesel operated pump.

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[84] Gesellschaft für Internationale Zusammenarbeit (GIZ), "Solar Powered Irrigation Systems (Spis) – Technology, Economy, Impacts" https://energypedia.info/images/temp/2/23/20160630122544.pdf (accessed 18th June 2018).

[85] *Ibid.*

[86] Parliamentary Office of Science and Technology (POST), "Carbon Footprint of Electricity Generation. " https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf (accessed 20th June 2019).

[87] S. Ould-Amrouche, D. Rekioua, and A. Hamidat, "Modelling Photovoltaic Water Pumping Systems and Evaluation of Their Co2 Emissions Mitigation Potential," *Applied Energy* 87, no. 11 (2010).

Nikzad et al. in north Iran found that CO_2 production from the off-grid solar irrigation pump (SIP) during the project's lifetime is 190-201 times lower than the conventional irrigation pump (CIP).[88] According to Hammad and Ebaid, in South Jordan, savings of CO_2 emission reached 30,000 tons per well. It summed up to about 1.5 million tons of CO_2 for the 55 Disi wells to extract underground water for mass household use.[89]

In India, almost 45 million tons of CO_2 added to the atmosphere by using diesel and electric water pumps annually, which is equivalent to 8%–12% of the country's total greenhouse gas emissions.[90] Thus the contribution of irrigation to greenhouse gas emissions might be significant, especially for agriculture-based countries like India and Bangladesh.

In Bangladesh's case, the diesel engine operated irrigation pump emits carbon dioxide and pollutes the environment. However, the solar pump is an environment-friendly irrigation technology.[91] Thus in Bangladesh, the total and projected reduction of CO_2 emission by SIPs and the monetary gain of the reduction is not well measured in the available studies.

During the production process of solar irrigation pumps, a certain amount of CO_2 is emitted depending on its size and capacity. However, these emission values are very tiny compared to those produced by fossil fuel combustion and nuclear systems.[92] Thus the amount of CO_2 produced in the manufacturing time of solar photovoltaic panels is negligible compared to the savings amount of the CO_2 produced from fossil fuel burning. Emission rates show vital variability due to the specific technology, operating environment, and other assumptions. These findings reflect that reducing greenhouse gas emissions to a greater extent would be possible using solar pumps instead of diesel or electric pumps for irrigation purposes.

Finally, some studies mentioned that solar irrigation pumps would create the over-extraction problem of groundwater. After installation, the marginal cost of water

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[88] Nikzad et al., "Technical, Economic, and Environmental Modeling of Solar Water Pump for Irrigation of Rice in Mazandaran Province in Iran: A Case Study."
[89] Hammad and Ebaid, "Comparative Economic Viability and Environmental Impact of Pv, Diesel and Grid Systems for Large Underground Water Pumping Application (55 Wells) in Jordan."
[90] Pushpendra Kumar Singh Rathore, Shyam Sunder Das, and Durg Singh Chauhan, "Perspectives of Solar Photovoltaic Water Pumping for Irrigation in India," *Energy Strategy Reviews* 22, (2018).
[91] Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh."
[92] Hammad and Ebaid, "Comparative Economic Viability and Environmental Impact of Pv, Diesel and Grid Systems for Large Underground Water Pumping Application (55 Wells) in Jordan."

withdrawal by the solar pump becomes almost zero. This problem could be solved by integrating solar panels with the grid. Thus, farmers would want to supply excess electricity into the public grid and earn profit rather than selling water to make profit, which leads to over-exploitation of groundwater.[93] However, other studies also mentioned that this over-extraction problem has a built-in solution with the solar irrigation pump (SIP) system. SIP with the suitable size and the limited operating time from morning to evening automatically checks the groundwater overexploitation problem.[94] In Bangladesh, grid connection with solar panels is not yet introduced because almost all SIPs are now operated in the off-grid areas. During the field survey, the views and opinions of farmers about this matter have been collected.

2.4 Gaps in the Earlier Literature

There are some studies about the use of solar energy in the agriculture sector, especially for irrigation purposes in different countries. Moreover, the potentiality and necessity of solar irrigation pumps in the country's agriculture sector are enormous. However, the application of this technology at the farmer's level is minimal yet. Some researchers have tried to find out the economic feasibility, environmental impact, and the barriers to the widespread installation of solar irrigation pumps (SIPs) in the context of Bangladesh. However, their studies are not sufficient enough. From the review of earlier literature, some gaps need to be identified and taken into consideration to conduct this study on the economic feasibility and environmental impacts of solar irrigation pumps in agriculture. The gaps that are found in earlier studies are listed below.

First, irrigation is highly dependent on the energy of Bangladesh, especially on electricity and diesel consumption. Moreover, electricity is also overly dependent on the indigenous reservation of natural gas. Thus the current status with a projection of the energy and its impact on the country's irrigation has not been portrayed clearly in existing studies. **Second**, several studies in other countries compared to the economic feasibility of all available energy options to run irrigation pumps. Nevertheless, few such efforts are found in earlier studies in the context of Bangladesh. **Third**, some studies calculated NPV, IRR, and PBP of an arbitrary SIP to measure the pump's economic feasibility. However, no

[93] J. Schnetzet and L. Pluschke, " Solar-Powered Irrigation Systems: A Clean-Energy, Low-Emission Option for Irrigation Development and Modernization", Food and agriculture organization of the United Nations, http://www.fao.org/3/a-bt437e.pdf. (accessed 12th April 2018).
[94] Agrawal and Jain, "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies."

study makes an exact comparison among the SIPs with various capacities. It would help find out which type of SIP would be the most profitable option for investment in Bangladesh. **Fourth,** few studies have tried to find out the impact of solar irrigation on the output in several countries of Africa. However, any study regarding this matter has not been found in the case of Bangladesh. **Fifth,** any logistic regression model is not yet implemented in the context of Bangladesh to realize the effect of different variables on adoption decision of a solar irrigation pump by the farmers. **Sixth,** the environmental benefits of SIP in monetary terms, especially in the context of Bangladesh, are rare. It would be helpful to review the decision about the given amount of grant or subsidy for installing a solar irrigation pump.

The maximum studies on solar irrigation pumps are related to the other countries of the world. Few studies are found regarding the economic feasibility and environmental impact of SIPs in the context of Bangladesh. There are some methodological pitfalls in earlier studies also. Furthermore, no studies yet try to deploy any logistic model to realize the effect of different variables on adopting a solar irrigation pump in the country. At last, most of the earlier studies are descriptive base on secondary data. They do not collect information from field surveys. There are few studies to measure the economic feasibility and environmental impacts of SIPs based on secondary data and primary data collected from the service providers and users of the pumps.

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Introduction

As the title of this study is 'Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh', where economic feasibility is known as cost-benefit analysis for determining the efficiency of a new project. It helps to identify expected profit against investment from a project.[95] Environmental impact indicates the environmental consequences (positive and negative) of a project. Thus, this chapter's methodology mainly attempted to measure the solar irrigation pump's economic feasibility and environmental impact. The research methodologies mainly used to satisfy this study's objectives have been described with justification in this chapter. In social science, every research work follows some specific and scientific methods. The present study maintained a well-defined methodology from the identification to the solution of the research problems. Again, the research's trustworthiness depends on the objectives, the nature of data, sampling techniques, and analysis.[96] In this study, an empirical method based on primary and secondary data has been followed to examine the SIP's economic feasibility and environmental impact in the Rajshahi region.

This chapter is organized as follows: section **3.1**, the present section, introduces the research methodology of this study; section **3.2** discusses the research approach, section **3.3** provides the detailed techniques of sample design and study area selection; **3.4** focuses on the empirical methods aiming to calculate the economic feasibility of solar irrigation pumps, section **3.5** provides the procedures to compare all available sources of energy for irrigation, section **3.6** shows the process to find out the effect of solar irrigation on the yield of crops, section **3.7** describes a binary logistic regression model to realize the effect of interest variables on the adoption decision of a solar irrigation pump, section, **3.8** deals with the procedure to measure the environmental impact of solar irrigation pumps, section **3.9** defines the techniques of data collection for the above analyses. At last, Section **3.10** discusses the procedures of data analysis and result presentation.

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[95] (DESA).

[96] C. R. Kothari, *Research Methodology (Methods and Techniques)*, Second Revised Edition (India: New Age International Publishers, 2004).

3.2 Research Approach

It is essential to clarify the research approach used in a study to achieve the research objectives. In general, there are two types of research approaches, i.e., quantitative approach and qualitative approach. This study mainly follows the quantitative approach, although the qualitative approach is also applied where it is necessary. A quantitative approach is a data-based approach that includes collecting, editing, sorting, and converting data into numerical form to make statistical calculations easy. An inference can be drawn based on the calculations. The quantitative approach is used to describe the respondents' socio-economic and demographic characteristics. It measures the economic feasibility of SIPs and identifies the determinants which influence the household's decision to adopt a SIP. This approach is also used to find out the environmental impact of SIPs in monetary terms.

Again, the qualitative approach is also used to attain the perception of the environmental impact of the SIPs. It also identifies the consequences on the users' lives. It realizes the qualitative factors that may influence the adoption decision of SIPs. Therefore, it is clear that mainly quantitative with qualitative data are used to satisfy the study's objectives. These data have been collected from the sample respondents, and the sample selection procedures have been described in section 3.3. The following specific approaches have been deployed in this study-

Then Niajalili[97] et al., Nikzad et al.,[98] Mahmoud and Nather,[99] Odeh et al.[100] Wazed et al.[101] Shinde et al. in the context of different countries, and M. A. Hossain et al.[102] in the context of Bangladesh compared the economic feasibility of diesel and solar irrigation pumps. Also, Meah et al., Shuba et al., and Rizi et al.[103] compare all available energy sources, especially diesel, electricity, and solar for irrigation. This study has calculated the

[97] Niajalili et al., "Techno-Economic Feasibility of Off-Grid Solar Irrigation for a Rice Paddy in Guilan Province in Iran: A Case Study."
[98] Nikzad et al., "Technical, Economic, and Environmental Modeling of Solar Water Pump for Irrigation of Rice in Mazandaran Province in Iran: A Case Study."
[99] Mahmoud and el Nather, "Renewable Energy and Sustainable Developments in Egypt: Photovoltaic Water Pumping in Remote Areas."
[100] Odeh et al., "Economic Viability of Photovoltaic Water Pumping Systems."
[101] Saeed Mohammed Wazed et al., "A Review of Sustainable Solar Irrigation Systems for Sub-Saharan Africa," *Renewable and Sustainable Energy Reviews* 81, (2018).
[102] M. Ayub Hossain et al., "Technical and Economic Feasibility of Solar Pump Irrigations for Eco-Friendly Environment," *Procedia Engineering* 105, (2015).
[103] Parvaresh Rizi et al., "A Financial Comparative Study of Solar and Regular Irrigation Pumps: Case Studies in Eastern and Southern Iran."

LCC of solar, diesel, and electricity-powered pumps. It compares all of these costs, as described in section 3.4.

Several earlier studies concentrated on measuring the economic feasibility and environmental impact of solar irrigation pumps (SIPs), mainly in the context of other countries of the world. Several tools of cost-benefit analysis have been deployed to measure the economic feasibility of SIPs. Such as García et al.,[104] Foster et al., and Pande et al.[105] calculated the payback period of SIP and Purohit [106]and Kandpal, Najmul Hoque et al.,[107] and Sarkar and Ghosh measured the net present value (NPV), internal rate of return (IRR), and payback period (PBP) of SIP. In this study, the standard NPV, IRR, and PBP have been calculated for large, medium, and small solar irrigation pumps in Bangladesh. The calculation methods of these financial indicators have been discussed in section 3.5.

Burney et al. PM Honrao,[108] S. Agrawal and A. Jain[109], Tahir and Habib, Liangzhi You et al.[110] mentioned that the adequacy and reliability of irrigation water significantly influence crop yield, increase productivity, and generate higher income from higher yields in different world countries. This study has compared the crops' output irrigated by solar and conventional energy sources in Bangladesh's greater Rajshahi region. For that purpose, information about crops' outputs using solar and diesel irrigation have been collected. Moreover, two mean tests have been performed to test the difference of outputs due to solar irrigation. The method of the test has been described in Section 3.6.

Then, A. Jain and T. Shahidi have deployed a logistic regression model to realize the effect of influential variables on the intent to adopt a solar irrigation pump in the context of Northern India.[111] This study implemented the model to realize the most critical factors which influence the widespread adoption decision of solar irrigation pumps in Bangladesh. In section 3.7, the detail of the model has been described.

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[104] Mérida García et al., "Comparing the Environmental and Economic Impacts of on- or Off-Grid Solar Photovoltaics with Traditional Energy Sources for Rural Irrigation Systems."

[105] Pande et al., "Design Development and Testing of a Solar Pv Pump Based Drip System for Orchards."

[106] Purohit and Kandpal, "Solar Photovoltaic Water Pumping in India: A Financial Evaluation ".

[107] Hoque et al., "Techno-Economic Evaluation of Solar Irrigation Plants Installed in Bangladesh."

[108] Honrao, "Economic Viability of Solar Irrigation Pumps for Sustainable Agriculture in Maharashtra: Adoption Response by Farmers. ."

[109] Agrawal and Jain, "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies."

[110] You et al., "What Is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach."

[111] Jain and Shahidi.

At last, the report of GIZ, Ould-Amrouche, et al., Nikzad et al.[112] showed that solar PV pump for irrigation is a far better option to mitigate CO_2 emission than the diesel operated pump. This study measured the net environmental impact of solar irrigation from the difference between the saved amount of CO_2 for the substitution of diesel and the emitted amount of CO_2 from the solar panels production process. The detail of this procedure has been discussed in section 3.8.

3.3 Sampling Design

Data is the collected factual materials commonly accepted in the scientific community as necessary to validate research findings. The collection, organization, and analysis of data are integral and critical parts of the research process. It helps researchers discover the answers to their research questions. Data is used to develop an understanding of a natural phenomenon and in analyzing and predicting future events.

This study is mainly based on primary data, which has been collected from three agro-ecological districts of Bangladesh, including Dinajpur, Rangpur, and Bogra. One Upazila from each of 3 districts, and then two unions from each Upazila were chosen randomly for collecting the required data. Finally, a total of 50 solar irrigation pumps were visited from six unions. These pumps have been selected from the list of total installed solar pumps of IDCOL. The primary data used in this research was mainly collected from empirical interviews using a standard questionnaire. Some secondary data have also been taken from various local and international census, journals, books, articles, literature, and IDCOL. A detailed description of the sampling framework is given in the following sub-sections: 3.3.1 selection of the study areas, 3.3.2 reasons for selecting the study areas, and 3.3.3 selection of the respondents or samples.

3.3.1 Selection of the Study Area

The selection of the study area is a vital part of the whole research process. In this study, the research area has been selected carefully to represent the area's real scenario under investigation. Here, the Rajshahi region indicates the greater Rajshahi region or

[112] Nikzad et al., "Technical, Economic, and Environmental Modeling of Solar Water Pump for Ir-
Rice in Mazandaran Province in Iran: A Case Study."

the country's former Rajshahi division. That is presently comprise Rajshahi and Rangpur divisions. Three main agro-ecological districts, such as Dinajpur, Rangpur, and Bogra from this region with solar irrigation pumps, are chosen to conduct this study. These districts are the most agriculture intensive districts with high cropping intensity. That is why the highest number of solar irrigation pumps has been installed in Dinajpur and then the Rangpur district. Moreover, recently solar irrigation pumps have been started to install in Bogra. The contribution of these three districts' agricultural production is more than any other districts of this region of Bangladesh. Thus, a considerable amount of irrigation is necessary to grow agricultural commodities in these areas. After choosing the districts, three Upazilas named Birganj from Dinajpur, Badarganj from Rangpur, and Nandigram from Bogra district have been selected for this study.

Figure 3.1 a: Map of Birganj Upazila, Dinajpur

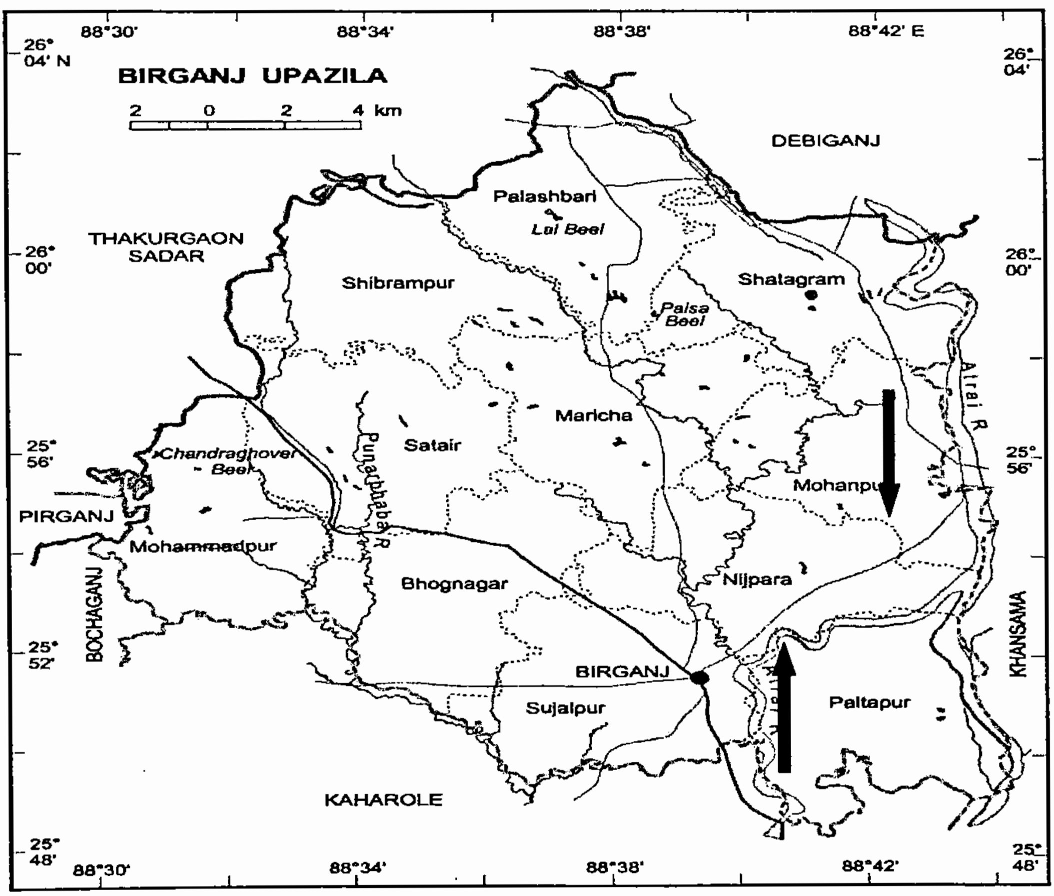

Figure 3.2 b: Map of Badarganj Upazila, Rangpur

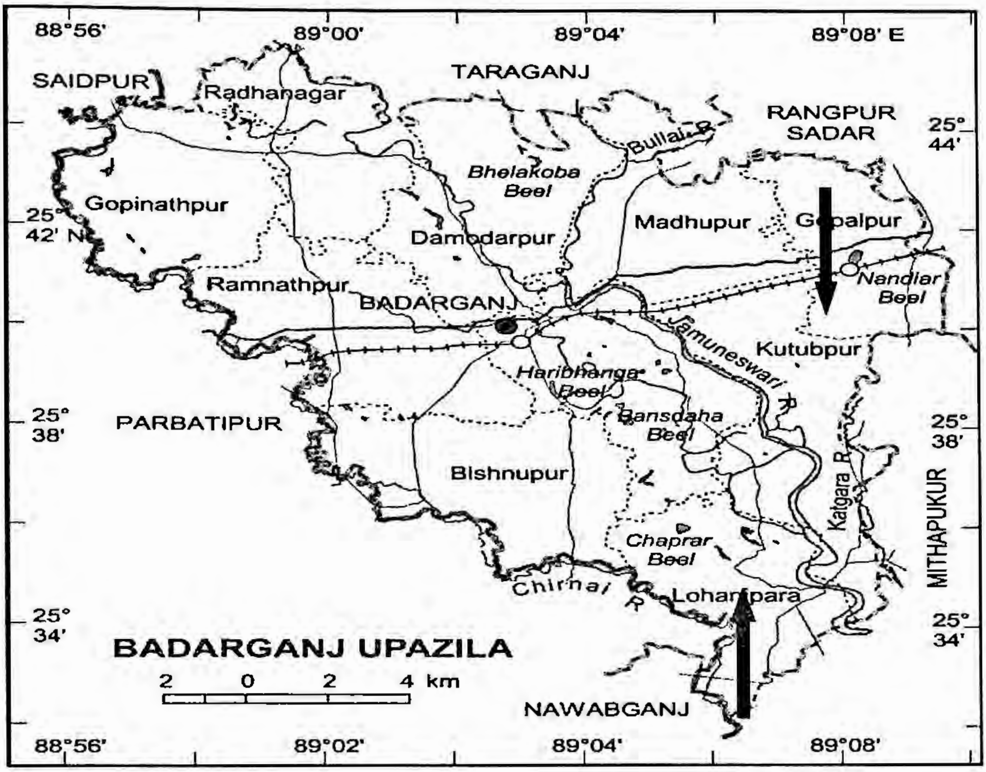

Figure 3.3 c: Map of Nandigram Upazila, Bogra

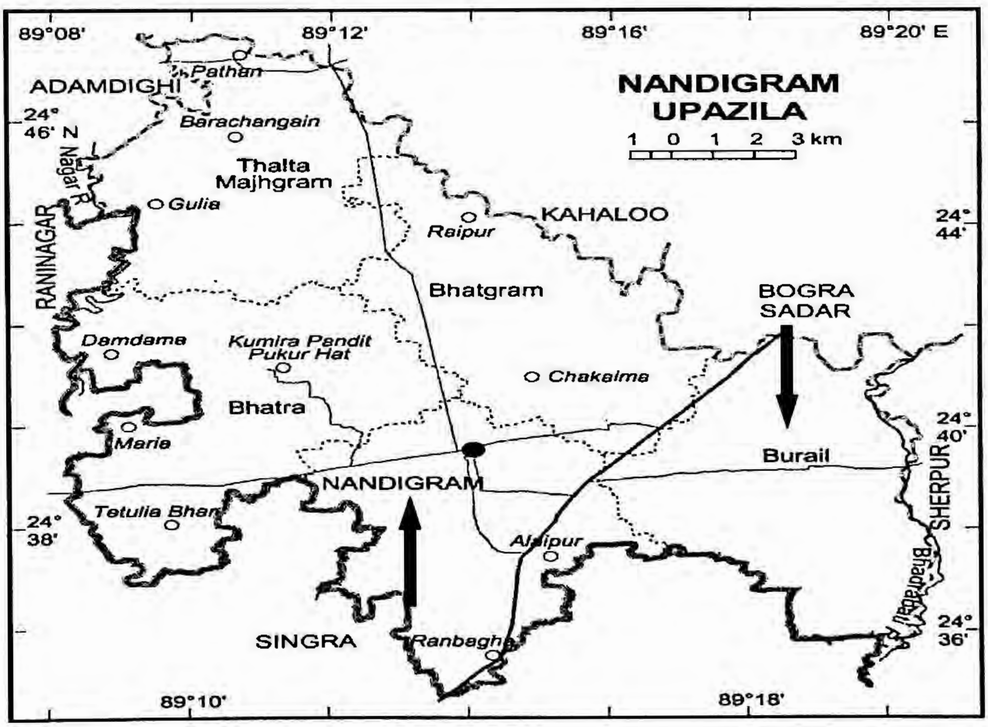

Figure 3.1: Study Areas in Maps

In the next steps, two unions are selected randomly from each Upazila. Thus, from Birganj Upazila, Mohonpur, and Nijpara unions (Fig.3.1.a); from Badarganj, Kutubpur, and Lohanipara unions (Fig.3.1.b); and from Nandigram, Nandigram, and Burail unions (Fig.3.1.c) have been selected. The study areas selected for this study are shown combinedly in Figure 3.1. A brief description of these three Upazilas is given below:

3.3.1.1 Birganj Upazila

Birganj is one of 13 Upazilas of Dinajpur district. It comprises 11 Unions, 186 Mouzas, 186 villages. The literacy rate of the Upazila is about 38.8%. Birganj has a population of 269893, and the density of the population is 653 per square kilometer. 74.04% of the people's primary source of income is agriculture. The main crops of this area are paddy, wheat, sugarcane, potato.[113] The first SIP was installed here about 5 years ago. At present, 333 SIPs are operating in the Dinajpur district. Among them, 185 SIPs were installed in Birganj Upazila.[114] 22 out of 185 pumps with different capacities have been selected randomly from Nijpara and Mohanpur unions for this study. These pumps are installed and operated by the two partner organizations (PO) named Solargao and Gazi.

3.3.1.2 Badarganj Upazila

Badarganj is one of 8 Upazilas of Rangpur district. It covers 10 Unions, 64 Mouzas, 120 villages. About 38.2% of people are literate of the Upazila. Badarganj has a population of 257846, and the density of the population is 846 per square kilometer. 69.54% of the people's primary source of income is agriculture. The main crops cultivated in this area are paddy, jute, wheat, potato, mustard seed, tobacco, and vegetables.[115] The first SIP was installed here about 5 years ago. At present, 177 SIPs are operating in the Rangpur district. Among them, 170 SIPs have been installed in Badarganj Upazila.[116] 22 out of these 170 pumps with different capacities have been selected randomly from Lohannipara and

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113 Banglapedia: National Encyclopedia of Bangladesh, "Birganj Upazila" http://en.banglapedia.org/index.php?title=Birganj_Upazila (accessed 10th January 2020).

114 Infrastructure Development Company Limited, "Idcol Solar Irrigation Projects" https://www.icimod.org/resource/17186 (accessed 20 August 2017).

115 Banglapedia: National Encyclopedia of Bangladesh, "Badarganj Upazila" http://en.banglapedia.org/index.php?title=Badarganj_Upazila (accessed 10th March 2020).

116 Limited.

Kutubpur unions for this study. These pumps are installed and operated mainly by the three partner organizations (PO) named Gazi, Soalrgao, and Gram.

3.3.1.3 Nandigram Upazila

Nandigram is one of 12 Upazilas of Bogra district. It consists of 5 Unions, 235 Mouzas, 245 villages. About 42.2% of people are literate of the Upazila. Nandigram has a population of 168155, and the density of population is 633 per square kilometer. 81.94 % of the people's primary source of income is agriculture. The main crops cultivated in this area are paddy, potato, wheat, vegetables.[117] Solar irrigation pumps have been being started to install in the Bogra district for the last 4 years. Moreover, 48 SIPs are now operating in the Bogra district. Among them, 21 SIPs have been installed in Nandigram Upazila. All of these pumps are being operated now in the Nandigram and the Burail union of Nandigram Upazila.[118] These pumps have been installed and operated by Grameen Housing and Energy Limited (GHEL) and Gram.

3.3.2 Reasons for Selecting the Study Areas

Bangladesh is one of the largest producers of food and non-food crops in the world. The country is second in jute production, fourth in rice and fisheries, fifth in tropical fruit, ninth in mango, eleventh in potato and tea, sixteenth in pineapple and onion, and seventeenth in banana production. One of the main reasons for getting this success is the availability of water for irrigation. For human activities and natural causes, the surface water's handiness has been reducing in recent decades. As a result, the farmers became highly dependent on groundwater for irrigation. For this purpose, they mostly depend on diesel-run and electricity operated machines to irrigate their land. On the other hand, this necessity has been increased due to HYV paddy's adoption and increasing cropping intensity of the cultivable lands. However, these conventional irrigation sources are not proven sustainable due to environmental, economic, and operational problems. That is why, at first high cropping intensive, non-inundated, and off-grid areas have been selected for the installation of the SIPs. For these reasons, the highest number of SIPs have been installed in northern and southern areas of Bangladesh, especially in Rajshahi and Khulna regions. Almost 600 SIPs in the Rajshahi regions (former Rajshahi division), about 2

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[117] Banglapedia: National Encyclopedia of Bangladesh, "Nandigram Upazila" http://en.banglapedia.org/index.php?title=Nandigram_Upazila (accessed 10th March 2020).
[118] Limited.

SIPs in the Khulna region, only 1 in the Dhaka region, and 2 in the Chittagong region have been installed. Then among 600 SIPs in the Rajshahi region, 330 SIPs in Dinajpur District, 177 SIPs in Rangpur district, and 48 SIPs in Bogra district have been installed.[119] The highest number of SIPs (185) and the 2nd highest number of SIPs (170) have been installed in Birganj and Badarganj Upazila, respectively, in the country. More SIPs have been installed in the Upazilas for the high cropping intensity, Boro's cultivation, and grid connectivity shortage. That is why these two Upazilas from Dinajpur and Rangpur districts were selected for this study. Moreover, Nandigram is also selected, as this Upazila has the highest number of SIPs in the Bogra district. After selecting three Upazilas from three districts purposively, 6 unions equally from the three Upazilas have been selected randomly for the study's field survey. The randomly selected unions are Mohonpur and Nijpara from Birganj Upazila; Kutubpur and Lohanipara from Badarganj Upazila; and Nandigram and Burail unions from Nandigram Upazila. 50 SIPs have been selected randomly and proportionately from these unions for the field survey. Finally, the sample users (farmers) of the 50 pumps have been selected randomly from the list provided by IDCOL and partner organizations (PO). Also, 100 samples of non-users (farmers) of solar irrigation were selected purposively from the adjacent areas of the 50 SIPs equally.

3.3.3 Selection of the Respondents

The respondent selection procedure has been discussed in this section. The method for selecting respondents for a particular study depends on the objectives of the study. Again, the sample must represent all relevant types of people. If the sample is not representative, it may give a bias impression of the real situation. Some groups may be over-represented, and their opinions may be magnified, while others may be under-represented.[120] There are also differences between probability (random) and non-probability (purposive) samplings. Probability sampling is representative as each individual in the population of interest has an equal likelihood to be selected. The study has followed a quantitative approach where the data have been collected from both primary and secondary sources. Primary data have been collected from the coverage areas of SIPs in the Rajshahi region. Secondary data have been collected from IDCOL, partner organizations (POs), and government organizations like BBS, BADC, and BMDA. In primary data, at first three Upazilas from

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[119] *Ibid.*

[120] Peter G Smith and Richard H Morrow, *Methods for Field Trials of Interventions against Tropical Diseases: A" Toolbox"* (Oxford University Press Oxford, 1991).

the three districts have been selected purposively. Then, unions, solar irrigation pumps, and the farmers have been selected using Fisher's random Table. Information about every installed solar irrigation pump's location, name of POs, panel capacity, cost of the pump, land coverage, and the number of service receiver farmers from the SIP in the Rajshahi region was collected from IDCOL. The summary of the sample selection procedure has been given in Table 3.1:

Table 3.1: Selection of Study Areas and Respondents

District (Purposive)	Upazila (Purposive)	Unions (Random)	Total number of SIPs	Sample SIPs (Random)	Number of farmers use sample SIPs	Sample farmers use SIPs (Random)	Sample farmers do not use SIPs (Purposive)
Dinajpur (13Upazilas)	Birganj (11 unions)	Nijpara	51	14	210	14×5=70	14×2=28
		Mohanpur	30	8	120	8×5=40	8×2=16
Rangpur (7 Upazilas)	Badarganj (10 unions)	Lohanipara	47	12	180	12×5=60	12×2=24
		Kutubpur	38	10	150	10×5=50	10×2=20
Bogra (12 Upazilas)	Nandigram (5 unions)	Nandigram	14	4	60	4×5=20	4×2=8
		Burail	7	2	30	2×5=10	2×2=4
Total = 03	03	06	187	**50**	750	**250**	**100**

According to the information of IDCOL (showed in table 3.1), the total number of SIPs in the mentioned 6 unions is 187. For the field survey, 50 SIPs have been selected from these 187 SIPs. Among them, 6 from Nandigram Upazila, 22 from Birganj, and another 22 SIPs from Badarganj Upazilas were selected randomly for this study using Fisher's Random Table.[121] The lists of the total number of service receiver farmers (750) from the 50 SIPs have been collected from partner organizations (PO).

Now the following formula given by Herbert and Raymond is used to determine the sample size of benefited farmers from 750 farmers[122]:

$$n = \frac{z^2.p.q.N}{e^2.(N-1)+z^2 p.q}$$

n_1 = size of sample
p = sample proportion, q = 1 – p
p= 0.5 and q=0.5

[121] Ronald A Fisher, A Steven Corbet, and Carrington B Williams, "The Relation between the Number of Species and the Number of Individuals in a Random Sample of an Animal Population," *The Journal of Animal Ecology*, (1943).
[122] Herbert Arkin and Raymond R Colton, "Tables for Statisticians. Barnes and Noble," *Inc., New York*, (1950)

z = 1.96 (as per table of area under normal curve for the given confidence level of 95%)

N= number of population, here 750

Level of significance or acceptable error, e = .05

Thus the required sample size is:

$$n_1 = \frac{1.96^2.(0.5).(0.5).750}{0.05^2(749 + 1.96^2(0.5).(0.5)} \approx 250$$

Thus 250 farmers have been chosen equally from the 50 SIPs for the interview. Besides this, 100 samples of non-users (farmers) of solar irrigation were also selected purposively from the adjacent areas of the 50 SIPs equally to collect the required information to satisfy this study's objectives.

3.4 Comparison of Alternative Energy Options' Costs for Irrigation (Life Cycle Cost Analysis)

Life cycle cost, or whole-life cost, is the process of estimating how much money would be spent on an asset throughout its useful life. Whole-life cost covers the costs from the purchasing time to the disposal time of an asset. The calculation of the financial cost is relatively easy. However, the calculation of environmental and social costs is relatively difficult to quantify and assign numerical values to determine the actual LCC of an asset. In this study, the emphasis has been given to measuring the financial cost of an asset. Typical areas of expenditure, such as planning, design, construction, operations, maintenance, renewal, depreciation, replacement, disposal, etc. are the LCC components. In this paper, the life cycle costs (LCC) of the irrigation pumps run by solar, electricity, and diesel have been measured for comparison. In LCC analysis, all costs are converted to present value by considering the inflation rate and discount rate during its total life cycle. Annualized life cycle cost (ALCC) has also been used to compare all available irrigation sources, such as solar pumps, electric pumps, and diesel pumps. Before adding all costs, all future costs (C) are converted into present value considering the relative rate of inflation and discount rate as follows:

$$PV = C \times \left[\frac{(1+i)}{(1+d)}\right]^n \quad \ldots\ldots (I)$$

PV is the present value of any future cost (C), 'i' is the relative rate of inflation, and 'd' is the discount rate per year, and 'n' is the time in years. The relative inflation rate accounts for the escalated increase or decrease in a commodity's prices compared to the general inflation rate. For any commodity, if the price escalation is expected as per the general inflation rate, then the relative rate of inflation would be considered zero. In this analysis, the relative rate of inflation has been considered zero. The discount rate accounts for the real value of money in the future, and in most of the world's economies, it is about 8-12%. Therefore 10% has been considered in this calculation. A discount rate of 10 % per year would mean that in real terms, it makes no difference to a farmer whether he has 100 Tk now or 110 Tk after one year. Conversely, a cost of 110 Tk one year from now has a present worth of 100 Tk. The present value of a cost in 'n' th year is calculated using Eq (I). However, for multiple future payments, costs are to be converted to present value for each year and then cumulated. For comparison purposes, annualized life cycle costs (ALCC) of a solar PV pumping system, electrified pumping system, and diesel operated pumping system have been calculated by dividing the LCC with a cumulated discount factor of 20 years.

Since the solar panels work for at least 20 years, a solar irrigation pump's life cycle cost has been measured for 20 years. Moreover, the solar PV pumping system's lifetime is highest among the three types of pumping systems considered here. Thus, LCCs of electrified and diesel operated pumping systems have also been calculated for 20 years.

3.5 Financial Analysis of Different Solar Irrigation Pumps

In this study, the standard methods of financial analysis such as **a)** Net Present Value (NPV), **b)** Simple Pay Back Period (PBP), **c)** Internal Rate of Return (IRR), and **d)** Benefit-Cost Ratio (BCR), have been calculated to determine the economic viability of different type of solar irrigation pumps (SIPs) in the study area. The methods are as follows:

3.5.1 Net Present Value (NPV)

NPV is defined as the difference of the present values (PVs) of the total cash inflows (benefits) and the cash outflows (costs). Suppose all future cash flows are incoming, and the only outflow of cash is the purchase price (PP). In that case, the NPV is simply the present value of future cash inflows minus the purchase price.

So, $$\text{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+d)^t} - \text{PP} \quad \text{.........} \quad \text{(II)}$$

CF = Cash flow

PP = Purchase price

t = Period of cash flows

d = Discount rate

NPVs have been calculated at the discount rates of 6%, 9%, and 12%, which symbolize typical bank interest rates. Thus, we can compare the gains between buying a solar irrigation pump by using money and saving the same amount of money in a scheduled bank.

3.5.2 Payback Period (PBP)

The payback period refers to the period required for the return on an investment to "repay" the sum of the original investment. For example, a $2000 investment, which returned $500 per year, will have a four-year payback period.

$$\text{PBP} = \frac{II}{NCI/Y} \qquad \text{...... (III)}$$

II = Initial Investment

NCI/Y= Net cash inflow per year

3.5.3 Internal Rate of Return (IRR)

The internal rate of return (IRR) of a potential investment is the annualized effective compounded return rate earned on the invested capital. IRR is the discount rate of interest that makes the net present value equal to zero. If the IRR becomes 15% (SIP with a lifetime of 20 years), buying a SIP brings enough revenue in 20 years to pay its cost and grants a return of 15% on the invested capital. Therefore, in this case, borrowing the required capital at less than a 15% interest rate and finance it for buying the SIP would be a profitable investment.

Formula of IRR:

$$0 = CF_0 + \frac{CF_1}{(1+IRR)} + \frac{CF_2}{(1+IRR)^2} + \frac{CF_3}{(1+IRR)^3} + \ldots\ldots + \frac{CF_n}{(1+IRR)^n} \qquad \text{...... (IV)}$$

$$0 = \text{NPV} = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$

CF_0 = Initial investment

CF_1, CF_2, CF_3 . . . CF_n = Cash flows

n = Each period

N = Holding period

NPV = Net present value

IRR = Internal rate of return

3.6 Effect of Solar Irrigation on the Yield of Crops (Two Sample t-test):

Firstly, information about the output before and after introducing the solar irrigation pump has been collected from the farmers. Then, the two-sample t-test has been performed in this study to find out the significance of the two outputs due to the use of solar irrigation pumps.

State the hypotheses. First, we assumed no difference in output due to solar and diesel irrigation for different crops. Thus the null and alternative hypotheses became as follow:

Null hypothesis: $\mu_1 - \mu_2 = 0$

Alternative hypothesis: $\mu_1 - \mu_2 \neq 0$

Note that these hypotheses constitute a two-tailed test. The null hypothesis will be rejected if the difference between the sample means becomes significant. Here μ_1 and μ_2 are the mean output due to the use of solar and diesel-powered irrigation.

Formulate an analysis plan. A two-sample t-test was conducted using the sample data at the significance level of 0.05 in this study.

Analyze sample data. Using the sample data, the standard error (SE), degrees of freedom (DF), and the t test statistic (t) have been computed as follows:

$$SE = \text{sqrt}\,[(s_1^2/n_1) + (s_2^2/n_2)]$$

$$DF = (s_1^2/n_1 + s_2^2/n_2)^2 \,/\, \{[\,(s_1^2\,/\,n_1)^2\,/\,(n_1 - 1)\,] + [\,(s_2^2\,/\,n_2)^2\,/\,(n_2 - 1)\,]\} \quad \ldots (V)$$

$$t = [\,(x_1 - x_2) - d\,]\,/\,SE$$

where s_1 is the standard deviation of sample 1, s_2 is the standard deviation of sample 2, n_1 is the size of sample 1, n_2 is the size of sample 2, x_1 is the mean of sample 1, x_2 is the mean of sample 2, d is the hypothesized difference between the population means, and SE is the standard error.

Interpret results. Since the P-value is less than the significance level (0.05), we cannot accept the null hypothesis. Hence we can conclude that the difference in outputs due to solar and diesel operated irrigation is significant.

3.7 Determinants of Solar Irrigation Adoption Decision: Logistic Regression Model

Logistic regression analysis is a technique that allows for estimating the probability that an event occurs or not by predicting a binary dependent outcome from a set of independent variables. In the empirical literature, a binary logistic regression model is proposed by A. Jain and T. Shahidi, in the context of India. It describes the effects of different variables on adopting a SIP that has been introduced in this study.[123] The logistic regression model is used to estimate the effects of various socio-economic, demographic, and farm-level factors on the adoption decision of solar irrigation pump. Thus, this model would also help realize the most important factors that influence the widespread adoption decision of solar irrigation pumps in the Rajshahi region of Bangladesh. The derivation process of the Logit model generally starts with the linear probability model, which is as follows:

If Y_i is a binary dependent variable that takes the value 1 and 0 with the probability P_i and $(1-P_i)$, respectively, and if X_i is the vector of either qualitative or quantitative independent variables, then the logistic model can be written as:

$$P_i = E(Y_i = 1/X_i) = \frac{1}{1+e^{-(\beta_1+\beta_2 X_i)}} \quad \ldots(1)$$

$$= \frac{1}{1+e^{-Z_i}} \quad [\text{Where, } Z_i = \beta_1 + \beta_2 X_i]$$

$$= \frac{1}{\frac{e^{Z_i}+1}{e^{Z_i}}}$$

$$= \frac{e^{Z_i}}{e^{Z_i}+1} \quad \ldots.(2)$$

Equation (2) is known as the (cumulative) logistic distribution function. Here, Z_i ranges from $-\infty$ to $+\infty$; P_i ranges between 0 and 1; P_i is non-linearly related to Z_i (i.e., X_i). An estimation problem is created when P_i is non-linear in explanatory variables (X_i) and parameters (β_i). Thus, with this non-linearity problem, one cannot apply the OLS method to estimate the parameters. Here, P_i is the probability of adopting solar irrigation pump by farmers and is given by:

$$P_i = \frac{e^{Z_i}}{e^{Z_i}+1} \quad \ldots(3)$$

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[123] Jain and Shahidi.

Therefore, ($1-P_i$) is the probability of not adopting solar irrigation pump by farmers and can be written as:

$$(1-P_i) = E(Y_i = 1/X_i) = 1 - \frac{1}{1+e^{-(\beta_1+\beta_2 X_i)}}$$

$$= 1 - \frac{1}{1+e^{-Z_i}}$$

$$= \frac{1}{e^{Z_i}+1}$$

$$\therefore (1-P_i) = \frac{1}{e^{Z_i}+1} \qquad ...(4)$$

Thus, the ratio of the probability of adopting solar irrigation pump to the probability of not adopting solar irrigation pump can be written as:

$$\frac{P_i}{(1-P_i)} = \frac{\frac{e^{Z_i}}{(1+e^{Z_i})}}{\frac{1}{(1+e^{Z_i})}}$$

$$\text{or,} \quad \frac{P_i}{(1-P_i)} = e^{Z_i} \qquad ...(5)$$

$\frac{P_i}{(1-P_i)}$ is the odds ratio in favor of adopting a solar irrigation pump. It is natural to start with the earlier logistic function and modify it to determine an appropriate decision curve. The logistic function can be written as by taking a natural log in both sides of equation (2):

$$L_i = \ln\left[\frac{P_i}{1-P_i}\right] = Z_i = \beta_1 + \beta_2 X_i \qquad ...(6) \qquad [\because Z_i = \beta_1 + \beta_2 X_i]$$

Where L_i is the log of the odds ratio, called the Logit, which is not only linear in explanatory variables (X_i) but also linear in the parameters (β_i). L_i is considered a and the equation (6) is called the Logistic regression model.

3.7.1 Specification of the Logistic Regression Model

According to the outcome of the model deployed by A. Jain and T. Shahidi in the context of northern India, the relevant variables such as 'investment plan for renting', 'total current irrigation cost', 'loan for agricultural investment', 'view on solar irrigation' and 'education' have a significant favorable influence on the decision of adoption solar irrigation pump. On the other hand, 'total installation cost', 'farmers' satisfaction with present irrigation setting', 'groundwater depth', and 'age' have a significant negative influence on the decision to adopt a solar irrigation pump. Other variables of the model like 'land parcels', 'size of operational landholding', 'cropping intensity', 'view on climate change', and 'monthly per capita expenditure' have no significant effect on the adoption decision of solar irrigation pump.

Thus some socio-economic, demographic, and farm-level characteristics influence the decision to adopt a solar irrigation pump. Different explanatory variables, such as age, education, size of operational land holding, an investment plan for renting, loan for agricultural investment, view on solar irrigation, farmers satisfaction with current irrigation setting, groundwater depth, land parcels, and cropping intensity are used in this study. Thus, by composing the above-stated variables, the empirical model has been specified as follows:

$$L_i = SIP_i = ln\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 AGE_i + \beta_2 EDU_i + \beta_3 OLH_i + \beta_4 LP_i + \beta_5 CI_i + \beta_6 IPR_i + \beta_7 GD_i + \beta_8 SWPI_i + \beta_9 LAI + \beta_{10} VSIP_i + \mu_i$$

In this equation, the dependent variable L_i or SIP_i is the log odds ratio in favor of adopting a solar irrigation pump. P_i is the probability of using a solar irrigation pump. The variables used in the above equation are stated as follows:

SIP = Log odds ratio in favor of adopting solar irrigation pump
AGE = Age of farmer
EDU = Level of education of farmers
OLH = Size of operational landholding
LP = number of land parcels
CI= Cropping intensity
IPR = Investment plan for renting
GD = Groundwater depth
SWPI = Satisfaction with present irrigation setting
LAI = Loan for agricultural investment
VSIP= View on solar irrigation pumps

In the above equation, β_0 is 'intercept'; β_1, β_2,..,β_{10} are 'regression coefficients' to be estimated, and u_i is the 'random error' term. In this case, some variables have been taken as continuous, and some are taken as dummy forms. The dependent variable is binary with a value of '1' for adopting a solar irrigation pump and '0' otherwise. The measurement of the dependent and independent variables used in the model is described in Table 3.2.

Table 3.2: Description of Variables Used in the Logistic Regression Model

Variable	Description	Category	Unit of Measurement	Expected Effects
Dependent variable				
SIP	Adoption of solar irrigation pump	Categorical	0 = No; 1 = Yes	
Independent variable				
AGE	Farmers' age	Continuous	In years	-
EDU	Farmers' education	Continuous	In years	+
OLH	Size of operational landholding	Continuous	In bigha	+
LP	Number of land parcels	Continuous	In numbers	-
CI	Cropping intensity	Continuous	In numbers	+
IPR	Investment plan for renting	Categorical	0 = No; 1 = Yes	+
GD	Groundwater depth	Continuous	In feet	-
SWPI	Satisfaction with present irrigation setting	Categorical	0= Unsatisfied; 1 = Satisfied	-
LAI	Loan for agricultural investment	Categorical	0 = No loan; 1= Loan for investment	+
VSIP	View on SIP	Categorical	0= No view; 1= Have a view	+

3.7.2 Expected Effects of the Variables

The expected effects on adopting a solar irrigation pump of different variables used in the logistic regression model are discussed briefly in this section. The coefficient associated with *farmers' age* is expected to have a negative sign. It is because the farmers might become more risk-averse as they become aged. Hence they may not want to adopt new technology for irrigation. Then the coefficient associated with *farmers' education* is expected to have a positive sign. It indicates that educated farmers could realize the long term economic and environmental benefits of SIP quickly. The farm size or *operational land holding* may positively influence the decision to adopt solar irrigation technology because larger farms could quickly utilize it. The coefficient associated with the *number of* *land parcels* of a farmer is expected to sign negatively. Because more fragmented land may create difficulties to irrigate all lands by a solar irrigation pump. Higher *cropping intensity* enhances farmers' ability to use solar irrigation pumps properly, so the coefficient associated with the land's cropping intensity is expected to be positive. *An investment plan for renting* may have a positive effect on the decision to adopt a SIP. Farmers who intend to install a SIP to provide irrigation facilities to neighbor farmers after personal use would have a greater chance of adopting solar irrigation. The next coefficient associated with *groundwater depth* is expected to have a negative sign. As groundwater depth increases, the installation cost of a SIP also increases. The coefficient of *satisfaction with the current irrigation setting* is expected to influence the decision to adopt a SIP negatively. It may have a negative sign because farmers who are satisfied with their current irrigation setting have lower odds of adopting solar pumps. A farmer who has taken loans to make investments on the farm has a higher chance of adopting a solar irrigation pump than a farmer who has not done so. Therefore the coefficient associated with a loan for agricultural investment is supposed to have a positive sign. It is expected that farmers who have a favorable view of the solar irrigation pump's effectiveness have a greater chance of using this technology. Thus, the coefficient associated with *'view on SIP'* is likely to have a positive sign.

3.8 Environmental Impact of Solar Irrigation Pump

In this section, the procedure to measure the net environmental impact of solar irrigation pump has been described. For this purpose, the environmental benefits, and the environmental costs of SIPs, have been calculated in the study. At first environmental benefit has been estimated in the following way:

As The Intergovernmental Panel on Climate Change (IPCC) Guidance, the most common methodological approach to calculate the environmental impact of any investment is to combine information on the extent to which human activity occurs (called activity data or AD) with coefficients that quantify the emissions per unit activity.[124] These are called emission factors (EF). The basic equation is, therefore, is as follows:

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[124] Roberta Q., "Guidelines for National Greenhouse Gas Inventories,Volume-2, Energy", International Panel on Climate Change, IPCC http://www.ipcc-nggpip.iges,or.jp/public/2006gl/vol2.html (... ...th May 2020).

$$\text{Emissions} = \text{AD} \bullet \text{EF} \quad \ldots\ldots (1)$$

AD= Activity data
EF= Emission factors

The primary activity data (AD) for this study is the substituted amount of diesel by solar irrigation pumps, and emission factors (EF) depend upon the diesel's carbon content. Therefore, CO_2 emissions can be estimated based on the total amount of fuels combusted and the fuels' average carbon content.

Mainly diesel operated irrigation pumps have been substituted by solar irrigation pumps (SIPs). Thus, diesel consumption has been reduced due to the use of SIPs. So, the relationship between diesel consumption and CO_2 emission is vital to measure the environmental impact of SIPs, and the relationship is as follows:

- 1 liter of diesel typically weighs 0.86 kg (the density of diesel is about 860 kg/m^3)
- About 87% of this is carbon, so 1 liter of diesel contains 0.86×87% =0.75 kg carbon.
- Each atom of carbon weighs 12 atomic units. When it combines with atoms of oxygen in the combustion process, it becomes CO_2, weighing 44 atomic units. Thus, 0.75 kg of carbon becomes 0.75×(44/12) = 2.8 kg CO_2.
- So, 1 liter diesel produces about 2.8 kg CO_2.[125]

The environmental benefit of a solar irrigation pump (EBSIP) in terms of CO_2 emission reduction is shown below:

$$\text{EBSIP} = \text{TDU} \times 2.8 \text{ kg} \qquad [1 \text{ liter diesel} = 2.8 \text{ kg } CO_2]$$

TDU = Total diesel used in 20 years in liter

In this study, the information about the monthly substituted amount of diesel by a solar irrigation pump has been collected. The information has been multiplied by 12 to calculate the yearly saved amount and, at last, multiplied by 20 to calculate the total necessary amount of diesel for irrigation in 20 years.

The environmental benefit of solar irrigation pump (EBSIP) can be expressed in monetary terms (MT) as follows:

[125] Joydip Kumar Dev, "Assessment of Potential Environmental Benefits of Using Solar Power for Irrigation Pump in Bangladesh" (Bangladesh University of Engineering and Technology, 2014).

$$\text{EBSIP in MT} = \text{EBSIP} \times \frac{CRCO_2}{T}$$

Here, EBSIP= Environmental benefit of a solar irrigation pump
MT = Monetary terms
$CRCO_2/T$ = cost of removal of CO_2 per ton

The up-to-date study of the David W Keith et al. price (or cost of removal) of per ton CO_2 has been calculated at least about 100 USD.[126] Moreover, 1ton CO_2 = 1000 Kg CO_2. In this study, the environmental benefit of the solar irrigation pump has also been expressed in Taka using the exchange rate of 1 USD = 80 Tk.

On the other hand, the environmental cost of SIPs has been calculated based on a study conducted by Krauter and Ruther. According to the study, the corresponding emission of CO_2 for the manufacturing of each kWp of PV panels (by poly-crystalline silicon & mono-crystalline silicon) is listed in Table 3.3.

Table 3.3: CO_2 Emissions for PV Module Production

PV Type	CO_2 emission for PV production (Kg CO_2/kWp)
Mono-crystalline	360
Poly-crystalline	170

Source: Krauter and Rüther (2004) [127]

Mainly poly-crystalline-silicon PV panels are used in the country. Thus, PV panels made from Poly-crystalline-silicon have been selected for this study. Finally, the environmental benefit from diesel substitution and environmental degradation from PV panels' production has been calculated to measure the solar irrigation pump's net environmental impact.

3.9 Techniques of Data Collection

The study is based on primary data along with secondary data and an extensive literature review. Most of the aggregated data for this study are not readily available in the required form. Hence extensive works for collecting, coordinating, and screening data from secondary sources have been done. Primary data have been collected from the sample farmers through well-designed structured questionnaires. It was prepared with great attention and care based on research questions following the research objectives. T

[126] David W Keith et al., "A Process for Capturing Co2 from the Atmosphere," *Joule* 2, ... (2018).
[127] Stefan Krauter and Ricardo Rüther, "Considerations for the Calculation of Greenhou... Reduction by Photovoltaic Solar Energy," *Renewable energy* 29, no. 3 (2004).

have also been collected to easily be fitted for the economic and environmental analysis and the estimation of the specified model.

To test the accuracy of the questionnaire, the researcher has made a pilot survey. The questionnaire is modified according to the expert (supervisor). It was finalized after necessary corrections. Both close-ended and open-ended questions are used in the questionnaire. These data have been collected from July 2019 to December 2019 from the sample areas.

Also, along with the primary data, some secondary data have been collected by reviewing different published and unpublished issues. The primary, secondary data sources are the Yearbook of Agricultural Statistics in Bangladesh, Statistical Yearbook of Bangladesh Bureau of Statistics (BBS), Infrastructure Development Company Ltd (IDCOL), Bangladesh Economic Survey, and Bangladesh Population Census. Moreover, many studies of the Bangladesh Institute of Development Studies (BIDS), Institute of Bangladesh Studies (IBS), Bangladesh Agricultural Research Institute (BARI), and other unpublished MPhil and PhD dissertations were the secondary data sources for this study.

3.10 Data Analysis and Results Presentation

After the collection of the data, almost all completed questionnaires were rechecked to avoid inconsistencies. The data have then been compiled, tabulated, coded, and analyzed according to the study's objectives. In this process, all the interviewees' responses have been given numerical codes and input into MS excel and Eviews for the financial, environmental, and logistic regression analysis. Then, the data were cleaned by producing frequency figures for each question and examined the outliers. At this stage, the data files have become ready for the final analysis.

Finally, processed data are analyzed statistically and empirically. Statistical analysis includes descriptive analysis and empirical analysis. The descriptive analysis includes calculating frequency, mean, percentage, standard deviation, etc. related to the respondents' socio-economic and demographic characteristics. Similarly, the empirical analysis includes the cost-benefit analysis, comparisons of irrigation cost of all sources, logistic regression model, measurement of CO_2 emissions reduction by the solar pump, etc. It would help analyze the economic feasibility and environmental impact of SIPs. The determining factors of deciding to adopt a SIP were also analyzed in this study. Finally, the study's findings are presented through tabulations and graphs in the dissertation and critically explain all findings by accomplishing the collected data analyses.

CHAPTER FOUR
ENERGY AND IRRIGATION SCENARIO OF BANGLADESH

4.1 Introduction

Bangladesh is an agricultural country because most of its land is being used for agriculture.[128] Moreover, according to the World Bank report, Bangladesh's agricultural land is calculated as just over 70% of its total land. Thus, the total cultivable land in Bangladesh is 8.52 million hectares in which the total cropped area is 14.94 million hectares.[129] Out of 8.52 million hectares of cultivable land, about 7.76 million hectares of land have already come under the irrigation facility[130] At present, the agriculture sector's total contribution to GDP is about 15.33%. The crop sector to GDP is 13.44%, and around 40% of total human resources rely on the agriculture sector.[131] One of the main objectives of Bangladesh is to achieve food security for its vast population. The main impediment is acquiring agricultural land to meet other urgent demands for the growing population, like establishing new residences, schools, hospitals, industries, roads, etc.

In 2019, the population of Bangladesh had reached 164 million. Then it would be about 178 million in 2030 and 202 million in 2050 according to the world population prospect of the United Nations; however, it was only 50 million in 1960.[132] At present, the recorded average population density of Bangladesh is about 1116 persons/km^2, which indicates her as one of the most densely populated countries in the world.[133]

Under this situation, it has become challenging to ensure food security for this vastly growing population. One of the most important solutions is to increase the productivity and cropping intensity of our cultivable land by increasing irrigable land. Thus, a sustainable and viable option of irrigation would play a vital role in ensuring Bangladesh's food security.

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[128] Bangladesh Bureau of Statistics, *Statistical Yearbook of Bangladesh*2010.
[129] *National Accounts Statistics*2016. Vol. 19.
[130]—Ministry of Power; *Ibid.*
[131] *National Accounts Statistics.*
[132] United Nations, "World Population Prospects 2019", Department of Economic and Social Affairs https://population.un.org/wpp/Download/Standard/Population/ (accessed 10 January 2020).
[133] World Population Review, "Bangladesh Population" https://worldpopulationreview.com/countries/bangladesh-population/ (accessed 9th Januaury 2020).

On the other hand, our country's energy demand is also growing remarkably due to the fast population increase. Increasing energy demand is not only diminishing the reserve of fossil fuels, e.g., natural gas and coal but also affecting the environment. Therefore, to meet energy demand and mitigate environmental problems, many countries are looking for renewable energy resources, e. g. solar and wind energy.[134] Solar energy is richly available in Bangladesh with a variation of average solar insolation between 4 and 6.5 $kW/m^2/day$.[135] For example, in the Rajshahi region, the isolation rate varies between 3.96 and 6.24 $kWh/m^2/day$. The maximum solar insolation occurs during February–June, and the minimum occurs during October–February. The available solar radiation rate in the country is suitable for generating power from sunlight.[136] The average bright sunshine hours vary from 6 to 9 hours per day; one of the essential positive indications of solar irrigation pumps' viability.

Currently, most of the pumps in the country are operating by diesel fuel. Every year, the country imports about 1.06 million ton diesel.[137] Bangladesh's Government usually provides subsidies in diesel prices to make affordable diesel for irrigation, which creates extra pressure. In this situation, solar irrigation would be a possible solution. It will reduce not only pressure on the economy also encourage farmers to cultivate more land under irrigation. As a result, it increases the production of crops. It helps in the rural economy as well as the national economy. The Government established Infrastructure Development Company Limited (IDCOL) in 1997 to bridge the financing gap for developing medium to large scale infrastructure and renewable energy projects in Bangladesh. The Government has proposed the mission and vision to install the 500 MW solar programs in the country. Under this program, IDCOL has already installed 6 million solar-home systems (SHS) by 2016, covering around 15% of the total population, and a plan to replace 18,700 diesel pumps with solar irrigation pumps within 2020.[138] Although there is an enormous potentiality of solar-powered irrigation, technology is not still prevalent, especially in developing countries. Under these circumstances, a clear idea about the present scenario of Bangladesh's energy and irrigation has been illustrated in this chapter. For these purpose

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[134] M. R. Islam, Y. Guo, and J. Zhu, "A Multilevel Medium-Voltage Inverter for Step-u Grid Connection of Photovoltaic Power Plants," *IEEE JOURNAL OF PHOTOVOLTAICS* 4
[135] Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Ban
[136] Islam et al., "Renewable Energy Resources and Technologies Practice in B
[137] corporation
[138] Ministry of Power.

an overview of the energy and irrigation of Bangladesh, standard features, the current state, and arrangements of solar irrigation systems and government policies regarding renewable energy promotion, have been summarized in this chapter.

4.2 Irrigation Scenario of Bangladesh

Irrigation is water utilization through ditches and pipes to plant roots to assist in crop production and sustain plant life. The primary purpose of irrigation is to provide water to crop field, which makes the land fertile. It is controversial that where the first irrigation started.

Many believe that the Sumerians of Mesopotamia invented agricultural irrigation in 8000 BCE. They collected water from the Tigris and the Euphrates rivers. Others believe that the Egyptians were the first to irrigate land in 5000 BCE, where they collected water from the Nile River. In the 1700s, the European people began to examine agriculture to develop new crop rotations, improve livestock breeding, design new machinery, and introduce new crops and fertilizer.[139] After this European revolution, the productivity of the land increased, and the labor requirement was decreased. The first domestic lawn sprinkler and impact sprinkler were invented in the 1890s and 1932, respectively. In the late 1960s, farmers in the US thought about drip irrigation, increasing crop production with minimum water. Up to the 1950s, traditional means of irrigation, e.g., swing baskets and dons, were the only irrigation systems in Bangladesh. In the early 1960s, modern technologies, e.g., shallow tube wells deep tube wells, were introduced to meet the rapidly growing population's increasing food demand.[140]

Three irrigation methods, such as basin, furrow, and sprinkler methods, are usually used in the country. In the basin method, water is released to flow freely over the land and through the crops. The land is flooded with 5–7 cm standing water, mainly used in rice cultivation. Level land is required for successful irrigation by this method. In the furrow method, water is supplied through the furrow in between lines. This method is suitable for the cultivation of sugarcane, potato, etc, which are sown in line. Sprinkler method can provide unif[illegible] distribution of water in the form of rain over the crops by nozzles. This method is m[illegible]

[139] Easy irrigation, "A History of Agricultural Irrigation" https://www.easy-irrigation.c[illegible]/a-history-of-agricultural-page-29?zenid=cl7ols72vlqo0bftksd6n74a87 (accessed 2020 10th January).
[140] Banglapedia: National Encyclopedia of Bangladesh, "Irrigation" http://en.banglapedia.org/index.php?title=Irrigation (accessed 11 January 2020).

suitable for undulated land and hilly areas. It is also suitable for irrigating soft soil, as water loss is kept to a minimum level.[141] In the Bangladesh basin method is widely practiced for rice cultivation. The furrow method is also standard for the cultivation of potatoes, sugarcane, etc. The sprinkler method is not very common as this method is expensive and almost all of the cultivable land of the country is flat.

In Bangladesh, surface water, groundwater, and rainwater are used for irrigation. Different rivers originating from outside of the country provide about 90% of our surface water. About 795,000 million m^3 surface water discharges through the two main rivers, i.e., Ganges and Brahmaputra.[142] During the rainy season, all rivers, haors, bills, and ponds are being fulfilled with water. But, in the dry season, the country suffers from water scarcity, especially for irrigation. Only about 22,155 km of rivers, 1922 km^2 standing water bodies, and about 1475 km^2 of ponds in the country are the primary sources of surface water during the dry season. However, these are not sufficient for the cultivation of Boro.[143] However, groundwater is an alternative source of water supply. The level (depth) of groundwater of the country varies over the year, i.e., decreases during the rainy season and increases during the dry season. The use of surface and groundwater is necessary to ensure crop production over the year and maintain sustainability in agriculture. In the last 30 years, the use of groundwater has created a revolution in agriculture. The first groundwater utilization was initiated in 1962 with 381 deep tube wells in the Dinajpur district.[144] Up to 2008, Barind Multipurpose Development Authority (BMDA) has installed more than 10,000 deep tube wells (DTWs) in the Varendra area in the northwest region. Moreover, many shallow tube wells (STWs) have been installed by private initiative in recent years.[145]

The deep tube-well (DTW), sallow tube well (STW), and the low lifting pump (LLP) are commonly used pumps for large and medium-scale water lifting in Bangladesh. Many manual devices such as don, swing basket, BRRI diaphragm pump, rower pump, treadle pump, and hand tube well are used for small-scale irrigations. In the year 2017–2018,

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[141] *Ibid.*
[142] "Utilization and Conservation of Water Resources in Bangladesh", Agricultural and Forestry Research Center, University of Tsukuba http://hdl.handle.net/2241/98644.
[143] *Ibid.*
[144] Nepal Chandra Dey et al., "Sustainability of Groundwater Use for Irrigation in Northwest Bangladesh ", National Food Policy Capacity Strengthening Programme http://fpmu.gov.bd/agridrupal/sites/default/files/ToR-2.pdf (accessed 22 January 2020).
[145] Md Rabiul Islam, Pejush Chandra Sarker, and Subarto Kumar Ghosh, "Prospect and Advancement of Solar Irrigation in Bangladesh: A Review," *Renewable and Sustainable Energy Reviews* 77, (2017).

1574859 irrigation pumps were operated to irrigate 5,275,064 ha lands in which about 19551821 farmers were involved. Among 1574859 irrigation pumps, 337237 (about 20% of total pumps) were operated by electrical motors to irrigate 2303245 ha (about 44% of total land), and 1237622 (about 80% of total pumps) were operated by diesel engines to irrigate 2971819 ha (about 56% of total) land.[146] Table 4.1 shows the number of different types of tube wells used for irrigation in the country.

Table 4.1: The Number of Irrigation Tube Wells Under Operation.

Fiscal year	DTW		STW		LLP		Total
	electricity operated	diesel operated	electricity operated	diesel operated	electricity operated	diesel operated	
2012–2013	32412	2910	253473	1270136	10856	159713	1729500
2013–2014	33179	2855	273755	1290036	10417	160624	1770866
2014–2015	33714	2852	276347	1273364	10496	156679	1753452
2015-2016	34647	2332	269847	1147161	9415	163764	1627166
2016-2017	34898	2277	286944	1112016	11822	164656	1612613
2017-2018	35121	2417	288873	1066979	13243	168226	1574859

Source: BADC (2020)[147]

Table 4.1 shows that the total electricity-operated deep and sallow tube well has increased in recent years. Simultaneously, the total number of diesel operated sallow tube wells has decreased mainly because diesel operated irrigation is more costly than electricity operated irrigation. It has also been found that the total number of irrigation pumps was about 1.57 million in 2017-18 in the country, among them 1.24 million were diesel operated. Therefore, about 80% of total pumps are operated by imported fossil fuel, which is a comparatively costly option for irrigation and environmentally hazardous. On the other hand, to import a huge amount of diesel, the Bangladesh government expenses a huge amount of foreign currency every year. Importing and distributing the required amount of diesel to the root level at a stable price is very difficult due to the political, financial, and other uncertainty in national and international markets. Under these circumstances, the country's policymakers proposed introducing solar irrigation pumps to replace the diesel-operated pumps as much as possible. It will ensure the sustainable, comparatively economical, and environmentally friendly option for irrigation in Bangladesh.

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[146] Bangladesh Agricultural Development Corporation, "Organization Wise Summary of Irrigation Equipme Used, Area Irrigated and Benefited Farmers" http://www.badc.gov.bd (accessed 10th January 2020).
[147] *Ibid.*

Hence, from the above discussion, it is clear that Bangladesh's irrigation activities still mainly depend on diesel and electricity. That is why in the following sections, the status of fossil fuels and electricity has been discussed.

4.3 Energy Status of Bangladesh

Bangladesh currently is a lower-middle-income country, but its GDP growth rate is one of the world's highest. For any country, the development of the energy sector is the precondition for the growth of GDP. Energy plays a vital role in implementing Vision-2121, Vision-2041, and achieving Sustainable Development Goals (SDGs).

In Bangladesh, about 70 percent of energy demand is met with natural gas. Among other fuels- oil, coal, biomass, etc., are vital. There is a vast reserve of coal in our country, but coal is less produced as well as used here. On the other hand, the natural gas reserve is limited. However, its production and consumption are the highest among the available resources. Besides those, energy demand is being met through imported oil and (Liquefied Petroleum Gas) LPG. Moreover, the Government has already started importing (Liquefied Natural Gas) LNG to increase gas demand. Recently, a part of energy demand is also being met by importing electricity from India. Also, especially in rural areas, biomass still is the primary source of energy.

On the other hand, using renewable energy instead of gas, coal, and oil has been started globally. It is essential for sustainable development and keeping up with the environment by preventing carbon emissions. Many countries like Sweden, Germany, China, and the USA are currently using renewable energy as a significant part of their energy demand. Bangladesh is also using renewable energy, but the percentage share of the renewable energy of total energy is still insignificant.

Using the Solar Home System (SHS) in on-grid and off-grid areas, about 325MW power is being generated. Besides, some poultry and dairy farms in which bio-gas plants are being set up, and these biogas are used for cooking and power generation. The biogas plants currently provide only about 1MW electricity in the country.[148] Thus, the estimated

[148] Hydrocarbon Unit, "Energy Scenario: Bangladesh ", Ministry of Power, Energy and Mineral Resources http://hcu.portal.gov.bd (accessed 05 February 2020).

final energy consumption is around 47 MTOE (Millions of tons of oil equivalent). In the country, the average increase in energy consumption is about 6% per annum. Per capita consumption of energy in Bangladesh is on an average of 293 kgoe (Kilogram Oil Equivalent), and per capita generation of electricity is about 464 kWh[149] which is lower than those of South Asian neighboring countries. Among the total energy, the contribution of Natural Gas in 961 BCF (billion cubic feet), which is 22.3 MTOE, and then biomass provides 13.6 MTOE energy. The summary of the total generated energy in Bangladesh in 2017-18 is as follows:

Table 4.2: Energy Status of Bangladesh in 2017-18 (MTOE).

Name of Fuel	Unit	Millions of tons of oil equivalent (MTOE)
Oil (Crude and Refined) in K ton	6948	6.9
LPG (Liquefied petroleum gas)	554	0.5
Natural Gas in BCF (Billion Cubic Feet)	961	22.3
Coal (Imported) in K ton	3395	2.1
Coal (Local) in K ton	923	0.6
RE (Hydro) in MW	230	0.2
RE (Solar) in MW	350	0.3
Electricity (Imported) in MW	625	0.5
Subtotal		33.4
Biomass		13.6
Total		**47**

Source: Ministry of Power, Energy and Mineral Resources (2020)[150]

So, the country is highly dependent on its indigenous reserve of natural gas to meet the demand for commercial energy. In fact, 70 percent of the total energy demand is met with natural gas. This pressure can be reduced by introducing more renewable sources of energy, especially solar electricity. The present status of the country's leading energy sources such as oil, natural gas, and electricity has been discussed in the following sections.

4.4 Oil (Petroleum)

Diesel is the dominant liquid fuel used in the country. The maximum number of irrigation pumps (two-thirds of the agriculture sector's total pumps) is operated by diesel. The patterns of supply and consumption of liquid fuels in the country are shown here.

[149] "Annual Report (2017-18)", Power Division, Government of the Peoples Republic of Ban[illegible] https://powerdivision.gov.bd/site/view/annual_reports (accessed 28th January 2020).
[150] Unit.

4.4.1 Supply of Petroleum Products

About 22% of the country's total commercial energy is generated from petroleum products such as diesel, petrol, octane furnace oil, etc. Only 6% of total liquid fuel is made locally from gas condensate. Thus, the other 94% of petroleum products are imported from abroad at present. Therefore, Bangladesh imports about 1.2 million metric tons of crude oil and 5.5 million metric tons (approx.) of refined petroleum products per annum. The petroleum production during the last 5 years in the country is illustrated in Table 4.3.

Table 4.3: Sale of Petroleum Products During Last 5 Years (Quantity in MT)

Products	2013-14	2014-15	2015-16	2016-17	2017-18
Octane	117452	126114	147557	186911	230280
Petrol	178674	166823	137360	232359	284668
Diesel	3242554	3396061	3606404	4000044	4835712
Kerosene	289871	263029	213685	170993	138403
Furnace oil	1202505	906771	711889	806440	925150
Jet A-1	323327	338829	347323	376700	408272
Others	130583	123796	91802	115283	125851
Total	**5484966**	**5321423**	**5256020**	**5888730**	**6948336**

Source: Ministry of Power, Energy and Mineral Resources (2020) [151]

So, the total consumption of petroleum was about 6.94 million MT in 2017-18 in Bangladesh. It will be about 10 million MT in 2030 if the demand for petroleum products grows at a rate of 2 to 4% per year.[152]

4.4.2 Consumption of Petroleum Products

The highest amount of liquid fuel is consumed by the transport sector, followed by power, agriculture, industry, and the commercial sector. Therefore, sector-wise consumption of petroleum products are transport-49.40%, power-26.94%, agriculture 15.70%, industry 4.86%, domestic-2.26%, and others 0.85% of the total production which is given in Table 4.4 and Figure 4.1:

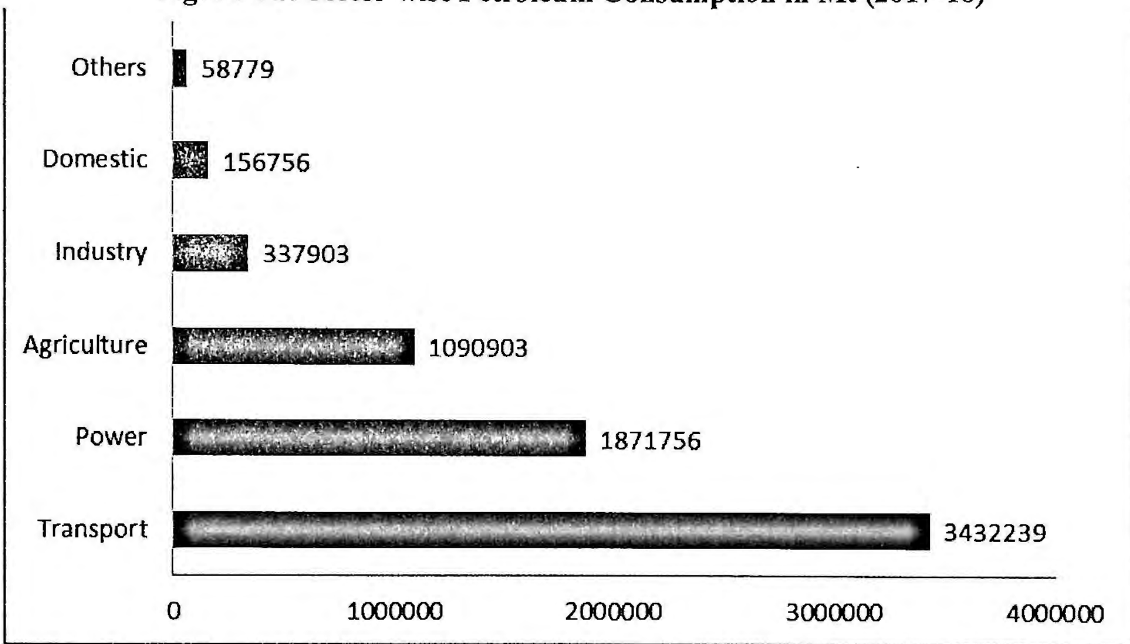
[151] *Ibid.*
[152] *Ibid.*

Table 4.4: Sector-wise Petroleum Consumption in 2017-18

Sector	Uses amount in MT.	Percentage share (%)
Transport	3432239	49.40
Power	1871756	26.94
Agriculture	1090903	15.70
Industry	337903	4.86
Domestic	156756	2.26
Others	58779	0.85
Total	**6948336**	**100**

Source: Ministry of Power, Energy and Mineral Resources (2020) [153]

Figure 4.1: Sector-wise Petroleum Consumption in Mt (2017-18)



Source: Ministry of Power, Energy and Mineral Resources (2020) [154]

Thus the agriculture sector consumed 3rd highest amount of diesel in 2017-18. Moreover, in this sector, diesel is mainly used for irrigation purposes. The amount of the required diesel in this sector is more than a million MT (Metric Ton). Besides, almost all of this tremendous amount of diesel was imported from abroad in exchange for valuable foreign currency. Thus, to reduce the government treasury pressure and get a sustainable irrigation source, a solar irrigation pump (SIP) would be an acceptable solution.

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153 *Ibid.*
154 *Ibid.*

4.5 Natural Gas

Natural gas is the main source of Bangladesh's commercial energy, which is being produced and consumed in a significant amount since 1970.[155] Since the first discovery in 1955, 26 gas fields, 24 onshore and 2 offshore, have been discovered in the country. Of them, 19 gas fields are now in production. The summary of the present state of natural gas has been given in Table 4.5.[156]

Table 4.5: Natural Gas Scenario at a Glance (2017-218)

Total number of gas fields	26
Number of gas fields in production	19
Present gas production capacity at (MMcfd)	2750
Avg. gas production rate at (MMcfd)	2633
Present Demand at (MMcfd)	3649
Present Deficit at (MMcfd)	1016
Total recoverable (Proven + Probable) reserve (TCF)	**28.69**
Cumulative Production (up to June,2018) (TCF)	**15.96**
Remaining Reserve (Proven + Probable) (at July,2018) (TCF)	**12.72**
Number of customers in millions (Apx.)	4.18

Source: Petrobangla, (2018)[157] *MMcfd=Million cubic feet per day; TCF=Trillion cubic feet*

Table 4.5 shows that total cumulative production was 15.96 trillion cubic feet (TCF), and the remaining reserve was 12.72 TCF up to mid-2018. Thus, more than half of the country's recoverable gas reserve has already been depleted to meet a massively growing population's demands. On the other hand, the average gas production rate was 2633 MMcfd, and demand was 3649 MMcfd; thus, the deficit was about 1000 MMcfd in 2018. The deficit is increasing every year as the recoverable reserve diminishes continuously.

4.5.1 Production of natural gas

The scenario of the gas production of the last 11 years has been illustrated in the following table and figure:

Table 4.6: Historical Production of Gas (2008-2018) in BCF

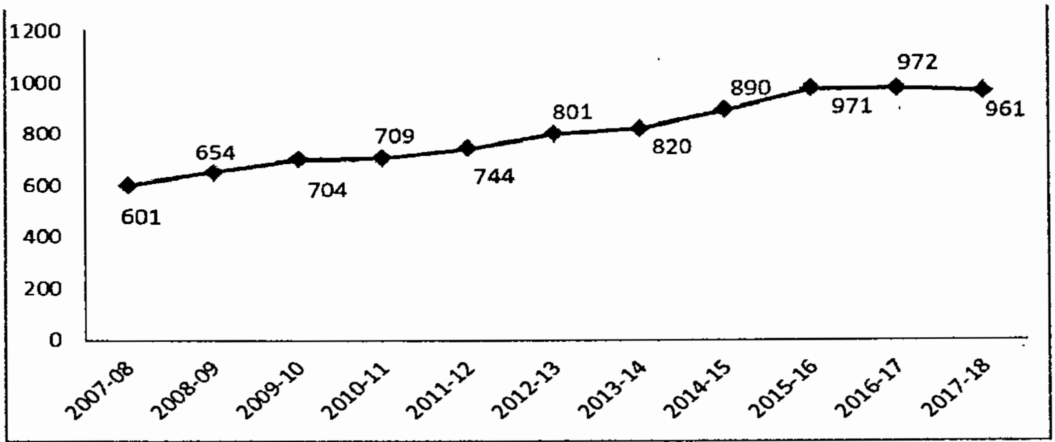
Year	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18

[155] Government of the People's Republic of Bangladesh Petrobangla, "Reserve of Natural Gas in Bangladesh.", Ministry of power, Energy and Mineral resources. Reserve of natural gas in Bangladesh http://www.petrobangla.org.bd (accessed 18th March 2019).
[156] Unit.
[157] Ramboll, *Gas Sector Master Plan Bangladesh* (Petrobangla, 2018).

Gas	601	654	704	709	744	801	820	890	971	972	961

Source: Ministry of Power, Energy and Mineral Resources (2020) [158] *BCF= Billion cubic feet*

Figure 4.2: Historical Production of Gas (2008-2018) in BCF



Source: Ministry of Power, Energy and Mineral Resources (2020) [159] *BCF= Billion cubic feet*

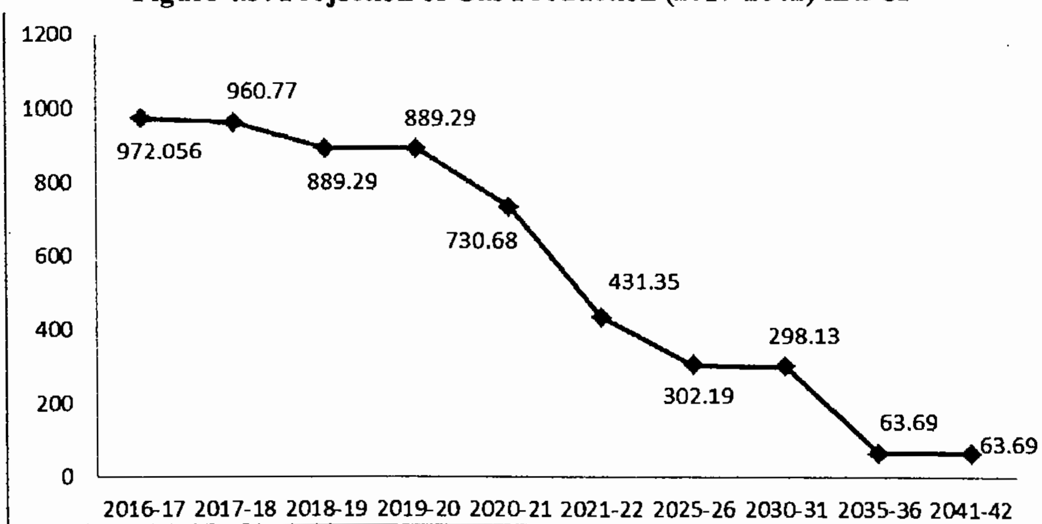
Thus, natural gas production has increased gradually up to 2016-17, and then it starts to decline from 2017-18. The projection (shown in Table 4.7 and Figure 4.3) also indicates that this trend will continue as the reserve of natural gas is depleting continuously.

Table 4.7: Projection of Gas Production (2017-2042) in BCF

Year	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2025-26	2030-31	2035-36	2041-42
Gas	972.056	960.77	889.29	889.29	730.68	431.35	302.19	298.13	63.69	63.69

Source: Ministry of Power, Energy and Mineral Resources (2020) [160] *BCF= Billion cubic feet*

Figure 4.3: Projection of Gas Production (2017-2042) in BCF



Source: Ministry of Power, Energy and Mineral Resources (2020) [161] *BCF= Billion cubic feet*

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[158] Unit.
[159] Unit.
[160] *Ibid.*
[161] Unit.

The projection from the above Figure 4.3 shows that after 2016-17 the country's total production of natural gas would be plummeting in the next 20 years. This is mainly because several large gas fields such as Titas, Bibiyana, and Jalalabad will run out within the next 10 years if the depletion continues at the present rate.[162] Thus at the end of 2041, the production will fall to 63.69 BCF from 972.06 BCF in 2017. Moreover, within these 20 years, the demand will rise from 1363.64 BCF to 3046.66 BCF, it means that demand will rise almost 3 folds, but production will fall by almost 15 folds within these 20 years. Therefore, the Government has taken the initiative to import LNG (liquefied natural gas) from abroad to meet the growing demand. They also aim to generate at least 10% of total power from renewable energy sources within 2020.

The energy policy would help sustainable development and keep the environment clean by preventing fossil fuel emissions. In this regard, solar power-based irrigation pumps can play a significant role and have already been used in several areas of the country. Its wide use will lessen the pressure on diesel, gas, electricity, and the environment.

4.5.2 Consumption of Natural Gas

A total of 961 billion cubic feet (BCF) of natural gas was produced in the year 2017–18, of which 40% used for electricity generation and 17% in the industry sector, 16% for domestic purpose, 16% for captive power, 5% for fertilizer industries, 5% for CNG and 1% for other purposes. It has been described in Table 4.8 and Figure 4.4.

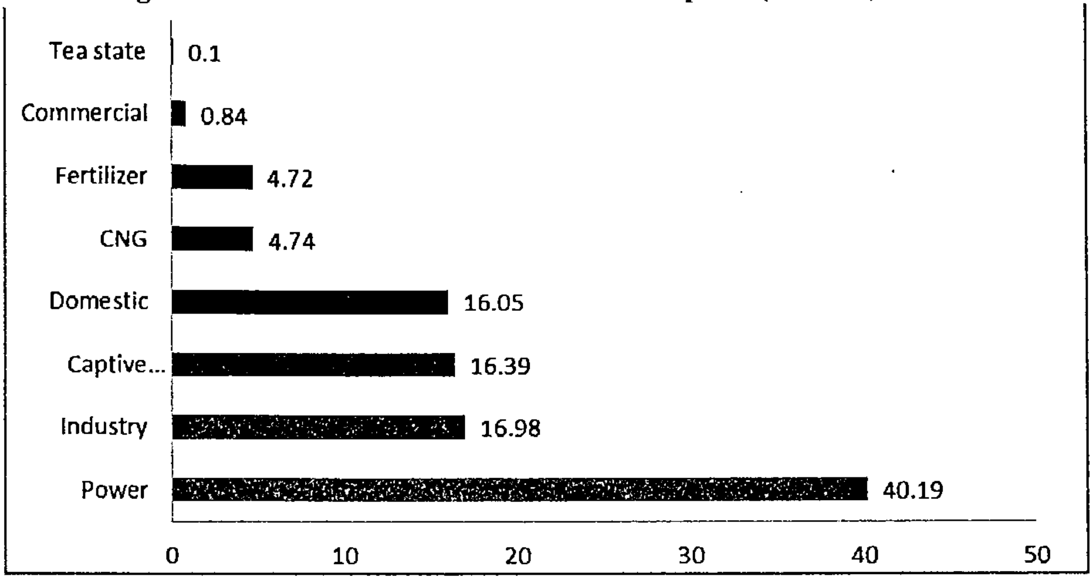
Table 4.8: Sector-wise Natural Gas Consumption (2017-18) in BCF

Sector	Amount of gas (BCF)	% share of the sector
Power	386.23	40.19
Industry	163.18	16.98
Captive power	157.51	16.39
Domestic	154.24	16.05
CNG	45.55	4.74
Fertilizer	45.36	4.72
Commercial	8.07	0.84
Tea state	0.96	0.10
Total	**961**	**100**

Source: Ministry of Power, Energy and Mineral Resources (2020)[163] *BCF= Billion cubic feet*

[162] *Ibid.*
[163] *Ibid.*

Figure 4.4: Sector-wise Natural Gas Consumption (2017-18) in BCF



Source: Ministry of Power, Energy and Mineral Resources (2020) [164] *BCF= Billion cubic feet*

In 2018, more than 60% of the country's total grid electricity was generated from 40% of the total produced natural gas.[165] That means natural gas is the primary source of the grid electricity of Bangladesh. When the supply of natural gas would shrink due to the depletion of the reservation, electricity prices would be increased further as the production cost of electricity from imported oil is higher than from the indigenous natural gas. After playing an important role in electricity generation, natural gas has also contributed to industrial growth in the country by ensuring fuel supply for heating and captive power generation at a favorable price. Besides, about 7% of the total population get direct benefits from natural gas for household purposes. Then, Compressed Natural Gas (CNG) is being used by about 250000 automobiles as fuel in the country. After expanding CNG facilities in the last decade, the quality of air has been improved dramatically in large cities, especially in Dhaka, and much foreign currency has been saved due to less amount of oil import. Last but not least, all the 7 urea fertilizer factories are dependent on natural gas for feedstock. The gas production has been fallen in recent years as any new reserve has not been discovered, and the proven reserve of natural gas is depleting continuously to meet the current rising demand. That is why the Government is now thinking about the alternative energy source and has the policy to generate at least 10% of total electricity from the renewable source of energy.

[164] *Ibid.*
[165] "Annual Report (2017-18)".

4.5.3 Demand for Natural Gas

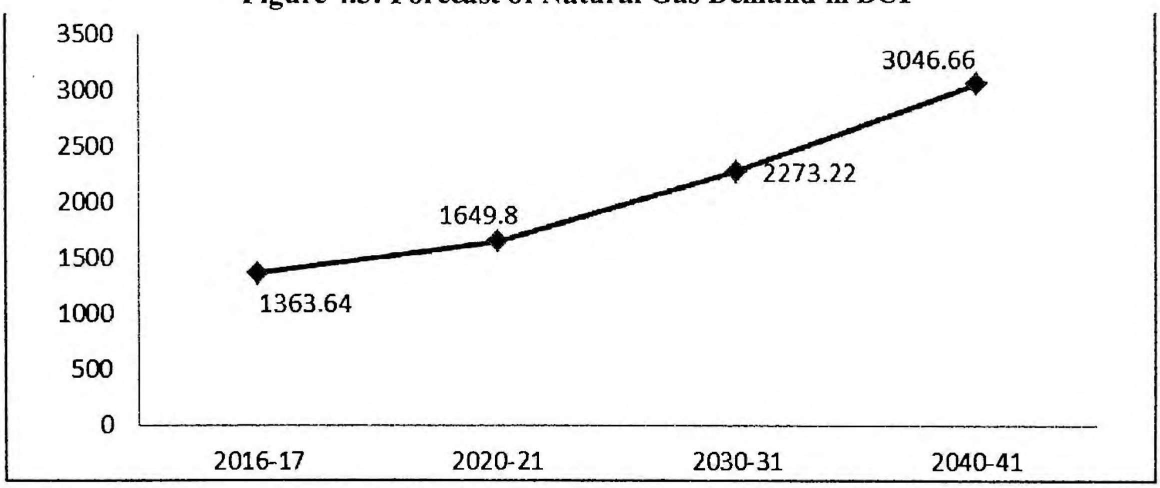
Being the almost single indigenous source of commercial energy, the demand for natural gas experienced swift growth over the last three decades, often outstripping the supply. The demand for gas in the country is about 1363.64 BCF. In contrast, the available supply was 972.06 BCF in 2018, indicating a shortage of about 390 BCF. It is also estimated that demand for natural gas will rise to about 2273 BCF by 2030 and about 3047 BCF by 2041.[166] The natural gas demand projection in the country is shown in Table 4.9 and Figure 4.5.

Table 4.9: Forecast of Natural Gas Demand in BCF

Year	2016-17	2020-21	2030-31	2040-41
Amount of gas	1363.64	1649.80	2273.22	3046.66

Source: Petrobangla (2018)[167] *BCF = Billion cubic feet*

Figure 4.5: Forecast of Natural Gas Demand in BCF

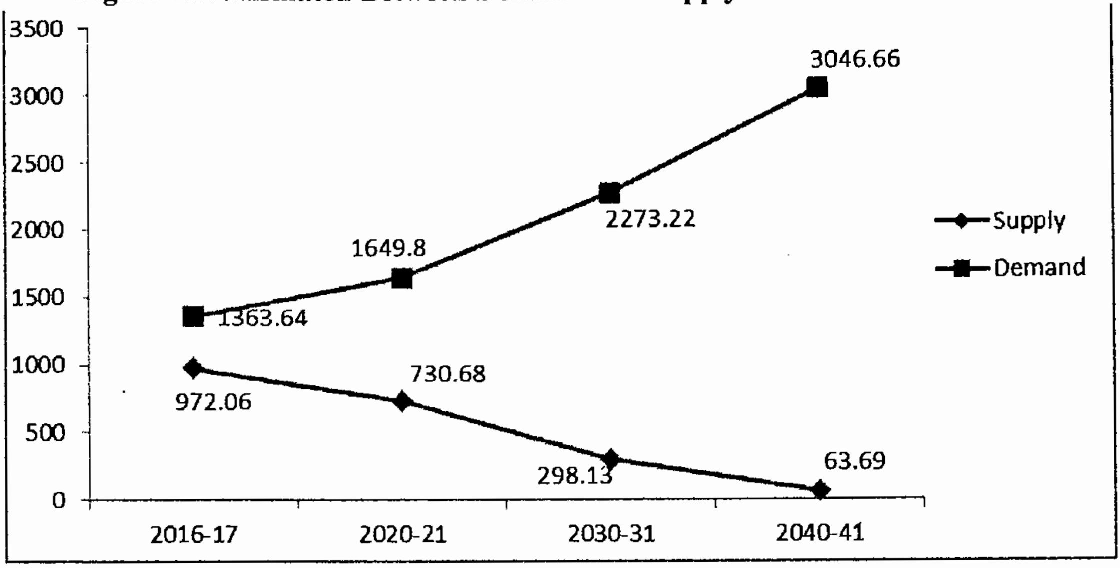


Source: Petrobangla (2018)[168] *BCF = Billion cubic feet*

On the other hand, at the end of 2041, the production will fall to 63.69 BCF from 972.06 BCF in 2017 (Shown in Figure 4.3). Within these 20 years, the demand will rise from 1363.64 BCF to 3046.66 BCF (Shown in Figure 4.5). It means that demand will rise by almost 3 folds, but production will fall by almost 15 folds within these 20 years. This mismatch between demand and supply of the natural gas of the country has been shown in Figure 4.6

[166] Unit.
[167] Ramboll.
[168] Ramboll.

Figure 4.6: Mismatch Between Demand and Supply of Natural Gas in BCF



Source: Petrobangla (2018) [169] *BCF = Billion cubic feet*

4.6 Electricity

Bangladesh is one of the energy-starved countries where per capita electrical energy consumption is only about 464 kWh, one of the lowest in the world.[170] As of June 2018, the total power installation capacity was 18753 MW, and the generation capacity was about 15000 MW because of the maintenance outage. However, the maximum generation obtained in 2018 was 10958 MW, which was less than 15000 MW. It has occurred due to fuel supply constraints. The distribution between the public and the private sector is 52% and 43%, respectively, of its total electricity generation capacity. Besides, Bangladesh has started to import 600MW electricity from India (started in October 2013), contributing 7% of total electricity. The summary of the power sector of Bangladesh is given in Table 4.10.

Table 4.10: Summary of Bangladesh's Electricity Status (2017-18)

Installed Capacity (MW)	18753
Generation capacity (MW)	15000
Maximum Generation (MW) in 2018	10958
Total Consumers (in Millions)	30.30
Transmission Lines (km)	11122
Distribution Lines (km)	457000
Per Capita Generation (including Captive) in Kwh	464
Access to Electricity (Including Off-Grid Renewable Electricity)	90%

Source: Power Division (2018) [171]

[169] Ramboll.
[170] "Annual Report (2017-18)".
[171] *Ibid.*

From the table, it is found that almost 90% of the total population of the country already has access to electricity, including the off-grid 5.8 million solar electricity connections, which is known as the solar home system (SHS). Moreover, the Government of Bangladesh has a target to reach power to every household by 2021.[172] Nevertheless, the per capita electricity generation of the country is not still at a satisfactory level. On the other hand, frequent power cuts and low voltage are additional grid electricity problems. These problems would be improved by increasing electricity generation from renewable sources of energy.

4.6.1 Production of Electricity

In Bangladesh, 68% of total electricity was generated from domestic fuels (natural gas, coal & hydro) and 24% from imported petroleum fuels (diesel and furnace oil). Among the fuels, natural gas and oil are the two dominating sources to generate electricity in the country. Natural gas and oil are accounting for 61.37% and 24.72% of total electricity, respectively. About 7.63% of total electricity (600MW) was imported from India as cross border energy trade. After that, about 2.70% of the total installed capacity is based on coal, which contributes 250 MW electricity of total generation. At present, new-renewable energy sources contribute about 1.95% of the total electricity generation. Finally, the conventional renewable energy source known as hydroelectric power provides 1.63% of the country's total installed capacity. The composition of the primary energy mix for power generation in 2018 is shown in Table 4.11 and Figure 4.7.

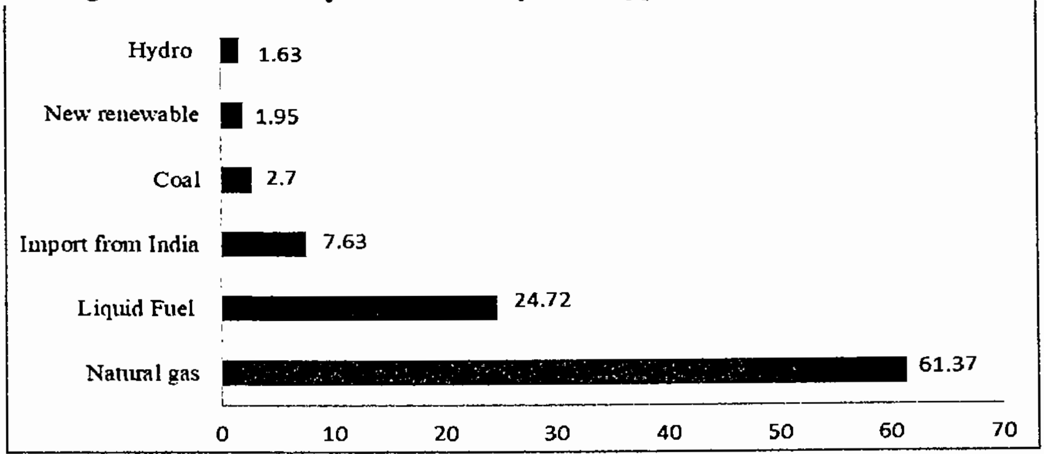
Table 4.11: Electricity Generation by Fuel Type (2017-18)

Source of electricity	Percentage share of electricity (%)
Natural gas	61.37
Liquid fuel (furnace and diesel oil)	24.72
Import from India	7.63
Coal	2.70
Hydro	1.63
New renewable (Solar, wind, and biogas)	1.95
Total	**100**

Source: Power Division (2018) [173]

[172] *Ibid.*
[173] *Ibid.*

Figure 4.7: Electricity Generation by Fuel Type in Percentage (2017-18)



Source: Power Division (2018) [174]

Figure 4.7 shows the installation capacity based on different fuels. The high depletion rate of the gas reserve threatens the power generation system's sustainability. More than 60% of the total power is now generated from the gas. Therefore, Power System Master Plan-2010 focuses on coal and targets 50% of power generation by coal within 2030 and then on the renewable sources of energy to produce at least 10% of the total generation from the renewable source within 2020.[175]

4.6.2 Consumption of Electricity

Households are the primary consumers of grid electricity. More than half of the total generated electricity was consumed at the household level in 2018. Then one-third of the total generated electricity was utilized in the industrial sector. The commercial and agriculture sectors have consumed the third and fourth highest share of electricity. The percentage consumption of the total electricity by the different sectors has been illustrated in Table 4.12 and Figure 4.8.

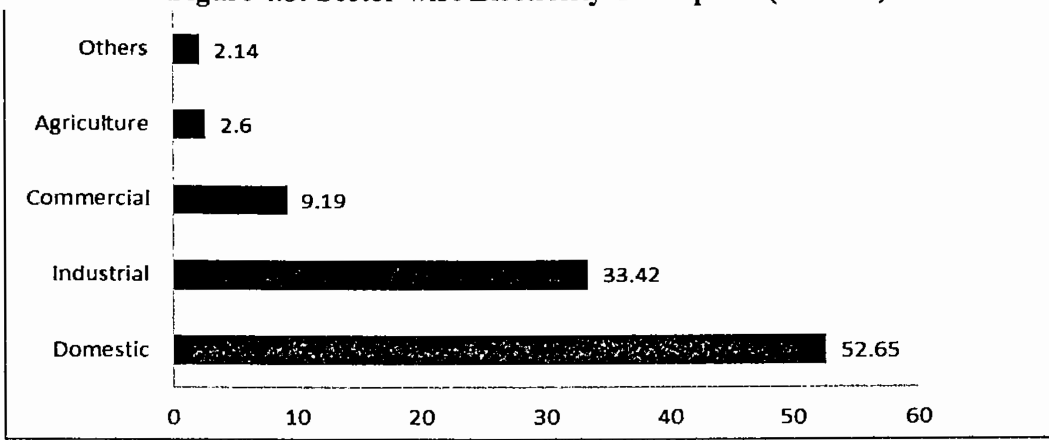
Table 4.12: Sector-wise Electricity Consumption (2017-18)

Sector	Percentage Share (%)
Domestic	52.65
Industrial	33.42
Commercial	9.19
Agriculture	2.6
Others	2.14
Total	**100**

Source: Ministry of Power, Energy and Mineral Resources (2020) [176]

[174] *Ibid.*
[175] Ministry of Power.
[176] Unit.

Figure 4.8: Sector-wise Electricity Consuption (2017-18)



Source: Ministry of Power, Energy and Mineral Resources (2020) [177]

Figure 4.8 shows that the agriculture sector consumed 2.6% of the total generated electricity. The critical share of this consumed electricity was used for irrigation purposes in 2018. Hence, the agriculture sector was the third highest sector in terms of liquid fuel consumption (about 1090903 MT) and the fourth-highest sector in terms of electricity consumption in 2018. Almost all of this energy was utilized for irrigation purposes. Therefore, for energy-strive countries like Bangladesh, this massive amount of imported liquid fuel and electricity would be saved by introducing solar irrigation pumps. It will also help achieve the government target to generate at least 10% of the total electricity from renewable energy sources within 2020. In the following section, the present status of renewable energy in Bangladesh has been discussed.

4.7 Renewable Energy

The available renewable energy sources of Bangladesh are solar, biomass, wind, hydropower, and biogas energy. These are the potential renewable energy to eradicate energy problems in Bangladesh.[178] This energy could play a vital role to meet up the growing energy demand of Bangladesh. However, the share of renewable energy is only about 3% of the total national energy consumption. The electricity generation in 2019 from renewable energy sources (e.g., solar PV, hydro, biomass, biogas etc.) was about 506.32 MW.[179] The SHS contribution is the highest of all renewable energy sources to

[177] Unit.
[178] Sustainable and Renewable Energy Development Authority (SREDA), "Electricity Installed from Renewable Energy", Power Division, Ministry of Power, Energy and Mineral Resources, Government of the Peoples Republic of Bangladesh http://www.sreda.gov.bd/index.php/re_master_pdf (accessed 15th February 2020).
[179] *Ibid.*

generate electricity. The second-highest contributor is hydropower. New-renewable energy sources like solar, wind have a great potentiality to generate electricity in Bangladesh. In Table 4.13, electricity generation from different sources of renewable energy has been depicted.

Table 4.13: Status of Renewable Energy (2019)

Method		MW
New-renewable energy	Solar Home System (5.8 million)	248.29
	Rooftop Photovoltaic (PV) at Government/Semi-Government offices	3.00
	PVs installation on commercial buildings and shopping centers	1.00
	PVs installation during new electricity connections	11.00
	Wind-based power plants	2.00
	Biomass-based power plants	0.40
	Biogas- based power plants	0.63
	Solar Irrigation	10.00
Conventional-renewable energy	Hydro-Electric power generation	230.00
Total		**506.32**

Source: SREDA (2020) [180]

Table 4.13 shows that 506MW electricity has been generated from renewable sources of energy in 2019. The Government has a target to produce at least 10% of the total electricity generation, which is about 1100MW (10% of 10958MW) from the renewable energy source within 2020. Therefore, the Government only has achieved about half of its target. To achieve the rest half of the target within a year would be very difficult. Under these circumstances, new-renewable energy, especially solar energy, has a great potentiality to generate quick electricity, especially in the off-grid areas. It has already been proved by the solar home system (SHS).

Besides, in the remote rural areas, the farmers also have a significant problem with irrigation facilities, mainly due to the high price of diesel and frequent load shading of the electricity. These problems can be resolved by the introduction of solar irrigation pumps at the mass level. It would also help achieve the Government's goal to generate 10% of total electricity from renewable sources of energy. Therefore, in the following sections, some crucial features of solar irrigation pumps (SIPs) and government policies regarding renewable energy have been discussed.

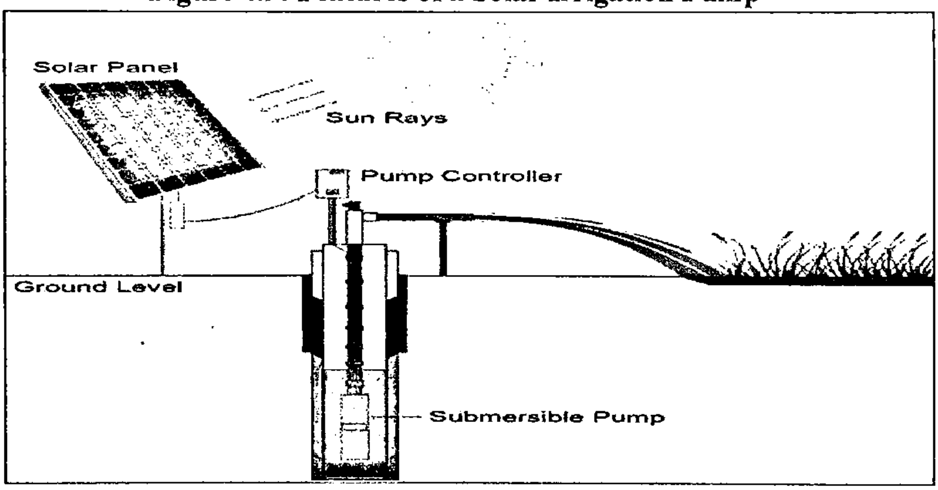
[180] *Ibid.*

4.8 Details of the Solar Irrigation Pump

Solar irrigation uses the sun's energy to power a pump that supplies water to cultivate crops. Solar pump's daily water delivery (photovoltaic pump, PVP) depends on the amount of PV panels installed, depth of the water level, and height of the storage tank (the addition of the depth and height is known as total pumping head). Solar panels turn sunlight into direct electricity (DC), and the electricity runs the solar pump.

Electricity produced by a solar panel is measured in Watt (W). PV panels come in different sizes. The more PV panels are connected, the more electricity is produced. Electric cables inter-connect the PV panels and transfer electricity to the water pump through a controller. It then regulates and stabilizes the electricity produced by PV panels. The electric cable connects to an electric submersible pump installed below the water level in the borehole from the controller. Some solar water pumps use alternating current (AC), so an inverter replaces the controller.

Figure 4.9: Features of a Solar Irrigation Pump[181]



Source: Vatio Energy India Private Limited (2017)

A solar pump capacity depends on the number of total installed solar modules or solar panels (Figure 4.9). So, the total power of 1.8 kWp solar pump is equal to the number of solar modules multiplied by each module's capacity (24×75 W_p) =1800 Wp. A tracking structure, a submersible pump, controller, installation materials, and pipe are necessary to

[181] Vatio Energy India Private Limited, http://vatioenergy.com/solarwaterpumping.html (accessed 22 October 2017).

install a solar irrigation pump.[182] The components of a typical solar irrigation pump are mentioned in Table 4.14.

Table 4.14: System Components of a 1.8 kWp Solar Irrigation Pump

Sr. No.	Description	Quantity
1	Solar Modules/panels 75 Wp	24
2	Array tracking structure	1
3	Submersible pump 2 HP	1
4	Motor/pump Controller	1
5	Installation kit	1
6	2″HDPE pipe (meter)	10

Source: Vatio Energy India Private Limited (2017) [183]

Besides, the solar panel cost is a vital part of the total investment for a SIP, which covers about 45% of the total cost. The installation and pump cost account for 18% and 16% of the total cost, respectively. Pipes and fitting costs are the lowest among all cost components account for 4% of the total cost.[184] Already, the pipes and fittings are locally available. Recently, Rahimafrooz Renewable Energy Limited, Electro Solar Power Limited, and other companies have assembled solar panels. Moreover, at present, submergible pumps are also being produced in Bangladesh. Thus, it is expected that the total investment cost will be reduced day by day. As, the cost of solar panels is decreasing rapidly due to continuous research, development, and the production of almost all components of SIP in the local market. The details of the installation cost of solar irrigation pumps have been given in Chapter five.

4.9 Infrastructure Development Company Limited (IDCOL)

IDCOL (Infrastructure Development Company Ltd. BD) is a fully government-owned financial institution. It started its operation in 1997 to catalyze private sector participation in infrastructure, renewable energy, and energy-efficient projects. It is the most considerable financial and monitoring authority in the renewable energy sector in Bangladesh. IDCOL receives funds from the Government of Bangladesh and multiple

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182 *Ibid.*
183 *Ibid.*
184 Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh."

development partners like the WB (World Bank), KfW (German government-owned development bank), KOICA (Korea International Cooperation Agency), JICA (Japan International Cooperation Agency), ADB (Asian Development Bank), USAID (United States Agency for International Development), GPOBA (Global Partnership of Output-Based Aid) and BCCRF (Bangladesh Climate Change Resilience Fund).[185] Then IDCOL gives grants, loans, and technical and promotional supports to the selected non-government organizations or partner organizations (POs). Some of the partner organizations (POs) are Grammen Shakti, Network for Universal Services and Rural Advancement (NUSRA), Rural Communication Network and Service Ltd (RCNSL), Rahimafrooz Renewable Energy Limited (RREL), Global Resource Augmentation and Management Ltd (GRAM), Jagorani Energy, ARS Bangladesh, Electro Solar Power Ltd., etc.[186] who is responsible for the implementation of solar irrigation projects. For the project's implementation, POs select the site, install the pump, and deliver water to the farmers. POs also collect fees from farmers and repay loans to IDCOL. IDCOL provides up to 40% subsidy and arranging 40% soft loan with the aid of donor agencies. Under this program, POs or individual investors of the irrigation system must invest only about 20% of the SIP's cost as a down payment.[187] Table 4.15 shows the financing structure for the implementation of solar irrigation pumps proposed by IDCOL.

Table 4.15: Financing Structure of Solar Irrigation Pump

Particulars	Percentage
Grant	40%
Debt	40 %
Equity (Down payment)	20%
Total	**100%**

Source: IDCOL (2017)[188]

Table 4.15 shows that 40% of the total price provided as a grant, the other 40% of the total price is offered as a loan to the SIP buyer at a 15% flat interest rate for 5 years by IDCOL. The remaining 20% of the total price has to be paid as a down payment by the investor to

[185] Limited.
[186] Infrastructure Development Company Limited, idcol.org/download/d4f1914587cceeede6d652df124ea7e1.docx (accessed 20 October 2017).
[187] Farzana Rahman, "Idcol Solar Irrigation Projects - Icimod" www.icimod.org/resource/17186 (accessed October 20 2017).
[188] Limited, "Idcol Solar Irrigation Projects".

purchase a solar irrigation pump. Almost all solar irrigation pumps in the country have been installed under this financial arrangement proposed by IDCOL.

4.10 Solar Irrigation Pumps in Bangladesh

Solar energy is richly available in Bangladesh with a variation of average solar insolation between 4 and 6.5 kW/m^2/day. For example, the following table shows the average solar insolation rate in different regions of Bangladesh. The Rajshahi region's isolation rate varies between 3.96 and 6.24 kWh/m^2/day. The maximum solar insolation occurs during February–June, and the minimum occurs during October–February. The available solar radiation or insolation rate in the country is suitable for generating power from sunlight. The average bright sunshine hours vary from 6 to 9 hours per day; one of the essential positive indications of solar irrigation pumps' viability. Table 4.16 shows the monthly solar insolation rate in different areas of Bangladesh.

Table 4.16: Monthly Solar Insolation Rate in Different Region of Bangladesh (kWh/m^2/day)

Month	Dhaka	Rajshahi	Sylhet	Bogra	Barishal	Jessore
January	4.03	3.96	4.00	4.01	4.17	4.25
February	4.78	4.47	4.63	4.69	4.81	4.85
March	5.33	5.88	5.20	5.68	5.30	4.50
April	5.71	6.24	5.24	5.87	5.94	6.23
May	5.71	6.17	5.37	6.02	5.75	6.09
June	4.80	5.25	4.53	5.26	4.39	5.12
July	4.41	4.79	4.14	4.34	4.20	4.81
August	4.82	5.16	4.56	4.84	4.42	4.93
September	4.41	4.96	4.07	4.67	4.48	4.57
October	4.61	4.88	4.61	4.65	4.71	4.68
November	4.27	4.42	4.32	4.35	4.35	4.24
December	3.92	3.82	3.85	3.87	3.95	3.97
Average	**4.73**	**5.00**	**4.54**	**4.85**	**4.71**	**4.85**

Source: Tanvir et al (2017) [189]

Table 4.16 shows that the greater Rajshahi region of Bangladesh has the highest level of average solar radiation. That is why; 618 out of 832 (From Table 4.17) solar irrigation pumps have been installed here. That is why, this study is interested in examining the viability of these installed solar irrigation pumps in this region. The total number of approved SIPs in Bangladesh was about 1140. Among them, the number of installed SIPs was 832 up to 2019. The information provided by IDCOL is given in Table 4.17.

[189] Rahamat Ullah Tanvir et al., "Prospects and Utilization of Renewable Energy in Banglade... iew Article " *International Journal of Scientific & Engineering Research* 8, no. 4 (2017).

Table 4.17: Division-wise Location of SIPs up to 2019

Region	Approved	Installed
Rangpur	705	574
Rajshahi	104	44
Khulna	325	211
Chittagong	2	2
Dhaka	4	1
Total	1140	832
Capacity in MW	**13.90**	**8.72**

Source: IDCOL (2019) [190]

So, from Table 4.17, it is clear that the formal Rajshahi division of Bangladesh is the prominent targeted place for the installation of SIPs. The prior matter for selecting a site is that the area should not be inundated during the rainy season. It should be an off-grid area where framers are presently using diesel pumps for irrigation. The area also should be a probable area for 3 to 4 crops per year. The conditions have been satisfied in many regions of the greater Rajshahi areas, where 618 solar irrigation pumps have been installed.

Moreover, the total generated power from the approved irrigation pumps would be about 13.90MW. However, the Government has a target to generate at least 150MW electricity from solar irrigation pumps.[191] Thus the installed capacity of SIPs should be increased rapidly to achieve the target. Also, at present, the projected irrigation pumps in Bangladesh within 2025 will be about 50000, which are illustrated year by year in Table 4.18.

Table 4.18: Installation Projection of Solar irrigation Pumps

Year	No. of Solar Irrigation Pump (SIPs)
2013	09
2014	80
2015	300
2016	450
2017	661
2018	1013
2019	1519
2020	2278
2021	3417
2022	5126
2023	7689
2024	11533
2025	15925
Total	**50000**

Source: IDCOL (2017) [192]

[190] Limited, "Idcol Solar Irrigation Projects".
[191] Ministry of Power.
[192] Infrastructure Development Company Limited, "Idcol Plans to Develop S[illegible]" http://www.idcol.org/home/solar (accessed 10 October 2017).

Thus, the total number of projected solar irrigation pumps will be about 50000 within 2025, a tiny share of 1.57 million conventional (mainly diesel operated) irrigation pumps.[193] At present (in 2019), the number of solar irrigation pumps is 832, but the projected number of solar irrigation pumps was 1519. Thus only about half of the targeted solar irrigation pumps have been installed up to 2019. Some of the installed solar irrigation pumps' details have been given in Table 4.19.

Table 4.19: Details of Some Installed Solar Irrigation Pumps

Location	POs	Water flow (m^3/day)	Pump capacity (kW)	Pump head/Lift (m)
Shapahar, Naogaon	GS	300	7.50	35.00
Fatiqchari, Chittagong	RCNSL	128	3.50	12.80
Sadar, Bogra	NUSRA	394	3.50	15.93
Dhamrai, Dhaka	NUSRA	381	7.50	17.30
Kaharole, Dinajpur	NUSRA	430	3.50	12.20
Shailkupa, Jhenaidah	NUSRA	430	7.50	15.30
Kumarkhali, Kushtia	NUSRA	383	7.50	17.60
Sadar, Thakurgaon	4SL	468	3.50	12.50
Ranisongkoil, Thakurgaon	4SL	468	3.50	12.20
Baliadangi, Thakurgaon	4SL	468	3.50	12.20
Birgonj, Dinajpur	4SL	504	5.50	13.60
Sadar, Panchagar	4SL	504	5.50	12.60
Autuary, Panchagar	4SL	504	5.50	12.60
Debiganj, Panchagar	4SL	504	5.50	12.60
Tetulia, Panchagar	4SL	504	5.50	12.60
Pirganj, Thakurgaon	4SL	504	5.50	13.20
Haripur, Thakurgaon	4SL	504	5.50	13.30
Gabtali, Bogra	GHEL	420	3.50	13.10
Dhunat, Bogra	GHEL	443	3.50	12.40
Sonatola, Bogra	GHEL	420	3.50	13.00
Pirganj, Rangpur	AVA	664	7.50	14.85
Birol, Dinajpur	AVA	679	7.50	17.46
Sadamahal, Setabganj, Dinajpur	AVA	664	7.50	14.76
BoroBalia, Sadar, Thakurgaon	AVA	613	5.50	12.46
Ghagrapara,Sadar, Panchagarh	AVA	594	7.50	12.61

[193] Hossain et al., "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh."

Location	POs	Water flow (m^3/day)	Pump capacity (kW)	Pump head/Lift (m)
Sadullahpur, Gaibandha	AVA	588	7.50	13.46
Badarganj, Rangpur	GRAM	373	4.00	10.25
Badarganj, Rangpur	GRAM	373	4.00	9.71
Badarganj, Rangpur	GRAM	373	4.00	10.91
Badarganj, Rangpur	GRAM	373	4.00	10.71
Badarganj, Rangpur	GRAM	373	4.00	10.71
Chowgacha, Jessore	ARS-BD	709	7.50	12.71
Chowgacha, Jessore	ARS-BD	709	7.50	12.71
Chowgacha, Jessore	ARS-BD	709	7.50	12.71
Chowgacha, Jessore	ARS-BD	709	7.50	12.71
Chowgacha, Jessore	ARS-BD	709	7.50	12.71
Chowgacha, Jessore	ARS-BD	740	7.50	16.01
Chowgacha, Jessore	ARS-BD	740	7.50	16.01
Shibganj, Bogra	GHEL	350	3.50	16.50
Sherpur, Bogra	GHEL	350	3.50	16.10
Shajahanpur, Bogra	GHEL	350	3.50	16.50
Chirirbandor, Dinajpur	RREL	645	11.00	14.57
Parbotipur, Dinajpur	RREL	576	11.00	18.71
Boda, Panchagar	RREL	594	7.50	12.51
Mithapukur, Rangpur	RREL	666	7.50	14.47

Source: IDCOL (2019) [194]

IDCOL, with the help of partner organizations (POs), has installed these solar irrigation pumps. Besides, IDCOL proposed two different models for implementing solar irrigation programs in the country; these are 'Fees for service model' and 'Fees for ownership model'. Almost all of the mentioned solar irrigation programs in Table 4.18 are examples of 'Fees for service model'. The standard features with the financial structures of these two models are mentioned below.

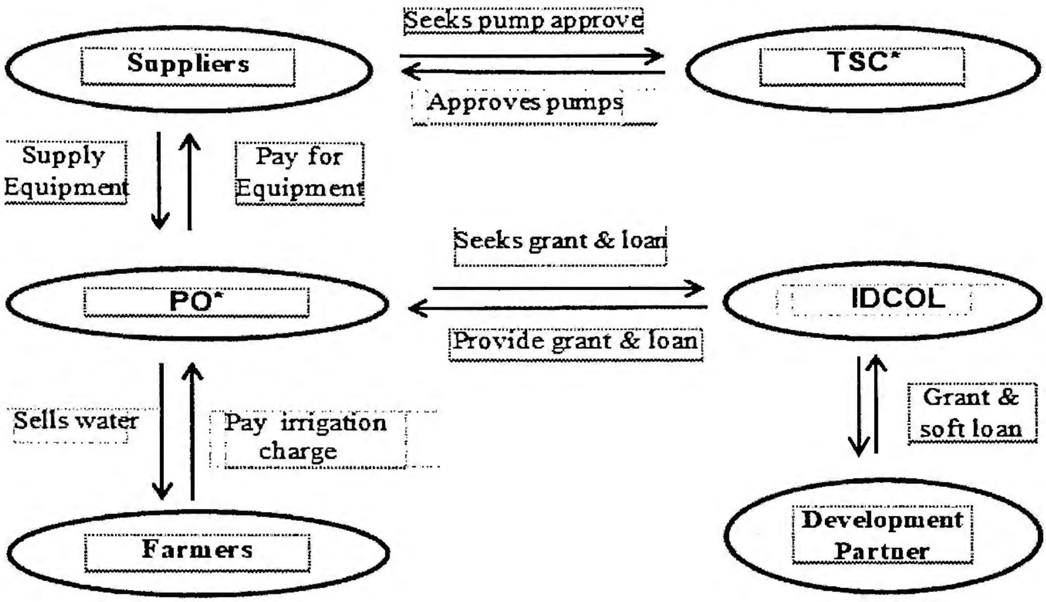
4.11 Fees for Service Model

'Fees for service model' is one of the two models proposed by IDCOL for in
managing solar irrigation pumps. According to this model, IDCOL collects

[194] Limited, "Idcol Solar Irrigation Projects".

loans from development organizations, and the Government then gives the grant and loan to the PO for the installation of a solar irrigation pump (SIP). After installation of the pump, PO sells water to farmers and collect irrigation fees from them. This model is depicted in Figure 4.10.

Figure 4.10: Fees for service model of SIP[195]



TSC: Technical Standards Committee of World Bank. PO= Partner Organization

4.11.1 Financing structure for 'fees for service' model

In this model, POs install solar irrigation pumps (SIPs), remain the owner of the installed pumps, and sell water to farmers in exchange for irrigation fees. Usually, in this model, the installed solar irrigation pumps' panel capacity varies from 9 to 20 kWp. Thus, the key features and financing structure of a typical 11 kWp solar irrigation pump are displayed in Table 4.20 as SIPs with this capacity are widely installed in this model. The updated price of 11 kWp SIP is almost 2500000 Tk and about 1000000 Tk of that is given as a grant. Another 1000000 Tk is offered as a loan from IDCOL. Moreover, the remaining 20% of the total price, or about 500000 Tk has to be paid as a down payment to purchase t This SIP can cover 40 bigha land for Boro cultivation and almost 100 bigha land for o crop cultivation. Key features of an 11 kWp SIP are given in Table 4

[195]Rahman.

Table 4.20: Key Features of an 11.0 kWp Solar Irrigation Pump (SIP)

Particulars	Quantity
PV capacity (kWp)	11
Flow rate (liter/day)	800000
Total head (meter)	14
Total cost (Tk)	2507440
Grant (40%) (Tk)	1005840
IDCOL loan (40%) (Tk)	1005840
Interest rate (%)	15
Down payment (20% of the pump cost) (Tk)	512800
Land coverage for Boro (bigha)	40
Land coverage for other crops (bigha)	80-120
Irrigation charge (Tk / bigha for Boro)	3000-3500

Source: IDCOL (2019)[196] *1USD= 80 Taka & 1 bigha=50 decimal*

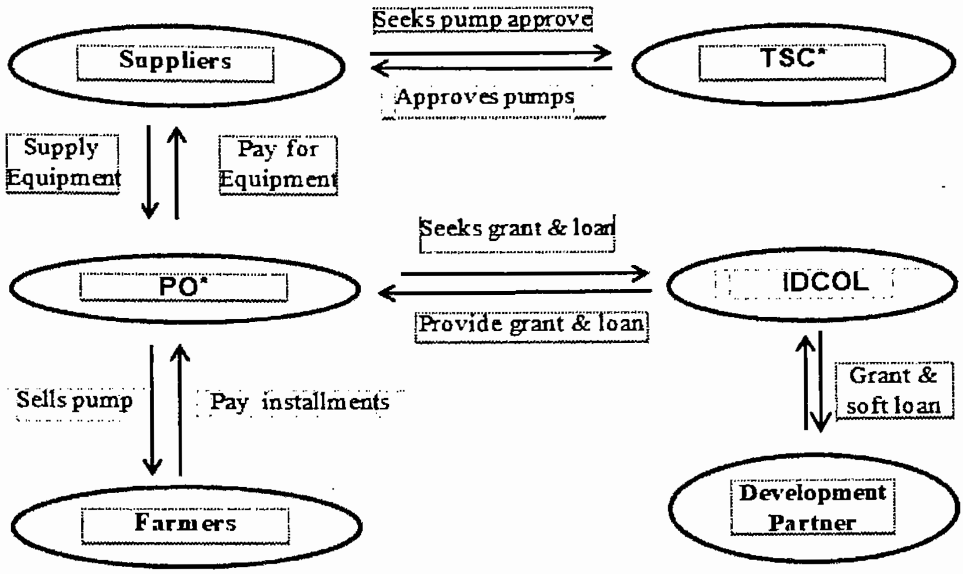
The solar pump with 11kWp capacity can withdraw 800000-liter water per day. It is enough to irrigate at least 40 bighas (20 acres) land for Boro cultivation. On average, 100 bighas (50 acres) land is sufficient for other crops like Amon, mustard, banana, chili, cucumber, sugarcane, potato, etc. cultivation. The irrigation charge for Boro cultivation for a season is about 35000 Tk per bigha, and the irrigation charge for other crops varies according to the water requirement of the crop. Partner organization (PO) receives a grant (in amount 1005840 Tk) and a loan (in amount 1005840 Tk) from IDCOL and pay 512800 Tk to install the SIP at the field level. After installing the SIP, the PO provides irrigation water to the farmers and collects irrigation fees to repay the loan and get the return on their investment. The details of this type of solar irrigation pump's cost benefit analysis have been given in Chapter five.

4.12 Fees for Ownership Model

The ownership model is almost the same as the service model; here, POs sell the solar pump instead of selling irrigation water to the farmers. The farmers pay installments instead of irrigation fees to the POs for purchasing the SIP. The other functions of the model remain unchanged. The capacity of the SIP in the ownership model is lower than the service model. In this model, the panel capacity of the installed SIP usually remains under 5kWp. The common feature of this model is illustrated in Figure 4.11.

196 Limited, "Idcol Solar Irrigation Projects".

Figure 4.11: Fees for Ownership Model of SIP[197]



TSC: Technical Standards Committee of World Bank. PO= Partner Organization

4.12.1 Financing Structure for 'Fees for Ownership' Model

In this model, any individual can be the owner of a solar irrigation pump by purchasing it. The farmer has to pay a down payment at a time and installment to pay off the received loan. Usually, the installed solar irrigation pumps' panel capacity varies from 2 to 5 kWp in this model. The key features and financing structure of a 4 kWp solar irrigation pump are displayed in Table 4.21.

Table 4.21: Key Features of a 4 kWp Solar Irrigation Pump (SIP)

Particulars	Quantity
PV Capacity (kWp)	4
Flow rate (liter/day)	250000-300000
Total Head (meter)	14.0
Total Cost (Tk)	676880
Grant (Tk)	270800
IDCOL loan (40%) for 5 years (Tk)	270800
Interest rate (%)	15
Down payment (20% of the pump cost) (Tk)	135200
Yearly installment by the farmer (Tk)	62284
Land Coverage for Boro (bigha)	16
Land Coverage for other crops (bigha)	30-60
Irrigation Charge (Tk/ bigha for Boro)	3000-3500

Source: IDCOL (2017)[198] *PO= Partner Organization, 1USD= 80 Tk & 1 bigha=50 decimal*

[197] Rahman.

Table 4.21 shows that, the price of 4 kWp SIP is almost 675000 Tk and about 270800 Tk as a grant. Another 270800 Tk as a loan would be given from IDCOL. The remaining 20% of the total price, or about 135000 Tk, has to be paid as a down payment to purchase the solar irrigation pump. This SIP can cover 16 bigha land for Boro cultivation and almost 30-60 bigha land for other crop cultivation. Table 4.21 also illustrates that the yearly installment amount is 62284 Tk to repay the loan. After 5 years, the total loan will be paid off. Then the irrigation cost for the farmer would become almost zero. That is why it would be a sustainable and economical option of irrigation for the farmers in the long run. The detail of this investment's cost-benefit analysis has been done in this study and given in Chapter five.

Finally, government policies and initiatives are vital to reduce the price of the SIP and increase the availability of SIPs at the mass level. In that regard, the Government has already taken the following policies and initiatives for the large scale dissemination of renewable energy in the country:

4.13 Government Policy and Initiatives

Bangladesh's Government has approved a renewable energy policy in 2008 effective from 2009, where the Government has set a target to generate 2000 MW electrical power by 2020 from renewable energy sources.[199] The renewable energy policy-2008 set the following objectives.[200]

- Harness the potential of renewable energy resources and dissemination of renewable energy technologies in rural and urban areas;
- Enable, encourage and facilitate both public and private sectors investment in renewable energy projects;
- Improve sustainable energy supplies to substitute indigenous non-renewable energy supplies;
- Scale-up contributions of renewable energy to electricity generation;
- Promote proper, efficient and environment-friendly use of renewable energy;
- Train, facilitate the use of renewable energy at every level of energy usage;
- Create a favorable environment and legal support to encourage the use of renewable energy;
- Promote the development of local technology in the field of renewable energy;

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[198] Limited, "Idcol Solar Irrigation Projects".
[199] Ministry of Power.
[200] Power Division, "Renewable Energy Policy of Bangladesh", Ministry of Power, Energy and Mineral Resources, Government of the People's Republic of Bangladesh http://www.powerdivision.portal... (accessed 15 March 2018).

- Promote clean energy for clean development mechanism; and
- Achieve the targets for developing renewable energy resources to meet 5% of the total power demand by 2015 and 10% by 2020.

Bangladesh's government has also taken several financial and fiscal incentives, e.g., exemption of income tax from commercial production of renewable power to promote access to modern reliable, affordable and sustainable energy services to national development. The most viable financial and fiscal incentives for renewable energy are as follows:[201]

- All renewable energy equipment and related raw materials in producing renewable energy equipment will be exempted from charging a 15% value-added tax (VAT).
- A network of microcredit support systems will be established, especially in rural and remote areas, to provide financial support to purchase renewable energy equipment.
- Sustainable and Renewable Energy Development Authority (SREDA) will consider providing subsidies to install solar, wind, biomass, or any other renewable/clean energy projects.
- Power Division of Ministry of Power, Energy and Mineral Resources/SREDA may help acquire land for renewable energy project(s).
- Both public and private investors in renewable energy projects shall be exempted from corporate income tax for 5 years.
- An incentive tariff may be considered for electricity generation from renewable energy sources, which may be 10% higher than the highest purchase price of electricity by the Government from private generators.
- The use of electricity and gas for water heating will be discouraged to promote solar water heaters.

Bangladesh's Government already hosted a 500 MW solar power development program. To implement this program, in 2012, the Government has established SREDA, which will be responsible for promoting renewable energy, energy efficiency, and energy conversion. Both public and private sectors have been working together to implement this project. In total, about 340 MW will be implemented by private sectors through some emerging fields, i.e., grid-tie solar park, solar irrigation, solar mini-grid, the solar system at the industrial and residential rooftop. Table 4.22 shows Government's sector-wise implementation plan of the 500 MW solar PV program.

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[201] *Ibid.*

Table 4.22: Government's Plan of 500 MW Solar Power Development Project

Types of projects			Capacity (MW)
Commercial solar power projects	Irrigation		**150**
	Mini-grid		25
	Park		135
	Rooftop	Residential and commercial building	10
		Industrial building	20
Social sector solar power projects	Electrification in health centers		50
	Electrification in remote educational institutions		40
	Electrification at union e-centers		7
	Electrification in religious establishments		12
	Electrification in remote railway stations		10
	PV system in government and semi-government offices		41
Total			**500**

Source: Ministry of Power (2019) [202]

It is estimated that about 30% of proposed renewable energy will be used for irrigation through around 19000 solar irrigation systems.[203] Each pump's average capacity will be 8 kWp with a head of 12–15 m and will cover about 13 ha of rice fields.[204] It will reduce about 95000-liter diesel consumption and a significant amount of CO_2 emission every day.[205] At present, IDCOL approved only 1140 SIPs for the installation at the field level. Thus, more initiatives have to be taken to install 19000 SIPs and generate 150MW renewable energy from installing solar irrigation pumps.

4.14 Conclusion

In this chapter, the present scenario of energy and irrigation of the country has been discussed elaborately. The focus has been given to petroleum, natural gas, and electricity because these are directly or indirectly used for irrigation purposes.

The total number of irrigation pumps is about 1.57 million in the country; among them, 1.24 million were diesel operated pumps. Therefore, about 80% of total pumps are operated by imported 1.06 million tons of diesel every year, which is a comparatively costly option for irrigation and environmentally hazardous. On the other hand, more than

[202] Ministry of Power.
[203] *Ibid.*
[204] *Ibid.*
[205] *Ibid.*

300000 pumps are now operated by electricity and utilized about 2.6% of the total generated electricity. Moreover, about two-thirds of the total electricity of the country is generated from natural gas. However, over half of the country's recoverable gas reserve has already been depleted to meet the growing population's demands. When the supply of natural gas would be reduced due to the depletion of the reservation, electricity price would be increased further as the production cost of electricity from imported oil is higher than from the indigenous natural gas. Besides, the per capita electricity generation of the country is not still at a satisfactory level. Frequent power cut and low voltage are the additional problems of the grid electricity. These problems would be improved by increasing electricity generation from renewable sources of energy.

That is why the Government is now thinking about the alternative source of energy and has the policy to generate at least 10% of total electricity from the renewable source of energy within 2020. However, in 2019, only about 3% of total energy has been generated from renewable energy source. The Government also has a target to generate at least 150MW electricity from the solar irrigation pumps. Yet, the total generated power from the approved irrigation pumps is only about 13.90 MW. Thus the capacity of SIPs should be increased rapidly to achieve these targets. Also, IDCOL fixed a target with the government policy line to install 50000 solar irrigation pumps within 2025, a very small share of 1.57 million conventional (mainly diesel operated) irrigation pumps. After the first installation of a SIP in 2010, only 1140 solar irrigation pumps have been confirmed for installation by IDCOL. At this pace, it would be difficult to achieve even the limited goal to install 50000 SIPs in the country by IDCOL.

The main barrier to the rapid replacement of conventional irrigation pumps with solar pumps is the high initial cost. Nevertheless, it is expected that solar pump's installation cost will be reduced day by day. Price of solar panels is decreasing rapidly due to continuous research, development, and production of almost all the components of SIP in the local market. Therefore, solar irrigation pumps have a great potentiality to supply water for irrigation, especially in off-grid areas. It would be able to solve the irrigation problems of the country, such as high prices and unstable supply of diesel and frequent load shading of the electricity and environmental pollution from fossil fuel, etc. It would also help achieve the Government's goal to generate 10% of total electr[illegible] renewable energy within 2020.

CHAPTER FIVE
DISCUSSION OF RESULTS

5.1 Introduction

The results found from the primary and secondary data analysis of this study have been discussed in this chapter. The Primary data have been collected from 250 solar pump users and 100 solar pump non-users to know about solar irrigation in detail. This chapter illustrates the opinion on SIPs from the user and non-user farmers of solar irrigation. Age, education, experience, occupation, and other information of the respondents have been discussed. Furthermore, some other essential features like the loan, operating time, irrigation fees, problems, and solutions of the solar irrigation service have been depicted. Also, it is believed that farmers' socioeconomic, demographic, and farm characteristics affect the views about new technology and their decision to adopt it. The life cycle cost analysis of solar, diesel and electricity-operated irrigation pumps has also been performed. Additionally, an elaborate discussion on different solar irrigation pumps' economic feasibility has been presented. A binary logistic regression model is performed in this chapter to determine the factors that influence the solar irrigation pump's adoption decision. Finally, the impact of solar irrigation pumps on the environment has been measured. These discussions have presented in the following sections:

In Section **5.2**, the respondents' socioeconomic, demographic, and farm-level characteristics are discussed elaborately. Next, section **5.3** provides a scenario of irrigation rates of different potions of energy. Then section **5.4** offers a life cycle cost (LCC) analysis of the available energy sources for irrigation. In section **5.5**, the findings of the economic feasibility of different solar irrigation pumps have been discussed. Section **5.6** shows the effect of solar irrigation on the outputs of crops; after that, in section **5.7**, a binary logistic regression model has been illustrated. At last, in section **5.8**, the environmental impact of solar irrigation pumps has been presented.

5.2 Socioeconomic, Demographic, and Farm-level Characteristics of the Sample Solar Pump Users

As discussed earlier, the required primary data have been collected from 350 farmers. Among them, 250 are solar irrigation users, and 100 are solar irrigation non-users. In this section, the collected data from the solar irrigation users are analyzed to portray the respondents' relevant demographic, social, and economic features. The sample solar pump users' demographic characteristics are the indicators to have a proper opinion about solar irrigation. Table 5.1 reveals the socioeconomic, demographic, and farm-level characteristics of the sample farmers. At first, the average age of the sample farmers is about 38.65 years. The sample solar irrigation users' formal education is only 5.19 years of schooling, and almost 40% are illiterate. The main occupation of 86% of the total respondents is agriculture. The rest, 14% of respondents with comparatively higher education, take agro-business and service as their primary jobs and agriculture as a secondary job. Thus almost all respondents who receive solar irrigation services are related to agriculture. Their average yearly income is about 180000 Tk, and the average farm size of the farmers is about 168.33 decimal. All the sample farmers have at least ten years of experience to cultivate different crops, and the average farming experience of the solar pump users is about 29 years. Subsequently, 80% of farmers mentioned that they never took any formal loans for agriculture purposes in the survey areas. They also stated that loan for investment in the agriculture sector, such as to buy a tractor; solar pump, requires a very complex and lengthy procedure. Table 5.1 provides the distribution of the basic demographic characteristics of the sample respondents.

Table 5.1: Demographic Profile of the Sample Solar Irrigation Users

S. No.	Demographic characteristics	Distribution in sample	Average
1.	Age (years)	21-30:14%; 31-40:41%; 41-50:14% & 51-65:31%	38.65
2.	Education (years)	Illiterate: 41%; Primary: 24%; Secondary: 21%; Higher Secondary/ Diploma: 7% & Tertiary: 7%	5.19
3.	Main occupation	Agriculture: 86%; Business: 7% & Service: 7%	_
4.	Yearly income	>100000: 4%; 100001-200000: 59%; 200001-300000: 20%; 300001-400000:17%	180000
5	Farm size (decimal)	≥100:14%; 101-200:33%; 201-300:30%; 301-400:20%; more than 400: 3%	168.33
6.	Farmers' Experience (years)	10-20:27%; 21-30: 28%; 31-40: 28%; above [illegible] 17%	[illegible]
7.	Agricultural loan	Loan for operational exp.: 15[illegible] [illegible]an for investment: 5%; No loan: 80%	

Source: Field survey, 2019

5.2.1 The Opinions of Solar Irrigation Users:

Solar irrigation pumps have been started to install in the country by the POs in recent years. About 90% of the respondent farmers have been using the solar irrigation service for 1 to 3 years. Moreover, only 10% of farmers have been using the service for about four years. Therefore solar power irrigation service is still a new concept in the country. The information collected from the solar irrigation users have been depicted in Table 5.2:

Table 5.2: Summary of the Opinion of Solar Irrigation Users

S.No.	Information/ Opinion	Distribution of sample
01	Views about solar irrigation	Extraordinary: 14%; good: 62% and moderate: 24%
02	Advantages of solar irrigation	Saving hours: 59%; Regular irrigation: 31% Environmental friendly: 10%
03	The environmental benefit of solar irrigation	No water contamination with diesel:44%; No air polution:30%;.No sound pollution:26%
04	Problems with solar irrigation	Higher fees than electricity: 62%; Limited sunshine in winter: 10%; Insincere operator: 9%; shortage of underground pipeline: 9%
05	The solution to the problems	Reduce irrigation fees: 75%; Training for operators: 13%; provide underground pipeline: 12%
06	Land provision to install SIP	Want to give:59%; do not want to give: 41%
07	Reasons to provide land	For rent of land:48%; for regular irrigation: 33%; for environmental benefitr:19%
08	View about climate change	Rainfall and temperature deteriorated: 79%; only one deteriorated: 11% & none of them deteriorated: 10%
09	Cropping intensity	3: 70% and 2: 30%

Source: Field survey, 2019

According to the information provided in Table 5.2, almost all users are satisfied with the solar irrigation service. All the interviewed farmers mentioned that solar irrigation is better than diesel irrigation. The main advantage of solar irrigation is that it saves farmer's working hours because they need not bring machines and diesel to the fields and operate it now. The second advantage of solar irrigation is its consistency because it is almost free from fuel supply uncertainty and frequent breakdown. The third advantage of solar irrigation is that it is free from environmental pollution. The main enviror[illegible]benefit of solar irrigation, in their view, it is free from water contamination with d[illegible]is also free from air and sound pollution.

On the other hand, the users' stated that, the problems of solar irrigation are high irrigation fees, the insincerity of the operators, shortage of underground pipelines, and limited sunshine in winter. Furthermore, the solutions to these problems are to reduce irrigation fees, increasing the coverage of the underground pipelines, and ensure proper training for the operators.

Then, about ten decimal of land is required to install a solar irrigation pump. Almost 60% of the respondent farmers want to give their land for installing a solar pump mainly due to the land's rent, sustainable source of irrigation, and the pump's environmental benefits. On the other hand, about 40% of farmers do not want to give their land to install SIP mainly because of the holding's limited size.

Almost 80% of the respondents believe that temperature is rising and rainfall decreasing for several years. Thus, the necessity for irrigation increases, and this incurred an additional cost for the farmers. In this regard, solar pumps can reduce the burden of irrigation costs.

At last, solar irrigation pumps at first have been introduced in high cropping intensive areas. Because in these areas, the demand for irrigation is high, and the pump can provide irrigation facilities all over the year, thus can maximize its earning. Table 5.2 reveals that the cropping intensity is 3 in 70% of selected areas, and the average cropping intensity is about 2.70.

5.3 Solar, Diesel, and Electricity Operated Irrigation Rates

In the visited areas, mainly two sources of irrigation are available. These are solar power irrigation and diesel operated irrigation. Some adjacent regions also have a grid-connected irrigation facility. In the sample area, many diesel operated irrigation pumps already have been substituted by solar-powered irrigation pumps.

The cropping intensity of the sample area is about three. Therefore, in a cropping year average, three crops are cultivated in a plot. Two types of paddy named Boro and Aman mustard, vegetable, jute, maize, banana, potato, chili, are the main cultivable items in the visited areas. The solar, diesel and electricity operated irrigation rates of these crops are mentioned below:

5.3.1 Boro

Boro is a high yielding variety (HYV) of paddy cultivated in the dry season in the country. This paddy is highly dependent on irrigation. Depending on the soil's quality and position, the required irrigation for Boro cultivation varies from 10 to 40 times per season. Generally, the fixed irrigation rate is practiced for Boro cultivation.

The most common fixed solar irrigation fee for Boro harvest is 3500Tk per bigha (50 decimal) for a season. The SIP operator ensures the proper amount of water supply in the farmer's land within this fee. Thus, the farmer need not stay on his land at irrigation time. So, he can save several working days in a season. As a result, he can give more time to his family or work in other income-generating activities.

Then, in diesel-operated irrigation, the machine rent's fixed amount is 2000Tk for a season in the visited areas. Many farmers have their diesel machines, but they face frequent breakdowns and high repair costs every year. Also, the farmer has to buy the required amount of diesel for irrigation. Thus, the cost of diesel irrigation is subject to the required amount of diesel. Generally, 1 to 1.50 liter diesel is necessary to irrigate a bigha land one time for Boro cultivation. For example, suppose the number of required irrigation is 30 for Boro cultivation. The necessary amount of diesel is 1 liter per bigha. In that case, the total cost for Boro harvest in 1 bigha land is (2000Tk + 30L × 70Tk) = 4100Tk in a season. Here, the price of 1 liter diesel is 70Tk. In electricity-operated irrigation, the fixed irrigation rate is 2500 Tk per season for Boro cultivation. The irrigation rates of these three options of irrigation for Boro cultivation have been mentioned in Table 5.3.

5.3.2 Amon

Generally, for Amon harvest, the required number of irrigation varies from 2 to 6. There are two available solar irrigation rates for Amon harvest in the visited areas; one is a fixed option of 1200Tk per bigha per season. Another is 5Tk per decimal or 250Tk per bigha for per irrigation. For example, suppose the total required number of irrigation is four. In that case, the total cost will be (250Tk ×4)=1000Tk for Amon harvest in one bigha in a season.

In the diesel operated machine, the irrigation fee is the machine's rent plus th[illegible] of required diesel and the labor cost to bring the machine to the cultivable lan[illegible] machine's rent is 100Tk for burning 1 liter diesel, and about 100Tk w[illegible]ld be necessar[illegible] get the machine at the required place. Moreover, the current price o[illegible]el is 70 Tk p[illegible] liter. Suppose the required number of irrigation for Amon cultivation is 4, and 1 liter diesel is necessary to irrigate one bigha land (50 decimal). In that case, the total cost for Amon harvest in one bigha by diesel will be (800Tk+4L×70Tk)=1080Tk in a season.

In electricity-operated irrigation, the charge for 1 hour of irrigation is 100 Tk. Usually, 1 hour is necessary to irrigate 1 bigha land. Thus, Amon harvest in 1 bigha land, 400 Tk would be needed to provide 4 irrigations in a season. So, electrified irrigation is the cheapest option for Amon harvest among the three available alternatives. Besides, the diesel and solar irrigation fees are almost equal for Amon harvest. However, solar irrigation is more convenient than diesel-run irrigation. In the rainy season, the diesel machines are generally kept in a secure place instead of in the cultivable land. Thus, to meet the unexpected necessity of irrigation, heavy machines have to be brought to the field, which is time-consuming and expensive. However, solar panels always remain in the field and can provide irrigation at any day time.

5.3.3 Other Crops

The solar irrigation fee for other crops like corn, potato, chili, mustard, and vegetable is 5Tk per decimal or 250Tk per bigha for one irrigation. On the other hand, the diesel irrigation fee for other crops is the summation of machine rent (100 Tk) for burning 1 liter diesel; labor cost (100Tk) to carry the machine at the field, and required diesel cost. Generally, 1 liter diesel is needed to irrigate one bigha land. Thus, diesel irrigation cost becomes about 270 Tk per irrigation in a bigha for other crops as the price of 1 liter diesel is 70Tk.

Finally, for electricity operated irrigation, the charge for 1 hour of irrigation is 100 Tk. Usually, 1 hour is necessary to irrigate one bigha land. Therefore, the electrified irrigation rate is the cheapest option. The solar and diesel irrigation rates are almost equal for other crop cultivation. However, solar irrigation is more convenient than diesel and electricity irrigation because it is free from interruption and uncertainty. Besides, it always remains ready to supply water on a sunny day. The summary of the irrigation rates has been given in Table 5.3.

Table 5.3: Solar, Diesel and Electricity Operated Irrigation Rate

Source	Boro/Bigha (Tk)	Amon/Bigha (Tk)	Others/Bigha (Tk)
Solar	3500/season	250/irrigation	250/irrigation
Diesel	4000/season	270/irrigation	270/irrigation
Electricity	2500/season	100/irrigation	100/irrigation

Source: Field survey 2019; Here, 1 bigha = 50 decimal

It has been clear from Table 5.3 that the electricity run irrigation rate is the lowest among the three irrigation rates. Moreover, on average, solar and diesel irrigation rates have been almost equal in the visited areas.

5.4 Life Cycle Cost (LCC) Analysis of Solar, Diesel, and Electricity Operated Irrigation Pump

Life cycle costs of 3 HP solar, diesel, and electricity operated pumps for irrigation have been calculated in this study to compare the costs of these available energy options of irrigation. The summary of the life cycle costs has been given in Table 5.4.

Table 5.4: Life Cycle Cost of 3 HP Solar, Diesel, and Electrified Pumps for 20 Years

Components	Solar irrigation pump		Diesel operated irrigation pump		Electrified irrigation pump	
Capital cost (Tk)	PV panel cost (40Tk×3500Wp)	140000	Diesel machine	20000	AC submersible pump cost	20000
	DC pump cost	30000				
	Mounting structure	40000	Construction of Shed	5000	connection cost	25000
	Construction of Shed	5000			Construction of Shed	5000
	Pipeline and strainer	6000	Pipe and strainer	6000	Pipe and strainer	6000
	Cables, switch board, base, light, etc.	5000	Cables, switch board, base, light, etc.	5000	Cables, switch board, base, light, etc.	7000
	Miscellaneous (transport, installation etc) cost (30% of total cost)	57600	Miscellaneous (transport, installation, etc.) cost (30% of total cost)	11100	Miscellaneous (transport, installation, etc.) cost (30% of total cost)	18600
	Total capital cost	**283600**	Total capital cost	**47100**	Total capital cost	**81600**
Maintenance cost(Tk)		24144		20050		6947
Replacement cost (Tk)		16122		28260		13319
Operational cost (Tk)		0		712190		134300
Life cycle cost (LLC)		**323867**		**807600**		**236166**
Annualized life cycle cost (ALCC) (Tk)		**38042**		**94861**		**27740**

Source: Author's calculation based on field survey data, 2019

Table 5.4 shows the four components: capital, maintenance, replacement, and operational cost of 3 HP solar, diesel, and electricity operated pumps for the LCC analysis. A short description of these four types of expenses of the pumps has given below:

5.4.1 Capital Cost of Solar, Diesel, and Electricity Operated Irrigation Pumps

Capital costs are the one-time expenses incurred on the purchase of land, buildings, construction, and equipment used to produce goods or services. In other words, it is the total cost needed to bring a project to an operable condition.

The main capital cost is the installation cost of a pump. At first, for the solar pump, the costs of solar photovoltaic panels, DC pump, mounting structure, accessories, and cables, are the main components of capital cost. In Bangladesh's Rajshahi region, the average solar radiation rate is about 5kWh/m^2/day. The average sunshine hour of the area is 8 hours per day. That is why the average amount of radiation during the day is about 625W/m^2. Therefore a factor of 0.625 is considered to determine the PV panel size of a solar pump. Likewise, the PV panel size of a 3 HP solar pump was calculated by dividing the pump wattage by the factor of 0.625, which was about 3500 Wp. Considering the current PV panel price of about 40Tk/Wp, the PV panels cost of 3 HP solar pump is about 140000 Tk. The total capital cost of the SIP is about 283600 Tk, which has been shown in the 1st row of Table 5.4.

In a diesel-operated irrigation pump, the diesel machine, pipe, strainer, cables, switchboard, base, and light, are the main capital costs. The total capital cost is estimated at 47100 Tk for a 3 HP pumping system.

Finally, for an electrified irrigation pump, the capital costs are the submersible pump, connection, pipeline, strainer, cables, and switchboard cost. The main contributor to the electrified pumping system's capital cost is establishing an electricity connection in the field site. Thus, the capital cost for a 3 HP electrified pumping system becomes about 81600 Tk.

5.4.2 Maintenance Cost of Solar, Diesel, and Electricity Operated Irrigation Pumps

The maintenance costs are necessary to keep a pump in good working co[illegible] main maintenance costs are the repairing and cleaning costs of the systems.

At first, the maintenance cost for a solar PV pumping syst[illegible]nsidered [illegible] capital cost per year. The maintenance cost is recurring i[illegible] needs to [illegible] throughout life. The cumulated discount factor is 8.51 for the entire life of 20 years, which corresponding to a discount rate of 10% and a relative rate of inflation of zero. Thus, throughout its life, a 3 HP solar pumping system's maintenance cost is 24144 Tk.

A diesel engine's maintenance cost is assumed 5% of total capital cost per year, approximately 2355 Tk per year. This annual maintenance cost was multiplied by the cumulative discount factor for 20 years (8.51) to obtain the lifetime maintenance cost of 20050 Tk for the 3 HP system.

Finally, the maintenance cost for the electrified pumping system was considered similar to the maintenance cost of solar operated pumps, which was 1% of the capital cost per year. The lifetime maintenance cost is 6947 Tk for a 3HP electrified pumping system.

5.4.3 Replacement Cost of Solar, Diesel, and Electricity Operated Irrigation Pumps

The replacement cost is necessary because most assets wear out and need to be replaced after the expected life period. Here in the case of a solar irrigation pump, the PV panels' minimum expected life period is 20 years. Thus the LCCs of the solar, diesel, and electricity operated irrigation pumps have been calculated for 20 years. The diesel machine, pump, wear, and accessories have an expected life span of 5 to 10 years. Thus after a certain period, these assets have to be replaced up to 20 years.

At first, in the solar pumping system, the DC pump needs to be replaced after ten years of operation. It requires one replacement in the 11th year in the solar pump's life cycle. The present worth of this future replacement of the pump was calculated at about 10514 Tk. Similarly, the computed replacement cost for the shed, cables, and pipelines in the 11th year of its life cycle was about 5608 Tk. Therefore the total replacement cost o[illegible]olar pump became 16122 Tk. These costs have been shown in the 3rd rows of Tabl[illegible]

Then, in a diesel-operated pump, the primary replacement co[illegible]ed from the [illegible] replacement, which performs optimally for about 5-6 years. [illegible] replaceme[illegible] diesel engines would be required in its life cycle of 20 yea[illegible] of the futu[illegible] replacement costs at the 6th, 11th, and 16th year of its establish[illegible]ent value resulted in the engine's total replacement cost is abo[illegible]2 Tk for [illegible]ilarly, the calculated replacement cost for the shed, cables, [illegible]s in the [illegible] cycle was about 5608 Tk. Therefore, the total replace[illegible]he diese[illegible] about 28260 Tk. These costs have been shown in the 3rd [illegible]5.4.

Finally, in the electrified pump, the submersible pump would be replaced after ten years of operation and requires one replacement in the 11th year in the 20 years cost analysis. The present worth of the future replacement of the pump would be about 7010 Tk. The replacement cost for the shed, cables, and pipelines in the 11th year of 20 years life cycle was found at about 6309 Tk. Therefore the total replacement cost of the electrified pump has been found 13319 Tk. These costs have been shown in the 3rd rows of Table 5.4.

5.4.4 Operational Cost of Solar, Diesel, and Electricity Operated Pumps

Operating or operational costs are the expenses that are related to the operation of a machine. In the case of irrigation pumps, the main operating cost is fuel cost.

The assumed operation time for all three types of irrigation pumps is 200 days throughout the year for a minimum period of 6 hours a day from morning to afternoon. Thus, the total cost to operate the pumps for 20 years is calculated as follows:

The solar pump's operational cost is almost zero because it runs by solar radiation, free of charge. However, in diesel and electricity run irrigation pumps, the total operating cost is related to the used amount of diesel and electricity.

While calculating the operational cost of the diesel pumping system, few assumptions were made. Considering the diesel's calorific value is about 10 kWh per liter, the diesel engine efficiency of conversion into dynamic energy is only about 30%. Thus, the diesel pump's energy generation capacity was calculated at about 3.3 kWh per liter of diesel. Besides, to operate the 3 HP pump for 1 hour needs 2.2 kilowatts energy as 1 HP is about 750 watts. According to the assumption, the pump operates 6 hours daily and 200 days in a year. Therefore, the daily and yearly necessity would be about 13.2 kWh and 2640 kWh energy, respectively. Thus approximately 4 liter daily and 800 liter diesel yearly is required to meet the diesel machine's energy demand. Moreover, 800 liter diesel's annual cost is about 56000 Tk, as the market price of 1 liter is 70Tk. Further, the relative rate of inflation for diesel was assumed at 5% since this fossil fuel is becoming scarce. The escalated price in the future is expected. The discount rate was considered 10[illegible] the calculated discount factor for 20 years would be 12.72. Finally, the total oper[illegible] for 20 years of the diesel pump has been found about 712190 Tk by multiplying th[illegible] diesel cost and the discount factor (12.72).

Finally, in the electricity operated 3 HP irrigation pump, the pumping system's main operational cost is electricity cost at a 4Tk/kWh tariff. Since the conventional energy source is becoming scarce, it is expected that the energy tariff will increase at a faster rate than the general inflation rate. The relative inflation rate for energy tariffs is considered at 5% while calculating the total operational cost in 20 years. The discount rate was considered 10% as similar to other cases. Thus the discount factor for 20 years has been calculated at 12.72.

Besides, it knows that 3 HP means 2.2 kilowatts as 1 HP is about 750 watts. Therefore, if a 3HP motor runs for 1 hour then it will consume 2.2kWh electricity. According to the assumption, the electric pump operates 6 hours daily and 200 days in a year; thus, daily and yearly consumption would be equal to 13.2 kWh and 2640 kWh, respectively. So, the yearly total cost of the consumed electricity would be about 10560Tk as the electricity tariff for irrigation is 4Tk/kWh. Finally, by multiplying the annual cost of electricity by the discount factor (12.72), the total operational cost for 20 years has been found about 134300 Tk for the electrified pumping system.

5.4.5 Life Cycle Cost of Solar, Diesel, and Electricity Operated Irrigation Pumps

Life cycle cost (LCC) and annualized life cycle cost (ALCC) of 3 HP solar, diesel, and electrified pumping systems are given in Table 5.4. The life cycle cost for 3 HP solar pumping system was found 323867 Tk and for diesel operated pump it was about 807600 Tk. In the case of the electrified pump, the cost was 236166 Tk. The life cycle costs have been converted to annualized life cycle cost (ALCC). It was done by dividing the LCCs with a cumulated discount factor (8.51) for 20 years to compare the three pumping systems. The ALCC for 3 HP solar, diesel, and electrified pumping systems is 38042 Tk, 94861 Tk, and 27740 Tk. The LCC and ALCC have been illustrated in the 5th and 6th rows of Table 5.4. Thus the analysis revealed that the ALCC of the solar pump is lower than the diesel pump but higher than the electrified pump.

The lowest amount of ALCC has been found for the electrified pump. The main reason that Bangladesh Energy Regulatory Commission (BERC) fixed the lowest tariff rate at 4Tk/kWh for irrigation. However, the average retail electricity 7.10Tk/kWh for other sectors. This subsidy in the irrigation lowest ALCC the electrified pumping system. However, the tariff rate would increased the future. On the other hand, the operational cost of the solar pump will always remain zero. Besides, the PV panel price reduced from 200Tk in 2010 to about 40Tk per watt at present for continuous research and development. That is why solar irrigation option would have a great potentiality in the agriculture sector of the country.

Finally, the ALCC of the diesel-operated pump was found at 94861Tk, which is almost 2.5 fold greater than the ALCC of the solar pump. Thus the farmers' irrigation cost would be reduced substantially if the solar irrigation pumps replace the diesel-operated pumps. That is why at first, as many as possible diesel pumps should be replaced by solar irrigation pumps.

5.5 Economic Feasibility of Large, Medium, and Small Solar Irrigation Pumps (SIPs)

The visited solar irrigation pumps have been categorized into three groups according to their capacity. This categorization would help analyze, explain, and compare the economic feasibility of different solar irrigation pumps. Thus, the visited 50 solar pumps have been classified into large, medium, and small in the following pattern:

1. Large solar irrigation pump (with more than 20 kWp solar panels)
2. Medium solar irrigation pump (with 6 to 20 kWp solar panels)
3. Small solar irrigation pump (with 1 to 5 kWp solar panels)

20 large, 25 medium, and 5 small solar irrigation pumps have been visited. Information collected from that SIPs is applied to measure the pumps' financial feasibility.

After installation, the POs own the medium and large SIPs, and the farmers usually possess the small solar irrigation pumps (SIPs). Several partner organizations (POs) such as Gazi, Solargao, Gram, and Grameen Housing and Energy Limited (GHEL) installed the solar irrigation pumps in the visited areas. POs appoint an operator for each large and medium solar pump to operate it, ensure its security, and collect the irrigation fees from the farmers receiving irrigation service. Usually, the operator is the local villager with several bigha of land and provides the necessary land to install the pump. The operator's compensation is 3000 Tk per month to ensure the pump's security and 20% of the total collected irrigation fees as commission per year.

The information about costs or *cash outflows* for installing and maintaining solar irri[illegible] pumps have been collected from the installers. The information [illegible] returns or ca[illegible] *inflows* of solar pumps has been collected from the operators an[illegible]rs. The ca[illegible] outflows and inflows are the main components for the financial analysis of the pump. The necessary information and the details of cash flows of the large, medium, and small solar irrigation pumps have been given below:

5.5.1.1 Large Solar Irrigation Pump

A large solar irrigation pump is installed and maintained by partner organizations (PO). They appoint an operator to operate and maintain the pump. A large SIP with 30kWp solar panels (120 solar panels each with 250W capacity) with 15kW pump can deliver about 1800000 liter water per day. It can provide irrigation facility to 100 bigha land for Boro cultivation and more than 120 bigha land for other crops cultivation. IDCOL offers 40% of the total price as a grant, the other 40% as a soft loan and the remaining 20% of the pump's total price has to be paid as a down payment. Thus the total installation cost of the large SIP after receiving a 40% grant becomes about 2793840Tk. In the visited areas, the common cultivable crops under the pump's coverage are Boro, Amon, mustard, potato, corn, etc. The pump's irrigation charge for Boro cultivation is 3500Tk per bigha for one season. For the other crop, this charge is 250Tk per bigha for every irrigation. The pump provides irrigation facilities on average 160 days in a year. On the other days of the year, the pump remains unused. However, the generated solar electricity from the PV panels can be utilized in alternative uses. Some alternative uses would be to supply the extra electricity in the national grid, operate husking, grinding machines, deliver drinking water to the adjacent household, etc. Frequently, installing this type of large solar irrigation pump without alternative use needs 20 decimal land. The necessary information of large solar irrigation pump has given in Table 5.5.

Table 5.5: Basic Information of a Large Solar Irrigation Pump

Panel capacity: 30 kWp (250W×120 panels)	**Pump capacity:** 15 kW (7.5 kW ×2 Pumps)
Water flow: 1800 m^3/day or 1800000 Liter/day	**Offers:** Irrigation facility to 100 bigha land (for Boro cultivation) and 120 bigha for other cultivations
Purchasing pattern: 40% grant, 40% loan and 20% down payment	**Total cost:** 4656400 Tk (**2793840** Tk after receiving 40% grant)
Irrigation Charge: 3500Tk/bigha/season for Boro and 250Tk/bigha/irrigation for other crops.	**Installed by:** Solargao/ Gazi/ Gram/ GHEL
Number of service receivers: 30	**Facility:** Irrigation only
Total required land for the installation: 20 decimal	**Total operating days:** 160/ year

Source: field survey 2019; (here, 1 bigha=50 decimal)

Besides, the Partner Organization (PO) also provided 3000-4000 feet of underground pipeline in the pump's surrounding fields for the maximum utilization of the groundwater. Now, for the comparatively large pump, the cash outflows and cash inflows are given below.

Cash Outflows

Cash outflows are all costs incurred from installing, maintaining, and running a solar irrigation pump. A typical large solar irrigation pump's cash outflows include the cost of the 30 kWp solar panels, 15 kW pumps, controllers, structure for holding the panels, cables, monotonous work, installation, transportation, and construction. The pump's total cost is about 4656400Tk, but after receiving a 40% subsidy, the total cost or cash outflows turned into 2793840 Tk. The detailed information about these costs collected from IDCOL and PO has been illustrated in Table 5.6.

Table 5.6: Cash Outflows of a Large SIP

Costs Items	**Cost (BDT)**
a. Equipment costs	
Solar panel 30 kWp	1756484
Solar pumping system – (pump 15 kW @ 1/10 years, motor, controller, etc)	1070972
Module mounting structure	226692
Cable & accessories 1/10 years	93128
Boring and related work	365640
Supply, testing, installation, transportation	182820
b. Construction Costs (Land, underground pipeline, tank, pump house, fencing)	887536
c. Legal and other fees	73128
Price	4656400
Price in field level with 40% subsidy	**2793840**
d. Running cost:	
Interest payment (6% p. a for 8 years)	111756
Operator's monthly salary:	3000
Commission (20% of total collected fees in a year)	9[illegible]

Source: IDCOL & PO

Table 5.6 shows that the pump's main fixed costs are the pane[illegible] pump, and co[illegible] costs. Besides the fixed costs, some running costs of the SIP [illegible] the operator's [illegible] commission on collected irrigation fee, interest payment on the given loan from IDCOL. Thus all fixed and running costs have been treated as cash outflows of the investment to install the pump. Here, the pump's fixed and running costs are about 2793840 Tk and 134800 Tk per year, respectively.

Cash Inflows

This large solar irrigation pumps only provides irrigation facility. So, the solar irrigation fee has been treated as the only return or cash inflow. The coverage of the SIP is about 100 bighas for Boro and 120 bighas for other crop cultivation. Then, on average, the irrigation rate is 3500Tk per bigha per season for Boro cultivation and 250Tk per bigha per irrigation for other crop cultivation. Moreover, at least two irrigations are necessary for other crop cultivation. Thus, the pump's total cash inflow from the irrigation fees for Boro, Amon, and other crop cultivation is about 470000Tk per year, shown in Table 5.7.

Table 5.7: Revenues or Cash Inflows of a Large SIP

Crops	Coverage (Bigha)	Rate (Tk per bigha)	Revenue / year (Tk)
Boro	100	3500	350000
Amon	120	250	60000
Potato / Wheat/ Mustard/ Vegetable	120	250	60000
Total revenue of the large solar irrigation pump per year (Tk)			**470000**

Source: field survey 2019; Here, 1 bigha=50 decimal

The cash flows are considered for 20 years as the solar panels' warranty period is at least 20 years. Without discounting the future returns into present value, the cash flows of a typical large solar irrigation pump for 20 years shows in Table 5.8.

Table 5.8: Large SIP's Cash Flows in 20 Years (Tk)

Total cash outflow (TC)	Total cash inflow (TR)	Net cash flow (Profit)
6074728	9400000	3325272

Source: Author's calculation based on field survey data, 2019

5.5.1.2 Large Solar Irrigation Pump with Alternative Use

Large solar irrigation pump with alternative use is installed and maintained at the field level by partner organizations (PO). Generally, alternative provisions like [illegible]ing and grinding machines have been introduced with the large solar irrigation pump. In that case, the large pump's panel capacity and coverage remain unchanged. Solar power is also used for husking paddy. Especially when irrigation is unnecessary, during the interval of two harvests, in the rainy season, or when one out of two pumps is sufficient to meet the irrigation requirement. The husking machine power is 10 HP or 7.5 kW, which is equal to each pump power. Thus, one water pump and the husking machine can run at the same time by solar electricity. After receiving a 40% grant from IDCOL, the solar irrigation pump's price with the paddy husking facilities became 2903840Tk. About 30 decimal land is necessary to install a large solar irrigation pump with an alternative use. The necessary information of large solar irrigation pump with a husking machine has given in Table 5.9.

Table 5.9: Basic Information of a Large SIP with Alternative Use

Panel capacity: 30 kWp (250W×120 panels)	**Pump capacity:** 15 kW (7.5 kW ×2 Pumps)
Water flow: 1800 m^3/day or 1800000 Liter/day	**Offers:** Irrigation facility to 100 bigha land (for Boro cultivation) and 120 bighas for other cultivations
Purchasing pattern: 40% grant, 40% loan and 20% down payment	**Total cost:** 2903840 Tk (after receiving 40% grant)
Irrigation Charge: 3500Tk/bigha/season for Boro and 250Tk/bigha/irrigation for other crops.	**Installed by:** Solargao/ Gazi/ Gram/ GHEL
Alternative Use: Paddy husking at the rate of 15Tk/Maund. (1 Maund=40kg)	**Facility:** Irrigation and husking
Number of irrigation service receiving farmers: 30	**Total operating days for irrigation:** 160/year
Total required land for the installation: 30 decimal	**Cultivable crops under this pump:** Amon, Boro, mustard, potato, corn, etc.

Source: field survey 2019; (here, 1 bigha=50 decimal)

Only two large SIPs with husking machines have been established almost in the visited areas. The SIPs have been providing irrigation and husking facilities without any repairing costs for four years. The solar pump provides irrigation facilities on average, 160 days in a year, and husking facilities all over the year when irrigation is unnecessary. The irrigation charge is 3500Tk/bigha for Boro cultivation per se[illegible] and 250Tk/bigha for other crop cultivation per irrigation. Moreover, the paddy [illegible] charge is 15Tk per Maund (1 Maund = 40 Kg), which is cheaper than the market husking rate by 5Tk per Maund.

Cash Outflows

Cash outflows are all costs incurred from installing, maintaining, and running the solar irrigation pump. These include the costs of the 30 kWp solar panels, 15 kW pumps, controllers, structure for holding the panels, cables, boring, installation, transportation, construction, etc. Thus the total cost of the SIP became about 4656400Tk. After receiving a 40% subsidy, the total cash outflow turned to 2793840 Tk. The initial cost also increases by 110000 Tk for the inclusion of the solar husking machine as the alternative use of a solar pump. The information about these costs collected from IDCOL and PO has been illustrated in Table 5.10.

Table 5.10: Cash Outflows of a Large SIP with Alternative Use

Costs Items	**Cost (BDT)**
a. Equipment costs	
Solar panel 30 kWp	1756484
Solar pumping system – (pump 15 kW @ 1/10 years, motor, controller, etc)	1070972
Module mounting structure	226692
Cable & accessories 1/10 years	93128
Boring and related work	365640
Supply, testing, installation, transportation	182820
b. Construction Costs (Land, underground pipeline, tank, pump house, fencing)	887536
c. Legal and other fees	73128
Price	4656400
Price in field level with 40% subsidy	**2793840**
d. Running cost:	
Interest payment (6% p. a for 8 years)	111756
Nightguard & operator's monthly salary:	3000
Collection fee (20% of total collection in a year)	98800
e. Alternative use cost	
Price of rice husking machine 1/10 years	60000
3-phase inverter 1/10 years	20000
Mounting structure and others	30000
20% labor cost of total revenue from husking paddy per year	648[illegible]

Source: IDCOL & PO

Table 5.10 shows that the pump's main fixed costs are the panel, pump, construction, husking machine costs. Besides the fixed costs, some of the pump's running costs are operator's salary, commission on collected irrigation fee, interest payment on the given loan, and labor cost for husking paddy. Thus the total cash outflows of large SIP's with alternative use are the installation cost and the running cost, which are about 2903840 Tk and 141280 Tk every year.

Cash Inflows

Alternatively, the cash inflows of the solar pump are the collected revenues from irrigation and husking services. The pump's irrigation coverage is about 100 bighas for Boro and 120 bighas for other crop cultivation. The irrigation rate is 3500Tk per bigha per season for Boro cultivation and 250Tk per bigha per irrigation for other crop cultivation. Thus, the total cash inflow from the irrigation service for Boro, Amon, and other crop cultivation is about 470000Tk per year. Besides, a 10 HP or 7.5kW husking machine can husk at least 12 Maund paddy every day and serve on average 180 days a year. Moreover, the husking charge by solar power machine is 15Tk per Maund. Thus the total revenue earned from the solar-powered husking machine is about 32400 Tk per year. The information about cash inflows of large SIP with alternative use has shown in Table 5.11.

Table 5.11: Cash Inflows of Large SIP with Alternative Use

Crops/ Alternative use	Coverage	Rate (Tk)	Revenue / year (Tk)
Boro **(Bigha)**	100	3500	350000
Amon **(Bigha)**	120	250	60000
Potato / Wheat/ Mustard/ Vegetable **(Bigha)**	120	250	60000
Husking paddy **(Maund /day)**	12	15	32400
Total cash inflows of large SIP with alternative use per year (Tk)			**502400**

Source: field survey 2019; Here, 1 bigha=50 decimal and 1 Maund =40 kg

Thus, the total revenue or cash inflow of the large SIP with alternati[illegible] is almost 502400 Tk in a year. Without discounting the future returns into p[illegible]e, the cash flows of a typical large solar irrigation pump with an alternative u[illegible]rs will be as follows:

Table 5.12: Cash Flows of Large SIP with Altern[illegible] 20 Years

Total cash outflow (TC)	Total cash inflow (TR)	[illegible]sh flow (P[illegible]
6394328	10048000	[illegible]53672

Source: Author's calculation based on field survey data, 2019

5.5.1.3 Medium Solar Irrigation Pump (SIP)

Medium solar irrigation pumps are also installed and maintained by partner organizations (PO). They appointed an operator to operate and maintain the pump. A medium SIP with 15kWp solar panels (60 solar panels each with 250W capacity) with a 7.5kW pump can deliver about 1100000 liter water per day. It can provide irrigation facility to 50 bigha land for Boro and more than 70 bigha land for other crops cultivation. IDCOL offers 40% of the total price as a grant, the other 40% as a soft loan and the remaining 20% of the pump's total price has to be paid as a down payment. Thus the total installation cost of the medium SIP after receiving a 40% grant becomes about 1881948Tk. Under the pump's coverage, The common cultivable crops are Boro, Amon, mustard, potato, corn, etc. The pump's irrigation charge for Boro cultivation is 3500Tk per bigha for one season. For the other crop the charge is 250Tk per bigha for every irrigation. About 20 farmers are receiving irrigation service from this solar pump. The pump is operated on average 160 days in a year. On the other days of the year, the pump remains unused. Ten decimal land is necessary to install this type of medium solar irrigation pump. The necessary information on a medium solar irrigation pump has given in Table 5.13.

Table 5.13: Basic Information of a Medium Solar Irrigation Pump

Panel capacity: 15 kWp (250W×60 panels)	**Pump capacity:** 7.5 kW (3.75×2 Pumps)
Water flow: 1100 m^3/day or 1100000 Liter/day	**Offers:** Irrigation facility to 50 bigha for Boro and 70 bigha for other crops cultivation
Purchasing pattern: 40% grant, 40% loan and 20% down payment	**Total cost:** 3136580 Tk (**1881948** Tk After receiving 40% grant)
Irrigation Charge: 3500Tk/bigha/season for Boro and 250Tk/bigha/irrigation for other crops.	**Installed by:** Gazi/ Solargao/ Gram/ GHEL
Number of service receivers: 20	**Facility:** Irrigation only (no alternative use)
Total required land for the installation: 10 decimal	**Total operating days:** [illegible]

Source: field survey 2019; (here, 1 bigha=50 decimal)

Besides, the Partner Organization (PO) provided about 200[illegible] [illegible]nd pip[illegible] in the pump's surrounding fields to ensure proper [illegible]tion of gr[illegible] [illegible] the medium pump, the cash outflows and cash inflow[illegible] below.

Cash Outflows

Cash outflows are the costs incurred from installing, maintaining, and running the solar irrigation pump. Cash outflows include the cost of the 15 kWp solar panels, 7.5 kW pumps, controllers, structure for holding the panels, cables, boring work, installation, transportation, and construction of a typical medium solar irrigation pump. Thus the pump's total cost becomes about 3136580 Tk, and after receiving a 40% subsidy, the total cash outflow turns into 1881948 Tk. Some of the pump's running costs are the operator's salary, commission on collected irrigation fees, interest payment on the loan, etc. The calculated average running cost of the pump is about 86000Tk per year. The components of cash outflows are depicted in Table 5.14.

Table 5.14: Cash Outflows of a Medium SIP

Costs Items	Cost (BDT)
a. Equipment costs	
Solar panel 15 kWp	878242
Solar pumping system – (pump 7.5 kW @ 1/10 years, motor, controller, etc)	721413
Module mounting structure	188195
Cable & accessories 1/10 years	62732
Boring and related work	313658
Supply, testing, installation, transportation	156829
b. Construction Costs (Land, underground pipeline, tank, pump house, fencing)	752779
c. Legal and other fees	62732
Price	3136580
Price in field level with 40% subsidy	**1881948**
d. Running cost:	
Interest payment (6% p. a for 8 years)	75278
Operator's monthly salary:	3000
Collection fee/commission (20% of total collection in a year)	51800

Source: IDCOL

Table 5.14 shows all types of cash outflows (fixed and running costs). The main four cash outflows components are panel and pump price, commission on collected irrigation charge, and operator's salary.

Cash Inflows

In the visited areas, all medium solar irrigation pumps only provide the irrigation facility. Thus, the irrigation fee is the only return or cash inflow of these pumps. The pump's irrigation coverage is about 50 bigha for Boro and 70 bigha for other crop cultivation. On average, the irrigation rate is 3500Tk per bigha per season for Boro cultivation and 250Tk per bigha per irrigation for other crop cultivation. Moreover, at least two irrigations are necessary for other crop cultivation. Thus, the pump's total cash inflow from the irrigation fees of Boro, Amon, and other crop cultivation is about 245000 Tk per year. This information has been depicted in Table 5.15:

Table 5.15: Revenues or Cash Inflows of a Medium Solar Irrigation Pump

Crops	Coverage (Bigha)	Rate (Tk per bigha)	Revenue / year (Tk)
Boro	50	3500	175000
Amon	70	250	35000
Potato / Wheat/ Mustard/ Vegetable	70	250	35000
Total revenue from medium solar irrigation pump per year (Tk)			**245000**

Source: Field survey 2019; Here, 1 bigha=50 decimal

The cash flows are considered for 20 years as the solar panels' warranty period is at least 20 years. Without discounting the future returns into the present value, the cash flows of a typical medium solar irrigation pump for 20 years will be as follows:

Table 5.16: Medium SIP's Cash Flows in 20 Years (Tk)

Total cash outflow (TC)	Total cash inflow (TR)	Net cash flow (Profit)
3965960	4900000	934040

Source: Author's calculation based on field survey data, 2019

5.5.1.4 Small Solar Irrigation Pump (SIP)

Small solar irrigation pump's financial structure is designed for 'fees for ownership model.' Here the pumps are installed by POs for the personal consumption of the farmers. A typical small SIP with 4kWp solar panels (16 solar panels each with 250W capacity) and 2.5kW pump can deliver about 350000 liter water per day. It can provide irrigation facility to 16 bigha land for Boro cultivation and more than 30 bigha land for other crops cultivation. IDCOL offers 40% of the total price as a grant, the other 40% as a soft loan and the remaining 20% of the pump's price has to be paid as a down payment. Thus, the small SIP's total cost after receiving a 40% (270752 Tk) grant becomes about 406128Tk. IDCOL also offers 270752 Tk as a loan, and the remaining 82000Tk has to be paid as a down payment. The basic information about this small SIP has been given in Table 5.17.

Table 5.17: Basic Information of a Small SIP

Panel capacity: 4kWp (250W×16 panels)	**Pump capacity:** 2.5 kW
Water flow: 350 m^3/day or 350000 Liter/day	**Offers:** Irrigation facility to 16 bigha land for Boro harvest and 30 bigha land for other crops.
Purchasing pattern: 40% grant, 40% loan and 20% down payment	**Total price:** **406128**Tk (after receiving 40% subsidy)
Irrigation Charge: 3500Tk/bigha/season for Boro and 250Tk/bigha/irrigation for other crops	**Installed by:** Solargao/ Gazi/ Gram/ GHEL
Land required for installation: 2-3 decimal	**Facility:** Irrigation only
Number of service receivers: 05	**Total operating days:** 160/ year

Source: field survey 2019; (here, 1 bigha= 50 decimal)

After purchasing, the farmer can save his irrigation cost and rent out the facility to the adjacent farmers. Thus he can earn from the irrigation charge at 3500Tk per bigha per season for Boro cultivation and 250Tk per bigha per irrigation for other crop cultivation. Only 2-3 decimal land is necessary for the installation of a small solar irrigation pump. The components of cash outflows and cash inflows of the small SIP are described in the following sections.

Cash Outflows

Cash outflows are all costs incurred from installing, maintaining, and running the solar irrigation pump. These include the cost of 4 kWp solar panels, 2.5 kW pumps, controllers, structure for holding the panels, cables, boring work, installation, transportation, construction, etc. Thus, the total cost of the small pump will be about 676880 Tk. After receiving a 40% subsidy, the cash outflows will be about 406128 Tk. The information about the costs collected from IDCOL has been illustrated in Table 5.18.

Table 5.18: Cash Outflows of a Small SIP

Cost Components	Cost (BDT)
Solar panel 4 kWp @ 1/20 years	246160
Pump (2.5 kW) @ 1/10 years	61520
Module mounting structure	102560
Cable & accessories @ 1/10 years	51280
Control unit (Schneider)	61520
Civil construction (pump house, water tank, fencing)	41040
Transportation, installation & erection	51280
Mark-up (10% on cost)	61520
Price	676880
Price in field level with 40% subsidy	**406128**
Interest payment (15% p. a for 5 years)	40610

Source: IDCOL & PO

Table 5.18 shows that the main fixed costs of cash outflows of the pump are panel price (246160 Tk), cost of module mounting structure (102560 Tk), pump price (61520 Tk), price of cable & accessories, etc. Besides the fixed costs, the pump's and cable's replacement cost would be necessary after ten years of installation. The running cost such as operator salary and commission on collected irrigation fees are not applicable for this case because the owner would serve as the operator and caretaker of the pump.

Cash Inflows

The pump can provide irrigation facilities to at least 16 bighas for Boro and 30 bighas for other crop cultivation. The irrigation rate is 3500Tk per bigha per season for Boro cultivation and 250Tk per bigha per irrigation for other crops cultivation. Moreover, on average, two irrigations are necessary for other crop cultivation. Thus, the small pump's total cash inflow from the irrigation fees of Boro, Amon, and other crop cultivation is about 86000Tk per year. The total revenue from the pump has been shown in Table 5.19.

Table 5.19: Revenue or Cash Inflows of a Small Solar Irrigation Pump

Crops	Coverage (Bigha)	Rate (Tk per bigha)	Revenue / year (Tk)
Boro	16	3500	56000
Amon	30	250	15000
Potato / Wheat/ Mustard/ Vegetable	30	250	15000
Total revenue from small solar irrigation pump per year (Tk)			86000

Source: field survey2019; Here, 1 bigha=50 decimal

The SIP's cash flows are considered for 20 years because solar panels' warranty period is at least 20 years. A typical small solar irrigation pump's cash flows without discounting the future returns into present values for 20 years will be as follows:

Table 5.20: Small SIP's Cash Flows in 20 Years

Total cash outflow (TC)	Total cash inflow (TR)	Net cash flow (Profit)
535176	1720000	1184824

Source: Author's calculation based on field survey data, 2019

5.5.2 Financial Indicators of Different Solar Irrigation Pumps

The information about cash outflows and cash inflows has been utilized to compute the financial indicators such as NPV (net present value), PBP (payback period), and IRR (internal rate of return) of each type of SIP. The indicators help to realize whether the pump is feasible or not. NPVs have been calculated at the discount rates of 6%, 9%, and 12%, which symbolize typical bank interest rates. Therefore, the comparison between the gains of installing the solar irrigation pump and saving the money in a scheduled bank will be possible. IRR is useful to show the actual return rate at which the net present value of all the cash flows (positive and negative) from an investment becomes zero. The PBP shows the time required for covering the project's total cost, and after the period, the project starts to earn a profit. The findings of the financial analysis are depicted in Table 5.21.

Table 5.21: The Outcomes of the Financial Analysis of Different SIPs

Solar irrigation pumps	NPV (6%) Tk	NPV (9%) Tk	NPV (12%) Tk	IRR (%)	Payback period (years)
1. a) Large solar irrigation pump	990167	224460	-316227	10.13	8.10
1. b) Large solar irrigation pump with alternative use	1135324	320069	-255617	10.54	7.82
2. Medium solar irrigation pump	-109868	-469166	-722579	5.27	12.91
3. Small solar irrigation pump	555470	358393	219356	20.1	4.84

Source: Author's calculation based on field survey data, 2019

In Table 5.21, large and medium (1 & 2) solar irrigation pumps represent 'fees for service model' because partner organizations (PO) install, own, and manage these solar irrigation pumps. Under these models, POs sell water to the farmers and collect irrigation fees from them. Besides, small (3) solar irrigation pumps represent the 'fees for ownership model' because an individual farmer can buy the pump from the PO. Table 5.21 demonstrates the results of all financial indicators of these SIPs. The findings of the financial indicators are explained as follows:

5.5.2.1 Net Present Values (NPVs)

According to Table 5.21, in the 1 (a) and 1 (b), net present values of the large solar irrigation pumps (without and with alternative use) became positive at 6% and 9% interest rates. However, NPVs have been found negative at 12% interest rate. At present, the bank offers on average 6% interest rate on all deposited amounts. However, the return from the investment is more than 9%. It means that investing in large solar irrigation pumps would be more profitable than keeping the money in the bank. Besides, all three NPVs increased by more than 1,00,000 Tk due to the introduction of alternative use (1 b) of the solar panels.

Then for the medium solar irrigation pump, net present values at all three interest rates became negative. It means that to deposit the money in a commercial bank at any interest rate would be profitable than to invest it in the medium solar irrigation pump.

Finally, net present values at all three interest rates turned highly favorable for a small solar irrigation pump. Thus, buying a personal solar irrigation pump is more profitable than saving the money in a bank at all available (6%, 9 %, or 12%) interest rates.

The calculated NPVs reveal that the most profitable option for investment is the small solar irrigation pump. The large solar irrigation pump is a moderately profitable option for investment. However, a medium solar irrigation pump is a non-profitable option for investment. So, installing a small solar irrigation pump for 20 years is a financially viable option for investment.

5.5.2.2 Internal Rate of Return (IRR)

IRR shows the actual gain or rate of return from an investment where NPV becomes zero. The IRRs for large solar irrigation pumps without (1a) and with (1b) alternative use has been found about 10.13% and 10.54%, respectively (Table 5.21). It means if 100 Tk is invested in the large SIP without (1a) and with (1b) alternative use in the current year, the amount will grow into about 110 Tk and 110.50 Tk, respectively, in the next year. Therefore the actual return would be increased by 0.50% per year due to the introductio of alternative solar power use. However, suppose 100 Tk is deposited in the bank this year. In that case, the bank will pay 106 Tk in the next year because it now offers a 6% interest rate on the deposited amount. That is why investing in a large solar pump seems profitable than keeping the money in a bank at the current interest rate.

In the medium solar irrigation pump (Table 5.21), the IRR was about 5.27%. Thus, if 100 Tk is invested in medium SIP in the current year, it will grow into 105.27 Tk in the next year. Nevertheless, if 100 Tk is deposited in the bank this year, the bank will pay 106 Tk in the next year because it offers a 6% interest rate on the deposited amount. That is why to keep the money in the bank would be more profitable than investing the money in a medium solar irrigation pump. Here the leading cause of the low IRR is the comparatively high installation cost of the pump.

Finally, the IRR of the small solar irrigation pump (Table 5.21) was found about 20.1%. The rate indicates that if 100 Tk is invested in the small SIP installation in the current year, then it will grow into about 120 Tk in the next year. However, if the amount is kept in the bank this year, it will be 106 Tk in the next year at 6% interest rate. Thus, investing in a personal small solar irrigation pump seems more profitable than to save the amount in a bank.

Thus from the IRRs, it is found that the most profitable option for investment is the small solar irrigation pump. Then the large solar irrigation pump reveals moderate profitability. However, the medium solar pump is not a profitable option for investment.

5.5.2.3 Pay Back Period (PBP)

The payback period shows the time required for covering the total cost of a project. After the payback period, the project starts to earn a profit. The simple payback period of the large solar irrigation pump with alternative use found 7.82 years. It was 8.10 years without any alternative use of the solar pump. Thus, it would take four months less to get back the initial cost with alternative use than without any alternative use. It means that after around 8 years, the initial cost of SIP will be recovered. After that, the pump will start to earn the profit up to the next 12 years as the solar panels' warranty period is at least 20 years

In the case of the medium solar irrigation pump, the simple payback period becomes about 13 years. Moreover, the panels' lifetime is at least 20 years; thus, after 13 years, the pump will start to earn profit for at least another 7 years. This payback period does not look impressive, mainly because of the pump's high installation cost and some running costs like the operator's salary and 20% commission on collected irrigation fees.

In the case of a small solar irrigation pump, the PBP is about 4.84 years, which is very attractive. After almost 4 years and 10 months, this investment will start to earn profit up to the next 16 years because the panels' warranty period is at least 20 years.

Therefore, the calculated PBP for the large solar irrigation pump is more than 5 years, for the medium solar irrigation pump is more than 10 years. For the small solar irrigation pump, it is less than 5 years. It indicates that installing a personal small solar irrigation pump is the most profitable investment option for irrigation.

5.6 Impact on Output due to the Use of Solar Irrigation

The farmers of survey areas have been using solar irrigation for the last 2 to 4 years. All farmers used diesel operated irrigation before the launch of SIPs in the regions. They quickly mentioned the difference in the crop output before and after the introduction of solar irrigation. Thus the impact of solar irrigation on the output has been calculated and discussed in this section. The information was collected from 250 farmers using solar-powered irrigation at present. Among them, 240, 237, 86, and 126 farmers harvest Boro, Amon, corn, and potato, respectively, regularly. Thus, the impact of solar irrigation on the output of Boro, Amon, corn, and potato has been estimated. The average plot size for the Boro cultivation is 148.56 decimal. Amon is 128.13 decimal, for corn is 85.28 decimal, and for potato is 58.78 decimal in the sample areas. Moreover, the required irrigation for Boro cultivation varies from 10 to 40, for Amon from 1 to 6, for corn from 2 to 8, and for potato from 1 to 4 in a season. The reasons behind this variation are the positio[illegible] quality of the plot. The four crops' output differences due to so[illegible] diesel irriga[illegible] depicted in Table 5.22.

Table 5.22: Pair Samples Test (Difference Between Average Solar and Diesel Irrigation Output/Decimal)

Crops	Ave. output of Boro by Solar irrigation (Kg)/decimal	Ave. output of Boro by Diesel irrigation (Kg) / decimal	t stat	Sig. (2-tailed) Paired sample test (p)	Comment
Boro	29.864	29.27	2.985	0.0064	**Significant**
Amon	22.26	21.33	3.562	0.0014	**Significant**
Corn	41.45	40.77	1.505	0.1709	Not Significant
Potato	100.18	90.55	1.091	0.3071	Not Significant

Source: Author's calculation based on field survey data, 2019

Table 5.22 shows that the outputs of all crops were increased due to the introduction of solar irrigation. However, only Boro and Amon's outputs increased significantly. The main reasons for increasing the Boro and Amon outputs are the availability and the uninterrupted water supply by solar irrigation. In diesel-operated irrigation, the farmers sometimes face irregular water supply mainly due to the machine's frequent breakdown and the interrupted supply of diesel. Also, the diesel irrigation machine is usually kept in a safe place in the rainy season. When irrigation becomes necessary due to a shortage of rain, a heavy machine needs to be brought into the field. It seems very difficult and costly due to the unavailability of labor and high wage. For these reasons, sometimes it would be challenging to arrange irrigation appropriately by diesel operated machines. However, SIP is free from these problems because it always remains in the field to supply water for irrigation. That is why the average output difference due to solar and diesel irrigation became significant for Boro and Amon cultivation.

On the other hand, the differences in corn and potato output using solar and diesel operated irrigation are not significant. The leading cause of the insignificant differences is the low requirement of irrigation to cultivate these crops. Also, the differences in the output of other crops like vegetables, mustard, banana, chili, etc., due to the use of solar irrigation are not significant for the same reasons.

5.7 Binary Logistic Regression Model

The logistic regression model is used to estimate the effects of various solar irrigation non-users' socioeconomic, demographic, and farm-level factors on the solar pump's adoption decision. The summary of the demographic profile of the sample solar irrigation non-users is given in Table 5.23.

Table 5.23: Demographic Profile of the Sample Solar Irrigation Non-users

Variables	Variable and unit	Continuous	Dummy
		Mean	Percentage
AGE	Age (years)	41.62	
EDU	Education (years of schooling)	5.12	
OLH	Size of operational landholding (bigha)	2.96	
LP	Number of land parcels	4.47	
CI	Cropping intensity	2.80	
GD	Groundwater depth (feet)	67	
IPR	Investment plan for renting (1, if want to rent; 0 otherwise)		1 = 78.89 0 =21.11
SWPI	Satisfaction with present irrigation setting (1, if satisfied; 0 otherwise)		1 = 25.48 0 = 74.52
LAI	Loan for agricultural investment (1, if receive loan; 0 otherwise)		1 = 18.56 0 = 81.44
VSIP	View on solar irrigation pumps (1, if have a view; 0 otherwise)		1 = 69.43 0 = 30.57

Source: Field survey, 2019; 1 bigha =50 decimal

Table 5.23 reveals that the average formal education of sample solar irrigation non-users is only 5.12 years of schooling. The table also shows that the average age and operational land holding of the sample farmers are 41.62 years and 2.96 bigha. Also, the average numbers of land parcels, cropping intensity, groundwater depth (feet) of the sample farmers' land are 4.47, 2.80, and 67 feet, respectively. It is also found that almost 79% of farmers are interested in providing solar irrigation facilities to the adjacent farmers in exchange for fees after buying a SIP. Only 25.48% of solar irrigation non-users are satisfied with the current irrigation setting. Furthermore, only about 19% of the sample solar irrigation non-users received a loan for agricultural investment. Finally, almost 70% of farmers have a clear idea about solar irrigation pumps' advantages and disadvantages. The expected impacts of these independent variables on the solar pump adoption decision have been discussed elaborately in Chapter three.

For evaluating the binary logistic regression model described in Chapter t[illegible] ers were asked to adopt a small personal SIP with 2.50 kWp pan[illegible] and 1.2 k[illegible] expense of 200000 Tk. It can cover 10 bigha land for Bor[illegible] bigha lan[illegible] crop cultivation. The capacity, price structure, and coverag[illegible] st potent[illegible] solar irrigation pump have been found from the pilot surv[illegible] ceiving [illegible] subsidy and 40% loan, the farmer will pay the remaining 20% of the total price as a down payment. Thus, the initial cost will be about 40000 Tk, and the monthly installment will be about 2000 Tk for four years to repay the 80000 Tk. The farmers who possess some land and selling some amount of their produced agriculture goods are asked to adopt the small solar irrigation pump at the mentioned price. So, the farmers pursuing agriculture only for subsistence and who do not sell their products are excluded from this logistic regression analysis. They are excluded based on the pilot surveys where it is found that they have a minimal interest to invest in their farms and also in solar pumps. For these farmers, the 'fees for service model' of SIP would be a more suitable irrigation option.

After collecting the information, the binary logistic regression model proposed by A. Jain and T. Shahidi has been estimated to determine the effect of relevant variables on the adoption decision of a solar pump. The relevant variables of the model are age, education, size of operational land holding, an investment plan for renting, loan for agricultural investment, number of land parcels, cropping intensity, groundwater depth, satisfaction with current irrigation setting, and view on solar irrigation used as the explanatory variables in the model. Here, by composing the above-stated variables, the estimated empirical model was as follows:

Table 5.24: The Effect of Interest Variables on the Adoption Decision of a SIP

Explanatory variables		Coefficient	Std. error	z-vale	p-vale
Age	(AGE)	-0.138*	0.081	-1.70	0.089
Education	(EDU)	0.017*	0.009	1.88	0.060
Size of operational landholding	(OLH)	0.041**	0.018	2.28	0.022
Number of land parcels	(LP)	-0.026	0.032	-0.81	0.418
Cropping intensity	(CI)	0.078	0.137	0.57	0.569
Investment plan for renting	(IPR)	0.613***	0.091	6.74	0.000
Groundwater depth	(GD)	0.113	0.104	1.09	0.276
Satisfaction with present irrigation setting	(SWPI)	-0.170**	0.072	-2.36	0.018
Loan for agricultural investment	(LAI)	0.221**	0.091	2.42	[illegible]
View on solar irrigation pumps	(VSIP)	0.903**	0.4[illegible]	[illegible]08	[illegible]
Constant		1.674	0.[illegible]	[illegible]	0.0[illegible]
Log likelihood : - 48.00; LR chi^2 (10): 135.67; Prob.> Chi^2: 0.000; [illegible]					

Note: ***, ** and * indicate the level of significance at 1%, 5% and 10%, [illegible]spectively.

Source: Author's calculation based on field survey data, 2019

Table 5.24 illustrates that the coefficient associated with farmers' *'age'* has a significant negative impact on the decision to install a SIP. Farmers may become more risk-averse as they grow older; thus, older farmers may not want to adopt new technology for irrigation. Another significant negative coefficient was found with *'satisfaction with present irrigation setting'*. This result indicates that farmers who are satisfied with their current irrigation setting have lower odds of adopting solar pumps.

Then the five explanatory variables have a significant positive impact on adopting the solar irrigation pump. The coefficient associated with farmers' '*education*' has a significant positive sign. It indicates that educated farmers could realize the long term economic and environmental benefits of SIP quickly. The coefficient of *'farm size or operational land holding'* has a significant positive impact on adopting solar irrigation technology because larger farms could efficiently utilize it. Also, the coefficient of *'investment plan for renting'* has a highly significant positive sign. It means a farmer who intends to install a SIP to provide irrigation facilities to neighboring farmers in exchange for fees would have a greater chance of adopting it. Moreover, from Table 5.24, it is observed that *'loan for agricultural investment'* is statistically significant, and its coefficient is positive. This result means that an increase in the availability of loans has a probability of increasing the chance to adopt a solar irrigation pump. Table 5.24 also shows that the coefficient of *'view on solar irrigation pumps'* is statistically significant and positive. Therefore, clear and available information about this new technology would help to decide to adopt it.

Finally, from Table 5.24, it is observed that the coefficients of 'number of land parcels', 'cropping intensity', and 'groundwater depth' are statistically insignificant. Therefore, these results bear no significant meaning in explaining the probable relationship between the mentioned variables and the decision to adopt a solar irrigation pump in Bangladesh's study region.

In summary, according to the outcome of the logistic regression model, the variables such as 'education', 'size of operational landholding', 'investment plan for renting', 'loan for agricultural investment' and 'view on solar irrigation pump' have a significant favorable influence on the solar irrigation pump adoption decision. On the other hand, 'age' [illegible] 'farmers satisfaction with present irrigation setting' significantly neg[illegible]uence s[illegible] irrigation pump adoption decision. Other variables of the model, [illegible]f land parcels', 'cropping intensity', and 'groundwater depth', have no significa[illegible]r irrigation pump adoption decision.

Marginal effects show the change in probability when the independent variable increases by one unit. With binary independent variables, marginal effects measure change, that is, the change in the predicted probabilities as the binary independent variable changes from 0 to l. The Table D2 (Appendix D) gives the average marginal effects of the predictors used in the model. In the study area education, investment plan for the future, view on solar irrigation pump, size of operational holding, satisfaction with the present irrigation setting and loan for agricultural investment have significant impact on the adoption decision of solar irrigation pump. A year increase in farmer's education, size of operational holding (in bigha), investment plan for renting, loan for agricultural investment and view on solar irrigation would on average 2.1%, 1.9%, 27.9%. 2.9% and 2.5% increase the probability of solar irrigation pump adoption, respectively. On the other hand, satisfaction with the present irrigation setting would on average 18.5% decrease the probability of solar irrigation pump adoption.

5.8 Environmental Effect of Solar Irrigation Pump (SIP)

SIPs have some direct potential to reduce greenhouse gas (GHG) emissions from irrigation activities by replacing fossil fuels with solar energy. At present, solar irrigation pumps substitute diesel operated irrigation pumps in the country. Thus, diesel consumption is reducing substantially due to the introduction of solar energy. As a result, CO_2 emission is decreased with the reduction of diesel consumption. Therefore the substitution of diesel is the primary environmental benefit of the SIPs. On the other hand, the CO_2 emission for the manufacturing of PV panels is the environmental cost of the SIPs. In this section, the solar irrigation pump's net environmental impact is calculated from the subtraction of the pump's environmental benefit and cost.

5.8.1 Large Solar Irrigation Pump

The main environmental benefit of a solar irrigation pump is the substitution of diesel by solar power. From the field visit, it was found that on average, 37.5 liter diesel for Boro, and about 3 liter diesel for other crop cultivation is necessary for one bigha land in a season. At first, the total substituted amount of diesel by the solar irrigation pump has been calculated. Then, the environmental benefit is estimated using the information that 1 liter diesel produces 2.8 kg CO_2 and the cost of reducing 1 ton CO_2 from the atmosphere is 100 USD. The calculation of the environmental benefit of the large solar irrigation pump is shown in Table 5.25.

Table 5.25: Environmental Benefit of the Large Solar Irrigation Pump

Crops	Coverage (bigha)	Required† number of irrigation per bigha /season	Required diesel per irrigation per bigha (Liter)	Required diesel (Liter)	CO_2 emission reduction (Ton)	Cost of CO_2 reduction (Tk)
Boro	100	25	1.5	3750	10.50	84000
Amon	120	2	1.5	360	1.008	8064
Others	120	2	1.5	360	1.008	8064
Total in a year				4470	12.516	100128
Total in 20 years				89400	250.32	**2002560**

Author's calculation based on field survey data, 2019; Here, 1 bigha=50 decimal; †=Average requirement; others= Potato / Wheat/ Mustard/ Vegetable

Thus, the large solar irrigation pump substitutes 4470 liter diesel and reduces CO_2 emission cost by 100128 Tk in a year. Finally, the tentative total environmental benefit of this investment in 20 years is about 2002560 Tk.

On the other hand, the large solar irrigation pump's main environmental cost is the emitted amount of CO_2 from solar PV panels' production process. Generally, the amount of emitted CO_2 is 170 Kg/kWp in manufacturing poly-crystalline silicon PV panels. Thus, the large solar irrigation pump with 30 kWp solar panel produces (170×30= 5100 kg) or 5.1 ton CO_2 in its life span. Moreover, the cost of reducing this amount of CO_2 is about (5.1 × 100 USD) or 40800 Tk.

Therefore, the large solar irrigation pump's tentative net environmental gain is (2002560 – 40800) Tk or 1961760 Tk. It would be more if the other environmental benefits of this investment, such as reducing water contamination, sound pollution, etc., have been considered.

The given subsidy for large solar pump is about 1862560 Tk, which is less than the calculated net environmental benefit of 1961760 Tk. Thus the amount of subsidy provided by the government and donor countries is justified for this investment.

5.8.2 Medium Solar Irrigation Pump

The main environmental benefit of a solar irrigation pump is th[illegible] of dies[illegible] solar power. From the field visit, it was found that on average, 3[illegible] for Boro and about 3 liter diesel for other crop cultivation is nec[illegible] for one b[illegible] At first, the total substituted amount of diesel by the p[illegible] een calc[illegible]

SIP's environmental benefit is estimated by using the information that 1 liter diesel produces 2.8 kg CO_2 and the 1 ton CO_2 reduction cost is 100 USD. The calculation of the environmental benefit of the medium solar irrigation pump is shown in Table 5.26.

Table 5.26: Environmental Benefit of the Medium Solar Irrigation Pump

Crops	Coverage (bigha)	Required† number of irrigation per bigha/ season	Required diesel per irrigation per bigha (Liter)	Required diesel (Liter)	CO_2 emission reduction (Ton)	Cost of CO_2 reduction (Tk)
Boro	50	25	1.5	1875	5.25	42000
Amon	70	2	1.5	210	0.588	4704
Others	70	2	1.5	210	0.588	4704
Total in a year				2295	6.426	51408
Total in 20 years				45900	128.52	**1028160**

Author's calculation based on field survey data, 2019; Here, 1 bigha=50 decimal; †=Average requirement; others= Potato / Wheat/ Mustard/ Vegetable

Thus the medium solar irrigation pump substitutes 2295 liter diesel in a year. Also, the price of CO_2 emission reduction due to the diesel substitution is about 51408 Tk in a year. Finally, the tentative total environmental benefit from this investment in 20 years is about 1028160 Tk.

On the other hand, this pump's main environmental cost is the emitted amount of CO_2 due to solar PV panels production. Generally, the amount of emitted CO_2 is 170 Kg/kWp in manufacturing polycrystalline silicon PV panels. Thus, the medium solar irrigation pump of 15 kWp solar panel emitted (170×15= 2550 kg) or 2.55 ton CO_2 in its life span. The cost of reducing this amount of CO_2 is about (2.55 × 100 USD) or 20400 Tk. Therefore, the medium solar irrigation pump's tentative net environmental gain in 20 years is (1028160 – 20400) Tk or 1007760 Tk. It would be more if the other environmental benefits of this investment, such as reducing water contamination with diesel, sound pollution, etc., have been considered.

The amount of subsidy for this pump is about 1254632 Tk, which is more than the calculated environmental benefit (1254632 – 1007760) Tk or 246872 Tk. If this pump's other environmental benefits (reduction of sound pollution and water contamination) are considered, the given subsidy would not be unjustified for the investment.

5.8.3 Small Solar Irrigation Pump

The main environmental benefit of a solar irrigation pump is the substituted amount of diesel by solar energy. From the field visit, it was found that on average, 37.5 liter diesel for Boro, and about 3 liter diesel for other crop cultivation is necessary for one bigha land in a season. At first, the total substituted amount of diesel by the solar irrigation pump has been calculated. The environmental benefit is estimated using the information that 1 liter diesel produces 2.8 kg CO_2 and the 1 ton CO_2 reduction cost is 100 USD. The calculation of the environmental benefit of the small solar irrigation pump is shown in Table 5.27.

Table 5.27: Environmental Benefit of a Small Solar Irrigation Pump

Crops	Coverage (bigha)	Required† number of irrigation per bigha/ season	Required diesel per irrigation per bigha (Liter)	Required diesel (Liter)	CO_2 emission reduction (Ton)	Cost of CO_2 reduction (Tk)
Boro	16	25	1.5	600	1.68	13440
Amon	30	2	1.5	90	0.252	2016
Others	30	2	1.5	90	0.252	2016
Total in a year				780	2.184	17472
Total in 20 years				15600	43.68	**349440**

Author's calculation based on field survey data, 2019; Here, 1 bigha=50 decimal; †=Average requirement; others= Potato / Wheat/ Mustard/ Vegetable

Thus the substituted amount of diesel by the pump is 780 liter per year. Besides, the cost of CO_2 emission reduction is about 17472 Tk per year. Finally, the small pump's tentative environmental benefit in 20 years is about 349440 Tk.

On the other hand, the small solar irrigation pump's environmental cost is mainly the emitted amount of CO_2 due to solar PV panel production. Generally, the amount of emitted CO_2 is 170 Kg/kWp in manufacturing poly-crystalline silicon PV panels. Thus, the small solar irrigation pump of 4 kWp solar panel emitted (170×4= 680 kg) or 0.68 ton CO_2 in its life span. Also, the cost of reducing this amount of CO_2 is about (0.68 × 100 USD) or 5440 Tk. Therefore, the small solar irrigation pump's net environmental gain is (349440 – 5440) Tk or 344000 Tk. It would be more if the other environmental benefits of this investment, such as reducing water contamination with diesel, sound pollution, etc., have been considered.

The pump's subsidy amount is about 270752 Tk, which is less than the pump's calculated net environmental benefit (370880 Tk). Thus the given subsidy is justified for this investment.

5.8.4 Comparison of the Subsidy and Environmental Benefit of Solar Irrigation Pump

IDCOL provides 40% of the total price of a solar irrigation pump as a subsidy. This study has made a comparison between the given subsidies with the net environmental benefits of solar pumps. The summary of the comparison has given in Table 5.28.

Table 5.28: Subsidy and Environmental Benefit of Different Solar Irrigation Pumps (Tk)

SIP	Panel capacity (kWp)	Price (Without subsidy)	Market Price (With subsidy)	Subsidy (40% of total price)	Subsidy/kWp	Net Env. benefit in 20 years	Net Env. benefit /kWp
Large	30	4656400	2793840	**1862560**	62085	**1961760**	65392
Medium	15	3136580	1881948	**1254632**	83642	**1007760**	67184
Small	4	676880	406128	**270752**	67688	**344000**	86000

Source: Author's calculation based on field survey data, 2019; PO= Partner Organization

Table 5.28 shows that the given subsidy is almost equal to the pumps' net environmental benefit in 20 years. The calculated net environmental benefit per kWp of small SIP has become the highest among the three types of SIPs. Table 5.28 shows that the net environmental benefit per kWp of the large and medium solar irrigation pumps is almost equal at around 6500 Tk. However, the small solar irrigation pump's net environmental benefit per kWp is more than 8500 Tk.

The financial indicators also show that a small solar irrigation pump is the most profitable option for investment. If the government provides more subsidy (more than 40% of the total price) on the small solar pumps' price, it would help the pump's mass adoption shortly. In that case, many farmers would be interested in installing it and getting the maximum benefit from the new environmentally friendly option for irrigation.

Finally, the net environmental benefit has been calculated by considering only the substituted amount of diesel by solar energy. If we consider reducing sound pollution, water contamination, etc., the actual gain would be more than the calculated benefit. So, it is clear that a solar irrigation pump is an environmentally friendly option for irrigation.

5.9 Conclusion

The study analyzed information collected from 250 user farmers and 10[illegible] non-user [illegible] of solar irrigation from the Rajshahi region of Bangladesh. Among [illegible] mo[illegible] are illiterate, the average experience of farming of the respondent[illegible] [illegible]ut 2[illegible] years. Also, the average yearly income of the sample f[illegible] is abou[illegible] average holding size of the farmers is around 168 decimal. All of our respondents have been using solar irrigation for about 1 to 4 years. So, solar irrigation is a comparatively new option of irrigation in the visited areas. Almost all farmers mentioned that solar irrigation is a better option than the diesel operated irrigation due to its time-saving, regular, and pollution-free nature of irrigation. Also, 60% of the respondent farmers want to provide land to install a solar pump, mainly for the land's rent and a consistent irrigation source. However, the other 40% do not want to provide land mainly because they do not have enough to provide 10 to 20 decimal land to install a SIP. According to the user's opinion, the main problem of solar irrigation is a high irrigation fee. Boro's current solar irrigation rate is about 3500 Tk, almost equal to the diesel operated irrigation rate and higher than the electricity run irrigation rate. The most typical electricity run irrigation rate is 2500Tk per season for Boro harvest. That is why the farmers demanded to reduce the solar-powered irrigation fee for Boro harvest from 3500Tk to 3000Tk.

The calculated ALCC for 3 HP solar, diesel, and electrified pumping systems were 38042 Tk, 94861 Tk, and 27740 Tk, respectively. ALCC of diesel operated pumping system has been found almost 2.5 fold greater than the ALCC of the solar PV pumping system. Thus the farmers' irrigation cost would reduce substantially if solar pumps will substitute the diesel-operated pumps.

In the economic feasibility, the large solar irrigation pumps were found moderately profitable. As the NPVs at 6% and 9% were positive. The values of the IRR and payback period were about 10.50% and 8 years, respectively. Thus, installing a large solar irrigation pump would be moderately profitable. It would return at a rate of approximately 10.50%, which is greater than the current bank interest rate (6%). Besides, the profitability of a large solar irrigation pump has been increased due to the introduction of alternative use.

Next, the financial indicators of medium size SIP have not seemed attractive. As the NPVs at all interest rates were found negative, IRR was at less than 6%, and the simple payback period was more than 12 years. Thus to install a medium solar irrigation pump wo[illegible]ot be a viable option for investment.

On the other hand, a small solar irrigation pump has been f[illegible]ofitable. [illegible] NPVs at all three interest rates of a small SIP were positive. The [illegible] was less than 5 years, and the IRR was more than 20%. Thus the financial in[illegible] SIP were found very lucrative. Though the financial indi[illegible]und very [illegible] small solar irrigation pumps have been found in the [illegible]

Then the estimated impact of solar irrigation on Boro output was significant. The Boro output has been significantly increased by more than 25 kg per bigha due to the introduction of solar irrigation. The impact of solar irrigation on Amon outputs was also found significant. However, in potato, corn, and other crops, the difference of outputs due to two options (diesel and solar) of irrigations was not significant. The available and uninterrupted water supply by the solar pump assures Boro and Amon's significant increase.

At last, from the logistic regression model, it has been found that independent variables such as, 'education', 'size of operational landholding', 'investment plan for renting', 'loan for agricultural investment' and 'view on solar irrigation pump' have a significant and favorable influence on the solar pump adoption decision. So the proper circulation about the positive impact of SIP on output and environment with an attractive price structure would help disseminate the pumps at the root level.

The calculated net environmental benefit of the solar irrigation pumps for 20 years was found almost equal to the given amount of subsidy. Thus the granted subsidies have been justified for these investments. The net environmental benefit per kWp of a small solar irrigation pump was the highest. Therefore the government should provide more subsidies for the personal consumption of a small solar irrigation pump.

CHAPTER SIX
MAJOR FINDINGS AND POLICY IMPLICATIONS

6.1 Introduction

Bangladesh is heavily dependent on traditional energy sources and imported fossil fuel, which harms the environment and economy. Renewable energy technologies are promoted to satisfy the country's rural energy needs mainly as a form of solar home system and solar irrigation pump. In this study solar irrigation pump's economic feasibility and environmental impact has been measured. As an agriculture-based country, irrigation is vital for ensuring the country's food security. The requirement for irrigation rises over the years, mainly due to the increase of the High Yielding Variety (HYV) use, decline of the water table, reduction of surface water sources, increase of cultivable areas, and volatility of climatic condition of the country. In recent years a sustainable source of irrigation has become essential for Bangladesh. In this regard, solar irrigation might be a reliable source. The greater Rajshahi region of Bangladesh, one of the most agricultural concentrated areas, has been selected for this study. The farmers of this area are highly dependent on irrigation to produce different crops. Moreover, several hundreds of solar irrigation pumps have already been deployed by partner organizations in this area. Therefore, this study attempted to analyze this new technology's economic feasibility and environmental impact in that area.

In this chapter, the significant findings of this study are summarized according to the objectives. Some policies are implicated based on the findings for improving solar irrigation service and its mass adoption. The chapter is organized as follows: Section 6.2 provides the results and main findings of the study. In Section 6.3, some policies are implicated to improve the pump's economic feasibility for large scale adoption. Finally, the limitations of this study are mentioned in Section 6.4.

6.2 Summary of the Results

Before introducing a mechanized irrigation system, Bangladesh was a food-deficit country with less than half of the present population. As the irrigation coverage area has increased to 72 percent of the cultivable area, the country produces sufficient rice for 160 million people. It indicates the importance of irrigation for food production. Moreover groundwater is the primary source of irrigation and cover about 77 percent of the total irrigated land. The DTWs installation in the country started in the middle of the 1960s and STWs in the early 1970s. In the early 1990s, the number of DTWs was the highest; then, its number started decreasing. Because of liberal import policy toward the end of the 1980s, the prices of STWs became affordable to small and medium farmers.[206] Therefore, its number started increasing at a rapid rate. Any farmers can buy water for cash or kind from STWs. Then the use of manual pumps almost came to an end. Still, the primary source of irrigation of the country is diesel operated STWs. However, it has some significant problems like frequent breakdowns of the machine and interrupted supply, and unstable diesel price. That is why; the government of Bangladesh is looking for an alternative source of irrigation. In this regard, solar irrigation would have the great potentiality for the country.

Thus, to realize solar irrigation's importance in the country, an analysis of the present energy and irrigation scenarios has been done as the first objective in chapter 4. The other objectives have been satisfied in chapter 5. The summary of the findings are given below:

6.2.1 Present Irrigation Scenario of the Country

The total number of irrigation pumps is about 1.57 million in the country; among them, 1.24 million were diesel operated pumps. Therefore, about 80% of total pumps are operated by imported 1.06 million tons of diesel every year, which is a comparatively costly option for irrigation and environmentally hazardous.

Additionally, more than 300000 pumps now operate by electricity and utilize about 2.6% of the total generated electricity. At present, about two-thirds of the total electricity of the country generates from natural gas. Besides, over half of the country's recoverable gas reserve has already been depleted to meet the growing population's demand. That is why the government is now thinking about alternative energy sources and has the policy to generate at least 10% of total electricity from renewable energy sources within 2020. However, in 2019, only about 3% of total energy has been generated from renewable energy sources. The government also has a target to generate at least 150MW electricity from the solar irrigation pumps. However, the total generated power fr[illegible] approved irrigation pumps would be about 13.90 MW. Therefore, the capacity o[illegible]ld be increased rapidly to achieve the targets.

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[206] Dr. Kshirode C. Roy, "History of Irrigation Development in Bangladesh [illegible]n2020.

Also, IDCOL fixed a target with the government policy line to install 50000 solar irrigation pumps within 2025. That is a minimal share of 1.57 million conventional (mainly diesel operated) irrigation pumps. After the first installation of a SIP in 2010, IDCOL has approved only 1140 solar irrigation pumps until today. At this pace, it would be difficult to achieve even the limited goal to install 50000 SIPs within 2025.

The personal consumption of SIPs is essential for the rapid replacement of conventional irrigation pumps with solar pumps. Financial indicators also reveal that a small solar irrigation pump for personal consumption is the most profitable investment option among all solar pumps. Nevertheless, a personal solar pump is not very common in Bangladesh due to its high initial cost.

6.2.2 The Perspective of the User

Information from 250 farmers under the coverage of 50 SIPs has been collected. According to the information, solar irrigation saves farmers' working hours because they do not need to bring a machine and diesel to the fields. The second advantage of solar irrigation is its consistency because it is almost free from fuel supply uncertainty and frequent breakdown. The third advantage of solar irrigation is that it is free from environmental pollution. Besides, 80% of solar irrigation users are concerned about the environmental benefit of this irrigation, and the main benefit, in their view, it is free from water contamination by diesel. Also, it is free of air and sound pollution.

On the other hand, according to the users' opinion, the problems of solar irrigation are high irrigation fees, operator's insincerity, shortage of underground pipelines, and limited sunshine in winter. Furthermore, the solutions to these problems are to reduce irrigation fees, increasing the length of the underground pipelines, and ensure proper training for the operators. Boro's current solar irrigation rate is about 3500 Tk per bigha per season, almost equal to the diesel operated irrigation rate and higher than the electricity run irrigation rate. The most typical electricity operated irrigation rate is 2500Tk per bigha per season for Boro harvest. That is why the farmers asked to reduce the solar irrigation fee for Boro harvest from 3500Tk to 3000Tk.

6.2.3 Life cycle cost analysis

Total life cycle cost (LCC) and annualized life cycle cost (ALCC) of 3 HP sola[illegible] and electrified pumping systems are calculated in this study. T[illegible] 3 HP solar pu[illegible] system's total life cycle cost is 323867 Tk, and the diesel operated pump is about 807600 Tk. In the case of the electrified pump, the cost is 236166 Tk. Moreover, the calculated ALCC for the solar, diesel and electrified pumps are 38042 Tk, 94861 Tk, and 27740 Tk, respectively. Thus, the ALCC of the solar pump is lower than the diesel pump but higher than the electrified pump. The lowest ALCC is found for electrified irrigation pump because Bangladesh Energy Regulatory Commission (BERC) fixed the lowest electricity tariff rate at 4Tk/kWh for irrigation. However, the average retail electricity tariff rate is 7.10Tk/kWh for other sectors.

Finally, the ALCC of the diesel-operated pumping system is almost 2.5 fold greater than the ALCC of the solar pumping system. Thus the farmers' irrigation cost would be reduced substantially if the solar irrigation pumps replace the diesel-operated pumps. That is why, as many as possible diesel pumps should be replaced by solar irrigation pumps.

6.2.4 Economic Feasibility

The visited solar irrigation pumps (SIPs) have been categorized into three groups according to their capacities, such as large, medium, and small SIPs. Some of the large irrigation pumps have alternative use options. Thus large SIP with the alternative provision is also considered. The economic feasibility of the SIPs has been measured in the study.

6.2.4.1 Large Solar Irrigation Pumps

The large solar irrigation pumps, without and with alternative use, were found moderately profitable. The NPVs at 6% and 9% were positive, but the values were negative at 12% interest rate. NPVs increased by more than 1,00,000 Tk due to the introduction of alternative use of solar panels. The IRR values were 10.13% and 10.54% for large SIPs without and with alternative use. Thus after the introduction of alternative use, the real return has been increased by about 0.50%. The simple payback period of the large solar irrigation pump with alternative use became 7.82 years. It found 8.10 years without any alternative use. Thus with alternative use, it would take four months less to get b[illegible]e initial installation cost.

Therefore, the large pump's financial outcome with alternative use [illegible]ore viable [illegible] the pump without any alternative use. A higher financial gain is po[illegible] introducing alternative use of SIPs. It may include delivering wa[illegible]r fish culti[illegible]holds, and hotel usages, supplying excess solar electricity to t[illegible]nal grid, etc.

6.2.4.2 Medium Solar Irrigation Pump

The financial indicators of a medium SIP have not seemed attractive. The NPVs at all interest rates were found negative, IRR was at less than 6%, and the simple payback period was more than 12 years of a medium SIP. Hence, installing a medium solar irrigation pump would not be a viable option for investment.

The leading causes of low IRR of the pump are the high installation cost, operator salary, and 20% commission on collected irrigation fees. Also, any alternative use of this pump was not found at the field level.

Though the financial analysis indicates that installing and operating a medium solar irrigation pump is not profitable, POs have installed numerous medium SIPs in visited areas. POs have installed 186 medium solar irrigation pumps in the Dinajpur and Rangpur districts.[207] They operate 186 medium solar irrigation pumps as 93 pairs of the pumps. A pair of medium solar irrigation pumps' irrigation coverage, total panel, and pump capacity is the same as a large solar irrigation pump.

However, according to the price list of IDCOL, the installation costs of a medium and a large solar irrigation pump are around 3000000 Tk and 5000000 Tk, respectively. So, a pair of medium solar irrigation pumps' installation cost is almost 6000000 Tk. However, one large solar irrigation pump's cost is around 5000000 Tk. So, the difference in the installation cost of these two options (2 medium or 1 large SIP) is more than 1000000 Tk. From this excess cost, the installers have received more than 400000 Tk as a grant (40% of total cost) and another about 400000 Tk as a soft loan (40% of total cost). Then, from these 93 pairs of medium solar irrigation pumps installation, the PO has received more than 37200000 Tk as a subsidy and other 37200000 Tk as a soft loan. Besides, the ownership of the pumps also remains in favor of the POs. Thus the price structure should be revised to save the given subsidy and soft loan from the medium SIPs. Then, it should be utilized to install the small solar irrigation pump for the farmers' consumption. Furthermore, the financial analysis also indicates that a small solar irrigation pump is the most profitable option among all types of solar pumps.

6.2.4.3 Small Solar Irrigation Pump

The outcomes of the small solar irrigation pump's financial analysis were better than the medium and large solar irrigation pumps' outcomes. The NPVs at all three interest rates

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[207] Limited, "Idcol Solar Irrigation Projects".

for a small SIP were positive. The payback period was less than 5 years, and the IRR was more than 20%. Thus the indicators of the small SIP were found attractive. So, It seems that the 'fees for ownership model' is more feasible than the 'fees for service model'. However, IDCOL, with the help of partner organizations, has installed mainly the large and medium scale SIPs and provides irrigation service to the farmers in exchange for fees. In the visited areas, only 5 small solar irrigation pumps have been found.

The total installation cost of a small solar irrigation pump (4kWp) offers by IDCOL is 676880 Tk, which will be about 406128 Tk after receiving a 40% subsidy. It still looks expensive for the individual farmer to consume it. Nevertheless, some farmers mentioned that it would be possible to reduce the solar pump's installation cost. As some provisions like underground pipelines, pacca shades are not essential for small SIPs. Besides by decreasing the panel and pump capacity, a personal solar irrigation pump's total price can be reduced. For example, a personal solar pump with 2.50 kWp panels and 1.2 kW pump can provide irrigation facilities to 10 bigha land for Boro cultivation. The market price of this type of small solar pump is about 200000 Tk.

At present, the solar panel's market price is 40-50 Tk/W. Nevertheless, the price list of IDCOL shows that the solar panel's cost is about 60Tk /W. Thus, by updating the small solar irrigation pump's price structure, small SIP's cost can be reduced to around 200000 Tk. After a 40% subsidy on this price, it would be an attractive investment option for farmers. It would also increase the acceptability and the adoption possibility of the small pump.

6.2.5 Impact on Output

It is found that the impact of solar irrigation on Boro output is notable. Boro output has been significantly increased by more than 25kg per bigha (50 decimal) due to solar irrigation. In the Amon harvest, the difference in output before and after introducing solar irrigation has also been significant. However, in the case of potato, corn, and other crops, the difference in outputs using these two irrigation options has not been significant. The causes of the significant increase in Boro and Amon's outputs are the availability and uninterrupted irrigation through solar irrigation. That is why a solar irrigation pump should be installed in the places where Boro is cultivated.

6.2.6 Logistic Regression Model

A binary logistic regression model proposed by A. Jain and T. Shahidi has been introduced in this study to measure the effect of relevant variables for solar pump adoption decisions. According to the outcome of the model, the variables such as 'education', 'size of operational landholding', 'investment plan for renting', 'loan for agricultural investment' and 'view on solar irrigation pump' have a significant favorable influence on the solar irrigation pump adoption decision. On the other hand, 'age' and 'farmers satisfaction with present irrigation setting' significantly negatively influence solar pump adoption decisions. Other variables of the model like 'number of land parcels', 'cropping intensity', and 'groundwater depth' have no significant effect on a solar pump adoption decision.

So the proper circulation about the positive impact of SIP on output and environment with an attractive price structure would help disseminate the pump at the root level as 'view on solar irrigation pump' have a significant favorable influence on the solar irrigation pump adoption decision.

6.2.7 Environmental benefit

IDCOL provides 40% of the solar irrigation pump's total price as a subsidy. The amount of subsidy will be justified if the amount would be equal or greater than the solar pump's net environmental benefit in 20 years. The net environmental benefit of solar irrigation pumps has been found almost equal to the given amount of subsidy in this study. Thus the given subsidies have been justified for the investments in solar pumps.

The net environmental benefit per kWp of the large and medium solar irrigation pumps is about 6500 Tk. However, the small solar irrigation pump's net environmental benefit per kWp is more than 8500 Tk. So, the calculated net environmental benefit per kWp of small SIP has become the highest among the three types of SIPs. If the government provides more subsidies (more than 40% of the total price) on the small solar pumps' prices, it will help the pump's mass adoption shortly. In that case, many farmers would be interested in installing it and get the maximum benefit from the new environmentally friendly option for irrigation.

6.3 Policy Implications

Solar irrigation pumps have a great potentiality to supply water for irrigation, especially in off-grid areas. Thus it would solve the irrigation problems such as high price and unstable supply of diesel and frequent load shading of the electricity, and environmental pollution from fossil fuel. Besides, solar irrigation pumps will help achieve the government's goal to generate 10% of total electricity from renewable energy within 2020. However, the current dissemination rate of this potential irrigation option is not at a satisfactory level. Nevertheless, continuous research and development reduce solar panels' price gradually. As a result, the total investment cost of a SIP is decreasing rapidly. Moreover, almost all of the components of SIP are now being produced in Bangladesh. It helps to reduce the pump's price in the local market. Based on the findings of this research, some policies can be implicated. Hence the policymakers, government, and non-government authorities may take necessary actions to accelerate the adoption rate of SIPs at the root level. The specific policies are as follows:

01. *Replace as many as possible diesel pump with solar pumps*

The calculated ALCC of a small diesel-operated pump is almost 2.5 fold higher than a small solar pump. Thus the farmers' irrigation cost would be reduced substantially if the solar irrigation pumps replace the diesel-operated pumps.

02. *Promote personal pump*

Financial indicators reveal that a small solar irrigation pump for personal consumption is the most profitable investment option among different solar pumps. The personal solar pumps' dissemination is essential for the rapid replacement of conventional irrigation pumps with solar pumps. Nevertheless, this is not yet very common in Bangladesh due to the pumps' high initial cost. In this regard, the government, the donors, and the policymakers should make small solar irrigation pumps available at the root level at an affordable price for the farmers' consumption.

03. *Introduce alternative use*

The SIPs' financial gain would be improved by introducing alternative uses because over half of the year, irrigation is unnecessary. This study found that the financial indicators of large SIP's have improved due to the introduction of alternative use. Thus the alternative uses of solar energy such as operating small farm machines, delivering water for fish cultivation, household, hotel usages, and supplying excess solar electricity to the national grid would provide an incentive in favor of this investment.

04. *Solar pumps' cost should be revised*

The solar pump cost should be revised regularly; especially, the panel price should be adjusted with the market price. Otherwise, the partner organizations (POs) would get benefit from the subsidy on over price. As, at present, POs mainly deploy solar pumps in the country. The panel's current market price is about 40-50 Tk/W. However, the panel price shows about 60Tk/W in the solar irrigation pump's installation cost list of IDCOL.

05. *Proportional price structure*

Solar irrigation pumps' price should be proportional to their capacity. IDCOL's price list of solar irrigation pumps shows that 15 kWp solar pump's price is about 3000000 Taka, but 30 kWp pump's price is about 5000000 Taka. The price differences between medium and large solar irrigation pumps encourage the POs to install 2 medium-sized pumps then marge, and operate them as a large pump. Thus they have received a considerable amount of money as grants and loans. This grant and loan should be given to install small solar irrigation pumps for the farmers' personal consumption. The financial analysis indicates that the small solar irrigation pump is the most profitable investment option for solar irrigation.

06. *Area for SIP installation*

Boro output has been significantly increased by more than 25 kg per bigha (50 decimal) due to solar irrigation. Therefore, installing a solar irrigation pump where Boro is cultivated would be the first preference.

07. *Circulation about SIPs*

Proper circulation about the SIP's positive impact on output and environment with an attractive price structure would help the pumps rapidly disseminate. As 'view on solar irrigation pump' has a significant influence on the solar irrigation pump adoption decision.

08. *Environmental benefit justifies the subsidy*

The calculated net environmental benefit of a solar pump is greater or equal to the given subsidy to install it. Besides, the net environmental benefit per kWp of small SIP is the highest among all types of SIPs. The government should continue to give subsidies in this sector, especially in small solar irrigation pumps.

6.4 Limitations of this Study

The present study is mainly based on primary data. The required data are collected from field surveys in the Rajshahi region of Bangladesh. So it cannot be said that the study is free from the problem. There are some limitations to the study, which need to be mentioned.

01. The updated information about the cost of the solar irrigation pump is not available on the website of the IDCOL or POs. The authorities also were reluctant to share the detailed cost information of the solar pump. So the study could not use up to date data about the solar pump's cost.

02. The information about the revenue of the pump has been collected from the field survey. Many variations have been found in the revenue of the same type of irrigation pumps. For simplicity, the maximum potential revenue from the pump's coverage area has been considered.

03. The installation cost and the economic feasibility depend on the pump's price, especially on the panel's price. For continuous research and development, the price of the panel is reducing day by day. Thus the economic feasibility may change in the recent future.

04. The study did not investigate the SIPs' impact on the groundwater level in detail. Because the farmers are using the pump only for 2 to 4 years, the farmers do not observe any impact on the groundwater levels in this short period. They mentioned that they are concerned about the groundwater level and always provide the necessary water for their cultivation. However, further research would require investigating the impact of the pump on the groundwater level and the farmers' livelihood in the long run.

Finally, this study's findings related to the SIPs economic viability and environmental impact will be applicable to greater Rajshahi region of Bangladesh. Making any conclusion about the pumps' viability for other parts of the country needs caution.

BIBLIOGRAPHY

Boooks

Boxwell, Michael. *Solar Electricity Handbook.* 7th ed. London: Greenstream Publishing 2013.

Bradford, Travis. *Solar Revolution.* United State: The MIT Press, 2006.

Kothari, Chakravanti Rajagopalachari. *Research Methodology : Methods and Techniques.* 2nd ed. New Delhi: New Age International, 2004.

Greiner, Alfred, and Willi Semmler. *The Golbal Environment, Natural Resources and Economic Growth.* New York: Oxford University Press, 2008.

Articles

Agrawal, Shalu and Abhishek Jain. "Sustainable Deployment of Solar Irrigation Pumps: Key Determinants and Strategies." *WENE Wiley Interdisciplinary Reviews: Energy and Environment* 8, no. 2 (2019).

Al-Masum, R. F., M. A. Ashraf and M. T. Islam. "Environmental Contamination by Co2 Emission through Irrigation Pump " *Bangladesh Journal of Environmental Science* 32 (2017): 204-207.

Ali, Bakir. "Comparative Assessment of the Feasibility for Solar Irrigation Pumps in Sudan." *Renewable and Sustainable Energy Reviews* 81, (2018): 413-420.

Arkin, Herbert and Raymond R Colton. "Tables for Statisticians. Barnes and Noble." *Inc., New York*, (1963).

Chakrabarty, Sayan, and Tawhidul Islam. "Financial Viability and Eco-Efficiency of the Solar Home Systems (Shs) in Bangladesh." *Energy* 36 no. 8 (2011): 4821-27.

Bassi, Nitin. "Irrigation and Energy Nexus: Solar Pumps Are Not Viable." *Economic and political weekly* 50, no. 10 (2015): 63-66.

Burney, Jennifer, Lennart Woltering, Marshall Burke, Rosamond Naylor, Dov Pasternak and Prabhu Pingali. "Solar-Powered Drip Irrigation Enhances Food Security in the

Sudano-Sahel." *procnatiacadscie Proceedings of the National Academy of Sciences of the United States of America* 107, no. 5 (2010): 1848-1853.

Closas, Alvar and Edwin Rap. "Solar-Based Groundwater Pumping for Irrigation: Sustainability, Policies, and Limitations." *Energy policy* 104, (2017): 33-37.

Fisher, Ronald A, A Steven Corbet and Carrington B Williams. "The Relation between the Number of Species and the Number of Individuals in a Random Sample of an Animal Population." *The Journal of Animal Ecology*, (1943): 42-58.

Foster, RE, D Alma, MPRoss and OM Avilez. "Ten-Year Reliability Assessment of Photovoltaic Water Pumping Systems in Mexico." *American Solar Energy Society*, no. 1 (2004): 9-14.

Hamidat, A., B. Benyoucef and T. Hartani. "Small-Scale Irrigation with Photovoltaic Water Pumping System in Sahara Regions." *RENE</cja:jid> Renewable Energy* 28, no. 7 (2003): 1081-1096.

Hammad, Mahmoud and Munzer S. Y. Ebaid. "Comparative Economic Viability and Environmental Impact of Pv, Diesel and Grid Systems for Large Underground Water Pumping Application (55 Wells) in Jordan." *Renewables: Wind, Water, and Solar* 2, no. 1 (2015).

Honrao, PM. "Economic Viability of Solar Irrigation Pumps for Sustainable Agriculture in Maharashtra: Adoption Response by Farmers. ." *Global Journal for Research Analysis* 4, no. 8 (2015).

Hoque, Najmul, Amit Roy, Mohd. Rafiqul Alam Beg and B. K. Das. "Techno-Economic Evaluation of Solar Irrigation Plants Installed in Bangladesh." *Int. Journal of Renewable Energy Development* 5 no. 1 (2016): 73-78.

Hossain, M. A., M. S. Hassan, M. A. Mottalib and M. Hossain. "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh." *Int J Energy Environ Eng* 6, (2015): 147–155.

Hossain, M. Ayub, M. Shoeb Hassan, M. Abdul Mottalib and Sultan Ahmmed. "Technical and Economic Feasibility of Solar Pump Irrigations for Eco-Friendly Environment." *Procedia Engineering* 105, (2015): 670-678.

Hossain, MA, MS Hassan, MA Mottalib and M Hossain. "Feasibility of Solar Pump for Sustainable Irrigation in Bangladesh." *International Journal of Energy and Environmental Engineering* 6, no. 2 (2015): 147-155.

Islam, M., Md Rabiul Islam and M. Beg. "Renewable Energy Resources and Technologies Practice in Bangladesh." *Renewable and Sustainable Energy Reviews,* (2008): 299-343.

Islam, M. R., Y. Guo and J. Zhu. "A Multilevel Medium-Voltage Inverter for Step-up-Transformer-Less Grid Connection of Photovoltaic Power Plants." *IEEE JOURNAL OF PHOTOVOLTAICS* 4, no. 3 (2014): 881-889.

Islam, M. R., M. R. Islam and MRA Beg. "Renewable Energy Resources and Technologies Practice in Bangladesh." *Renewable and Sustainable Energy Reviews* 12, no. 2 (2008): 299-343.

Islam, Md Rabiul, Youguang Guo and Jianguo Zhu. "A Review of Offshore Wind Turbine Nacelle: Technical Challenges, and Research and Developmental Trends." *Renewable and Sustainable Energy Reviews* 33, (2014): 161–176.

Islam, Md Rabiul, Pejush Chandra Sarker and Subarto Kumar Ghosh. "Prospect and Advancement of Solar Irrigation in Bangladesh: A Review." *Renewable and Sustainable Energy Reviews* 77, (2017): 406-422.

Jain, Abhishek and Tauseef Shahidi. *Adopting Solar for Irrigation: Farmers' Perspectives from Uttar Pradesh*. Council on Energy, Environment and Water (CEEW), India, 2018.

Keith, David W, Geoffrey Holmes, David St Angelo and Kenton Heidel. "A Process for Capturing Co2 from the Atmosphere." *Joule* 2, no. 8 (2018): 1573-1594.

Kelley, Leah C., Eric Gilbertson, Anwar Sheikh, Steven D. Eppinger and Steven Dubowsky. "On the Feasibility of Solar-Powered Irrigation." *Renewable and Sustainable Energy Reviews* 14, no. 9 (2010): 2669-2682.

Kumar, A. and T. Kandpal. "Renewable Energy Technologies for Irrigation Water Pumping in India: A Preliminary Attempt Towards Potential Estimation." *Energy Energy* 32, no. 5 (2007): 861-870.

Lipu, M. S. H and T. Jamal. "Techno-Economic Analysis of Solar Concentrating Power (Csp) in Bangladesh." *International Journal of Advanced Renewable Energy Researches (IJARER)* 2, no. 5 (2013): 3.

Mahmoud, Elham and Hoseen el Nather. "Renewable Energy and Sustainable Developments in Egypt: Photovoltaic Water Pumping in Remote Areas." *APEN</cja:jid> Applied Energy* 74, no. 1 (2003): 141-147.

Mahtab, Sania Binte and Abrar Morshed. "Achievements of a Pilot Solar Powered Irrigation Project in Bangladesh." *International Advanced Research Journal in Science, Engineering and Technology* 5, no. 9 (2018).

McDermott, Maura and James E. Horne. "The Next Green Revolution : Essential Steps to a Healthy, Sustainable Agriculture." *Food Products Press, New York* (2001): 226.

Meah, Kala, Sadrul Ula and Steven Barrett. "Solar Photovoltaic Water Pumping Opportunities and Challenges." *RSER Renewable and Sustainable Energy Reviews* 12, no. 4 (2008): 1162-1175.

Mekhilef, S., S.Z. Faramarzi, R. Saidur and Zainal Salam. "The Application of Solar Technologies for Sustainable Development of Agricultural Sector." *Renewable and Sustainable Energy Reviews* 18, (2013): 583-594.

Mérida García, A., J. Gallagher, A. McNabola, E. Camacho Poyato, P. Montesinos Barrios and J. A. Rodríguez Díaz. "Comparing the Environmental and Economic Impacts of on- or Off-Grid Solar Photovoltaics with Traditional Energy Sources for Rural Irrigation Systems." *Renewable Energy* 140, (2019): 895-904.

Mohammed Wazed, Saeed, Ben Richard Hughes, Dominic O'Connor and John Kaiser Calautit. "A Review of Sustainable Solar Irrigation Systems for Sub-Saharan Africa." *Renewable and Sustainable Energy Reviews* 81, (2018): 1206-1225.

Narale, PD, NS Rathore and S Kothari. "Study of Solar Pv Water Pumping System for Irrigation of Horticulture Crops." *International Journal of Engineering Science Invention* 2, no. 12 (2013): 54-60.

Niajalili, Mehdi, Peyman Mayeli, Mohammad Naghashzadegan and Amin Haghighi Poshtiri. "Techno-Economic Feasibility of Off-Grid Solar Irrigation for a Rice Paddy in Guilan Province in Iran: A Case Study." *Solar Energy* 150, (2017): 546-557.

Nikzad, Amirhossein, Mahmood Chahartaghi and Mohammad Hossein Ahmadi. "Technical, Economic, and Environmental Modeling of Solar Water Pump for Irrigation of Rice in Mazandaran Province in Iran: A Case Study." *Journal of Cleaner Production* 239, (2019): 118007.

Odeh, I., Y. G. Yohanis and B. Norton. "Economic Viability of Photovoltaic Water Pumping Systems.". *SE Solar Energy* 80, no. 7 (2006): 850-860.

Omer, Abdeen Mustafa. "Solar Water Pumping Clean Water for Sudan Rural Areas." *Renewable Energy* 24, no. 2 (2001): 245-258.

Osma-Pinto, German and Gabriel Ordóñez-Plata. "Measuring the Effect of Forced Irrigation on the Front Surface of Pv Panels for Warm Tropical Conditions." *Energy Reports* 5, (2019): 501-514.

Ould-Amrouche, S., D. Rekioua and A. Hamidat. "Modelling Photovoltaic Water Pumping Systems and Evaluation of Their Co2 Emissions Mitigation Potential." *Applied Energy* 87, no. 11 (2010): 3451-3459.

Pande, P. C., A. K. Singh, S. Ansari, S. K. Vyas and B. K. Dave. "Design Development and Testing of a Solar Pv Pump Based Drip System for Orchards." *Renewable energy.* 28, no. 3 (2003): 385-396.

Parajuli, Ranjan, Govind Raj Pokharel and Poul Alberg Østergaard. "A Comparison of Diesel, Biodiesel and Solar Pv-Based Water Pumping Systems in the Context of Rural Nepal." *International Journal of Sustainable Energy* 33, no. 3 (2014): 536-553.

Parvaresh Rizi, Atefeh, Afshin Ashrafzadeh and Azita Ramezani. "A Financial Comparative Study of Solar and Regular Irrigation Pumps: Case Studies in Eastern and Southern Iran." *Renewable Energy* 138, (2019): 1096-1103.

Powell, J. W., J. M. Welsh and R. Farquharson. "Investment Analysis of Solar Energy in a Hybrid Diesel Irrigation Pumping System in New South Wales, Australia." *Journal of Cleaner Production* 224, (2019): 444-454.

Purohit, P and TC Kandpal. "Solar Photovoltaic Water Pumping in India: A Financial Evaluation " *Int J Ambient Energy* 26, (2011): 135–46.

Radulovic, Verena. "Are New Institutional Economics Enough? Promoting Photovoltaics in India's Agricultural Sector." *Energy Policy* 33, (2005): 1883-1899.

Rahman, M. Wakilur and Lovely Parvin. "Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades " *J. Water Resource and Protection* 3, (2009): 216-225.

Rathore, Pushpendra Kumar Singh, Shyam Sunder Das and Durg Singh Chauhan. "Perspectives of Solar Photovoltaic Water Pumping for Irrigation in India." *Energy Strategy Reviews* 22, (2018): 385-395.

Roblin, Stéphanie. "Solar-Powered Irrigation: A Solution to Water Management in Agriculture?" *Renewable Energy Focus* 17, no. 5 (2016): 205-206.

Roy, Dr. Kshirode C. "History of Irrigation Development in Bangladesh." *Daily Sun*2020.

Sarkar, Md Nazmul Islam and Himanghshu Ranjan Ghosh. "Techno-Economic Analysis and Challenges of Solar Powered Pumps Dissemination in Bangladesh." *Sustainable Energy Technologies and Assessments* 20, (2017): 33-46.

Shinde, V. B. and S. S. Wandre. "Solar Photovoltaic Water Pumping System for Irrigation: A Review." *Afr. J. Agric. Res. African Journal of Agricultural Research* 10, no. 22 (2015): 2267-2273.

Smith, Peter G and Richard H Morrow. *Methods for Field Trials of Interventions against Tropical Diseases: A" Toolbox"*: Oxford University Press Oxford, 1991.

Surendra, TS and SVV Subbaraman. "Solar Pv Water Pumping Comes of Age in India." In *The twenty-ninth IEE photo-voltaic specialists conference*, 1485–88, 2002.

Tanvir, Rahamat Ullah, Muhammad Rubayat Bin Shahadat, Manoj Ghosh and Mohammed Khan. "Prospects and Utilization of Renewable Energy in Bangladesh: A Review Article " *International Journal of Scientific & Engineering Research* 8, no. 4 (2017).

Uddin, M. N., M. A. Rahman, M. Mofijur, J. Taweekun, K. Techato and M. G. Rasul. "Renewable Energy in Bangladesh: Status and Prospects." *EGYPRO Energy Procedia* 160, (2019): 655-661.

Wakeyo, Mekonnen B. and Cornelis Gardebroek. "Share of Irrigated Land and Farm Size in Rainwater Harvesting Irrigation in Ethiopia." *Journal of arid environments* 139, (2017): 85-94.

Wazed, Saeed Mohammed, Ben Richard Hughes, Dominic O'Connor and John Kaiser Calautit. "Solar Driven Irrigation Systems for Remote Rural Farms." *Energy Procedia* 142, (2017): 184-191.

Williams, Daniel E, Dennis M Obeng, Kwaw Anaman and Fred O Akuffo. "Tests on Photovoltaic Radial Centrifugal Pump Systems." *Renewable Energy Transforming Business*, (2008): 402–13.

Xu, He, Jiahong Liu, Dayong Qin, Xuerui Gao and Jinyue Yan. "Feasibility Analysis of Solar Irrigation System for Pastures Conservation in a Demonstration Area in Inner Mongolia." *Applied Energy* 112, (2013): 697-702.

You, Liangzhi, Claudia Ringler, Ulrike Wood-Sichra, Richard Robertson, Stanley Wood, Tingju Zhu, Gerald Nelson, Zhe Guo and Yan Sun. "What Is the Irrigation Potential for Africa? A Combined Biophysical and Socioeconomic Approach." *Food Policy* 36, no. 6 (2011): 770-782.

Yu, Yingdong, Jiahong Liu, Hao Wang and Miao Liu. "Assess the Potential of Solar Irrigation Systems for Sustaining Pasture Lands in Arid Regions – a Case Study in Northwestern China." *Applied Energy* 88, no. 9 (2011): 3176-3182.

Yu, Yingdong, Jiahong Liu, Ying Wang, Chenyao Xiang and Jinjun Zhou. "The Feasibility of Solar Water Pumping System for Cassava Irrigation in Guangxi Autonomous Region, China." *Energy Procedia* 142, (2017): 447-454.

Yu, Yingdong, Jiahong Liu, Ying Wang, Chenyao Xiang and Jinjun Zhou. "Practicality of Using Solar Energy for Cassava Irrigation in the Guangxi Autonomous Region, China." *Applied Energy* 230, (2018): 31-41.

Thesis

Bengtsson, Niclas, and Johan Nilsson. "Solar Water Pumping for Irrigation: Case Study of the Kilimanjaro Region in Tanzania." Bachelor Thesis, Halmstad University, 2015.

Dev, Joydip Kumar. "Assessment of Potential Environmental Benefits of Using Solar Power for Irrigation Pump in Bangladesh." Bangladesh University of Engineering and Technology, 2014.

Hakim, Md. Azizul. "Project on Study of Solar Based Irrigation System in Bangladesh." master's project, Daffodil International University, 2014.

Report

"Annual Report (2017-18)", Power Division, Government of the Peoples Republic of Bangladesh https://powerdivision.gov.bd/site/view/annual_reports (accessed 28th January 2020).

(DESA), Annual Report of Dhaka Electric Supply Authority. 2012.

(FAO), Food and Agriculture Organization. The State of the World's Land and Water Resources for Food and Agriculture—Managing Systems at Risk Rome, Italy, 2011.

Hoffman, Allan, "Water, Energy, and Environment", IWA Publishing http://www.oapen.org/download?type=document&docid=1004280.

Matabadal, Ashwin. Country Report : Bangladesh. Rabobank Netherland, 2011.

Matabadal, Ashwin, Rabobank Nederland Country Report : Bangladesh.Nederland, 2011

"Utilization and Conservation of Water Resources in Bangladesh", Agricultural and Forestry Research Center, University of Tsukuba http://hdl.handle.net/2241/98644.

Document

Bangladesh Bureau of Statistics, *National Accounts Statistics*. Dhaka, 2016.

BBS. National Accounts Statistics, 2016. Vol. 19.

Bangladesh Bureau of Statistics, National Accounts Statistics. Dhaka, 2016.

Biddut Sorborah Karjokrom, Sech Moushum (2017), BBS, 2017.

Hossain, Mahabub, Abdul Bayes, and SM Fakhrul Islam, BRAC, *A Diagnostic Study on Bangladesh Agriculture*.Dhaka, 2015.

National Accounts Statistics, 2016. Vol. 19.

Ramboll. Gas Sector Master Plan Bangladesh, Petrobangla, 2018.

Statistics, Bangladesh Bureau of. Statistical Yearbook of Bangladesh, 2010.

Summary of Daily Electricity Generation, 2013.

Encyclopedia

"Irrigation." In *Banglapedia : National Encyclopedia of Bangladesh*. 1 vols. Dhaka: Asiatic Society of Bangladesh, 2003.

Magazine Article

"Encouraging Growth of Solar Home System in Bangladesh." *F[illegible]ancial Express*. [illegible] July, 2017.

Roy, Dr. Kshirode C. "History of Irrigation Development in Banglades[illegible] *Sun*2020.

Web page

Bangladesh, Banglapedia: National Encyclopedia of, "Badarganj Upazila" http://en. banglapedia.org/index.php?title=Badarganj_Upazila (accessed 10th March 2020).

Bangladesh, Banglapedia: National Encyclopedia of, "Birganj Upazila" http://en. banglapedia.org/index.php?title=Birganj_Upazila (accessed 10th January 2020).

Bangladesh, Banglapedia: National Encyclopedia of, "Irrigation" http://en.banglapedia. org/index.php?title=Irrigation (accessed 11 January 2020).

Bangladesh, Banglapedia: National Encyclopedia of, "Nandigram Upazila" http://en. banglapedia.org/index.php?title=Nandigram_Upazila (accessed 10th March 2020).

BPDB, "Government of the Peoples Republic of the Bangladesh", Power Division http://www.powerdivision.gov.bd (accessed May 12 2017).

Commission, Bangladesh Energy Regulatory, "Berc Electricity Tariff Order (Retail)" http://www.berc.org.bd/site/notices/999da7ce-b204-4bcc-987c-49678efa9983/BERC-Electricity-Tariff-Order-Retail- (accessed 20 January 2020).

Corporation, Bangladesh Agricultural Development, "Organization Wise Summary of Irrigation Equipment Used, Area Irrigated and Benefited Farmers" http://www.badc.gov.bd (accessed 13 December 2017).

Corporation, Bangladesh Agricultural Development, "Organization Wise Summary of Irrigation Equipment Used, Area Irrigated and Benefited Farmers" http://www.badc.gov.bd (accessed 10th January 2020).

Dey, Nepal Chandra, Sujit Kumar Bala, AKM Saiful Islam and Md. Abdur Rashid, "Sustainability of Groundwater Use for Irrigation in Northwest Bangladesh ", National Food Policy Capacity Strengthening Programme http://fpmu.gov. bd/agridrupal/sites/default/files/ToR-2.pdf (accessed 22 January 2020).

Division, Power, "Renewable Energy Policy of Bangladesh", Ministry of Power, Energy and Mineral Resources, Government of the People's Republic of Bangladesh http://www.powerdivision.portal.gov.bd (accessed 15 March 2018).

Exchange, Sustainability, "How Much Energy Do You Use" https://www.sustainability exchange.ac.uk/files/cambridge_regional_college_sus_how_much_energy_do_you _use_pdf.pdf (accessed 8 February 2020).

(GIZ), Gesellschaft für Internationale Zusammenarbeit, "Solar Powered Irrigation Systems (Spis) – Technology, Economy, Impacts" https://energypedia.info/images/temp/2/23/20160630122544.pdf (accessed 18th June 2018).

Greenmatch, "Pros and Cons of Solar Energy" https://www.greenmatch.co.uk/blog/2014 /08/5-advantages-and-5-disadvantages-of-solar-energy (accessed 25 Nov 2018).

Irrigation, Easy, "A History of Agricultural Irrigation" https://www.easy-irrigation.co.uk /a-history-of-agricultural-page-29?zenid=cl7ols72vlqo0bftksd6n74a87 (accessed 2020 10th January).

Limited, Infrastructure Development Company, "Idcol Plans to Develop Solar Irrigation Pump" http://www.idcol.org/home/solar (accessed 10 October 2017).

Limited, Infrastructure Development Company, "Idcol Solar Irrigation Projects" https:// www.icimod.org/resource/17186 (accessed 20 August 2017).

Limited, Infrastructure Development Company, idcol.org/download/d4f1914587cceeede 6d652df124ea7e1.docx (accessed 20 October 2017).

Limited, Vatio Energy India Private, http://vatioenergy.com/solarwaterpumping.html (accessed 22 October 2017).

Limited, Infrastructure Development Company, "Idcol Solar Irrigation Projects" https://www.icimod.org/resource/17186 (accessed 20 August 2017).

Ministry of Power, Energy and Mineral Resource, Government of the Peoples Republic of Bangladesh, "Renewable Energy Policy of Bangladesh" http://pv-expo.net/BD/Renewable_Energy_Policy.pdf (accessed 6 Nov 2018).

Ministry of Power, Energy and Mineral Resources, Government of the People's Republic of Bangladesh, "500 Mw Solar Programme" http://www.powerdivision.portal.gov.bd (accessed 23 October 2017).

Nation, United, "World Population Prospects 2019", Department of Economic and Social Affairs https://population.un.org/wpp/Download/Standard/Population/ (accessed 10 January 2020).

(POST), Parliamentary Office of Science and Technology, "Carbon Footprint of Electricity Generation. " https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf (accessed 20th June 2019).

Petrobangla, Government of the People's Republic of Bangladesh, "Reserve of Natural Gas in Bangladesh.", Ministry of power, Energy and Mineral resources. Reserve of natural gas in Bangladesh http://www.petrobangla.org.bd (accessed 18th March 2019).

Rahman, Farzana, "Idcol Solar Irrigation Projects - Icimod" www.icimod.org/resource/17186 (accessed October 20 2017).

"Renewable Energy " https://www.studentenergy.org/topics/renewable-energy#reference-1 (accessed 12 March 2020).

Review, World Population, "Bangladesh Population" https://worldpopulationreview.com/countries/bangladesh-population/ (accessed 9th Januaury 2020).

Roberta Q., "Guidelines for National Greenhouse Gas Inventories,Volume-2, Energy", International Panel on Climate Change, IPCC http://www.ipcc-nggpip.iges,or.jp/public/2006gl/vol2.html (accessed 10th May 2020).

Schnetzet, J. and L. Pluschke, " Solar-Powered Irrigation Systems: A Clean-Energy, Low-Emission Option for Irrigation Development and Modernization", Food and agriculture organization of the United Nations, http://www.fao.org/3/a-bt437e.pdf. (accessed 12th April 2018).

Shuba, V.R., A. Bharadwaj, A.A. Thatte, S. Harish, K.K. Iychettira, R. Perumal and G. Nayak, "Harnessing Solar Energy: Options for India, " Center for Study of Science, Technology and Policy, Bangalore http://shaktifoundation.in/wp-content/uploads/2014/02/cstep-harnessing%20solar%20energy%20-%20final%20report.pdf (accessed 20th February 2018).

(SREDA), Sustainable and Renewable Energy Development Authority, "Electricity Installed from Renewable Energy", Power Division, Ministry of Power, Energy and Mineral Resources, Government of the Peoples Republic of Bangladesh http://www.sreda.gov.bd/index.php/re_master_pdf (accessed 15th February 2020).

Tahir, Z. and Z. Habib, "Land and Water Productivity: Trends across Punjab Canal Commands", International Water Management Institute http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR14.pdf (accessed 5th June 2019).

Unit, Hydrocarbon, "Energy Scenario: Bangladesh ", Ministry of Power, Energy and Mineral Resources http://hcu.portal.gov.bd (accessed 05 Februar[illegible]).

Appendices

Appendix A: Questionnaire on Economic Feasibility and Environmental Impact of Solar Irrigation Pumps in Rajshahi Region of Bangladesh

Questionnaire for solar irrigation User

Module 1- Information on respondent (Socio-economic Information)

1.1 Name:	Upazila:
Village:	District:
Union:	Mobile No.:

1.2 Gender of farmer: (i) Male (ii) Female

1.3 Age of farmer: .... Years

1.4 Education (years of schooling): .... Years

1.5 Occupation: (i) Main occupation: .... (ii) Secondary occupation: ....

1.6 Farming experience: ....years

1.7 Total family members: Total: .... Male: .... Female: ....

1.8 Number of earners in your family: ....

1.9 Number of family member engaged in agriculture: ....

1.10 Loan for agriculture.................

1.11 View on climatic variations:

1.12 Yearly Income:

Sectors	Output (Mon)	Price (Taka/Mon)	Revenue	Production Cost	Net Income
Agriculture	....	....	....	....	....
Service/Remittance/Wage, etc.					
Total Income					

Module 2: Information about solar irrigation pump (SIP) users

2.1 Total Land: (1 bigha=........................decimal)

2.2 Land under solar irrigation pump: .... in bigha

2.3 How many years do you use solar irrigation pump? .... year ....months

2.4 If not having all land under solar irrigation, mention the reasons: ....

2.5 Land division (number of land parcels) and cropping intensity:

	Number of land parcels	Cropping intensity
Total cultivable land		

2.6 Detail cost of solar irrigation **Own pump □ or Purchase water □**

Sl No	Name of crop	Total land	Months of Cultivation	No. of irrigation	Rate of solar irrigation	Cost of solar irrigation
	....	....	....	....	....	....
	....	....	....	....	....	....
	Calculated irrigation cost /bigha/year					

2.7 Detail yearly output from solar irrigation and prior diesel irrigation:

Serial No	Name of crop	Total land	Cultivation time (month)	Output from solar irrigation (Mon)	Prior output from Diesel irrigation
	....	....	....	....	....
	....	....	....	....	....
	Calculated total output from a bigha/year				

2.8 If output increases in solar irrigated land, the reason of this increasing: ....

2.9 Please compare the service of solar irrigation with diesel operated irrigation ....

2.9a If solar irrigation is better, how much is it? ....

2.9b What aspect of solar irrigation is better now? ....

2.9c If solar irrigation is worse, why? ....

2.10 Do you pay the irrigation fees every year? ....

2.10a If yes, how many times in a year? ....

2.10b If no, how often do you pay the irrigation charge?......

2.11 How many days solar irrigation pump generally serves for irrigation in a year?

2.12 Have the solar panels any alternative use when it is not used for irrigation? ....

2.12a If yes, what type of alternative use? ....

2.12b If no, what type of alternative use would be useful for solar panels? ....

2.13 Do you concern about the environmental benefit of the SIP? ....

2.13a If yes, what type of environmental benefit? ....

2.14 Overall how satisfied are you with solar irrigation service? ....

2.15 Would you support further initiatives to expand SIP projects in your area? ....

2.16 How the SIP is installed and managed in your area? ....

2.17 If you asked to provide 4 to 8 decimal land for the installation of SIP, will you agree? ....

2.17a If yes, why...

2.17b If no, why..

2.18 Do you face any problem with solar irrigation service? ....

2.18a what would be the possible solution of the problems? ....

2.19 Do you have any suggestion about the efficient management of the solar irrigation pump?......

2.20 Do you have any suggestion about the land arrangement for the installation of the SIP? .....

Module 3-Detail information related to diesel irrigation from SIP users (Who owned diesel machine)

3.1 Did you have your own diesel machine ? ....

3.2 How many days (app.) did you use the machine for irrigation in a year?....................

3.3 What was the (app.) capacity of the diesel machine? .... bigha for boro cultivation and .... bigha for other crops in a year.

3.4 Mention the total **yearly cost** (installment & running) of the diesel machine

SL	Particular	Amount (Tk)	Guaranty (Years)
	....	....	....
	....	....	....
	Previous yearly expenditure of diesel irrigation (app.)	.... Tk	

3.5 Mention the **yearly revenue** of the diesel machine.....................

Particular	Amount
Total irrigated land (bigha)	
Rental income (if any) (Tk.)	
Income from alternative use (if any)* (Tk.)	
Others (Income)..	
Total	

*Alternative use: husking/threshing/grinding crops, driving vehicle, driving boat, catching fish, filling pond etc.

3.6 Problems with diesel machine irrigation? ....

3.7 Environmental problem with diesel irrigation machine? ....

3.8 How satisfied were you with diesel machine irrigation? ....

Thank you for your given time and patience.

Questionnaire for solar irrigation Non-user

Module 1- Information on respondent (Socio-economic Information)

1.1 Name:	Upazila:
Village:	District:
Union:	Mobile No.:

1.2 Gender of farmer: (i) Male (ii) Female

1.3 Age of farmer: .... Years

1.4 Education (years of schooling): .... Years

1.5 Occupation: (i) Main occupation: .... (ii) Secondary occupation: ....

1.6 Farming experience: ....years

1.7 Total family members: Total: .... Male: .... Female: ....

1.8 Number of earners in your family: ....

1.9 Number of family member engaged in agriculture: ....

1.10 Loan for agriculture................

1.11 View on climatic variations: ....

1.12 Yearly Income:

Sectors	Output (Mon)	Price (Taka/Mon)	Revenue	Production Cost	Net Income
Agriculture	....	....	....	....	....
Service/Remittance/Wage, etc.					
Total Income					

Module 2- Information about solar irrigation pump (SIP) non-user

2.1 Total land: (1 bigha =........................decimal)

2.2 Land division (number of land parcels) and cropping intensity of total cultivable land:

	Number of land parcels	Cropping intensity
Total cultivable land		

2.3 Detail yearly cost of (**diesel □ or electricity □**) irrigation: **Own machine □ or Purchase water □**

Sl No	Name of crop	Total land	Cultivation time (month)	No. of irrigation	Rate of irrigation	Cost of irrigation	Required amount of diesel	Required amount of electricity
	.....	....	......	......	.....	.....	......	....
	.....	....	......	......	.....	.....	......	....
	Calculated irrigation cost /bigha/year							

2.4 How satisfied are you with diesel/electricity machine irrigation? ....

2.5 Have you informed about solar irrigation? ....

2.5a If yes, from where have you informed about solar irrigation? ....

2.6 Why don't you receive the irrigation service from the SIP? ....

2.7 Do you have good relationship with the solar irrigation pump operator? ....

2.7a If no, what is the cause of not having good relationship? ....

2.8 If the installer will ask you to provide 4 to 8 decimal land for the installation of SIP, will you agree?

2.8a If yes, why ....

2.8b If no, why.......................

<u>Module 3-Information about diesel/ electric irrigation machine</u> (Who has diesel machine)

3.1 How many days (approximately) do you use the machine for irrigation in a year?

3.2 What is the approximate capacity of the diesel machine? ....

3.3 Mention the total **yearly cost** (installment & running) of the diesel / electric machine

SL	Particular	Amount (Tk)	Guaranty (Years)
	....	....	....
	Previous yearly expenditure of diesel irrigation (app.)	....	

3.4 Mention the **yearly revenue** of the diesel / electric machine....................

Particular	Amount
....	....
Total	

3.5 Problems with diesel/electricity machine irrigation? ....

3.6 Environmental problem with diesel/electricity irrigation machine? ....

Module 4- Choice experimental question [Non-users of SIP]

4.1 Have you heard anything about the personal consumption of SIP ....

4.2 Will you want to purchase a small solar irrigation pump (with 1.2 kW pump)? ....

(By 40,000 Tk. as down payment and about 2000 Tk. as monthly installment for 4 years Moreover, the coverage is 10 bigha for Boro cultivation & 20 bigha for other crops cultivation and after 4 years it will provide almost free irrigation service for at least 16 years)

4.2a If no, why? ....

4.3 If the cost would less, would you be able to buy it personally? ....

4.3a If yes, what would be the tentative amount of down payment?............................. Tk.

4.3b If yes, what would be the tentative amount of installment/month for 4 years?........Tk

4.4 Is there any chance to purchase the pump in group?....................................

4.4a If yes, what would be the number of farmers in the group? ....

Thank you for your given time and patience.

Appendix B: Some of the Visited SIPs

প্রকল্প কোড	প্রকল্প এলাকা	গ্রাম	ইউনিয়ন	উপজেলা	জেলা	পাম্পের ক্ষমতা (কিলোওয়াট)	স্পন্সর	প্রকল্পের অবস্থা
5220GZI02009	পূর্ব দাড়িয়াপুর পূর্বকান্দর-২(এ)	দাড়িয়াপুর	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02010	পূর্ব দাড়িয়াপুর পূর্বকান্দর-২(বি)	দাড়িয়াপুর	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02011	নখাপাড়া কান্দর সরদারপাড়া-১	নখাপাড়া সরদারপাড়া	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02012	নখাপাড়া কান্দর সরদারপাড়া-২	নখাপাড়া সরদারপাড়া	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02017	কইকুড়ি পূর্ব কান্দর-১	কইকুড়ি	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02018	কইকুড়ি পূর্ব কান্দর-১	কইকুড়ি	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02035	সাওতাল পাড়ার ডাঙ্গা-১	দক্ষিণ পলাশবাড়ি	মোহনপুর	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI02036	সাওতাল পাড়ার ডাঙ্গা-২	দক্ষিণ পলাশবাড়ি	মোহনপুর	বীরগঞ্জ	দিনাজপুর	৭.৫	গাজী-২	চলমান
5220GZI03027	বড় বোচাপুকুর (বালাকান্দর)	বড় বোচাপুকুর	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	১৫	গাজী-৩	চলমান
5220GZI03028	নিজপাড়া (দশ বিঘার ডাঙ্গা)	মন্ডলপাড়া	নিজপাড়া	বীরগঞ্জ	দিনাজপুর	১৫	গাজী-৩	চলমান
5430GZI01027	সাজানোগ্রাম-১(এ)	সাজানোগ্রাম	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	গাজী-১	চলমান
5430GZI01028	সাজানোগ্রাম-১(বি)	সাজানোগ্রাম	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	গাজী-১	চলমান
5430GZI01029	সাজানোগ্রাম-৩(এ)	সাজানোগ্রাম	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	গাজী-১	চলমান
5430GZI01030	সাজানোগ্রাম-৩(বি)	সাজানোগ্রাম	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	গাজী-১	চলমান
5430SLG03035	উত্তর মাদাইখামার, লোহানীপাড়া-১	লোহানীপাড়া	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	সোনারগাঁও-৩	চলমান
5430SLG03036	উত্তর মাদাইখামার, লোহানীপাড়া	লোহানীপাড়া	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৩.৭৫	সোনারগাঁও-৩	চলমান

	-২							
5430SLG03043	গকিরডোবা কোদালধোয়া	লোহানীপাড়া	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৭.৫	সোলারগাঁও-৩	চলমান
5430GZI02175	মাদাইখামার বিলপাড়া-১	মাদাইখামার	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৭.৫	গাজী-২	চলমান
5430GZI02176	মাদাইখামার বিলপাড়া-২	মাদাইখামার	লোহানীপাড়া	বদরগঞ্জ	রংপুর	৭.৫	গাজী-২	চলমান
5430GRM02003	দক্ষিন বাউচন্ডি ফেসকিপাড়া -১	দক্ষিন বাউচন্ডি ফেসকিপাড়া	কুতুবপুর	বদরগঞ্জ	রংপুর	৩.৭৫	গ্রাম-২	চলমান
5430GRM02004	দক্ষিন বাউচন্ডি ফেসকিপাড়া -২	দক্ষিন বাউচন্ডি ফেসকিপাড়া	কুতুবপুর	বদরগঞ্জ	রংপুর	২.২	গ্রাম-২	চলমান
5430GZI02149	চকিদারের ডাঙ্গা (কলেজপাড়া) রুস্তমাবাদ-১	রুস্তমাবাদ	কুতুবপুর	বদরগঞ্জ	রংপুর	৭.৫	গাজী-২	চলমান
5430GZI02150	চকিদারের ডাঙ্গা (কলেজপাড়া) রুস্তমাবাদ-২	রুস্তমাবাদ	কুতুবপুর	বদরগঞ্জ	রংপুর	৭.৫	গাজী-২	চলমান
5860GHL02006	দলা সিংড়া (শুকানগাড়ী)	দলা সিংড়া	গোহাইল	নন্দীগ্রাম	বগুড়া	৭.৫	জিএইচইএল-২	চলমান
5860GHL02007	কামুল্লাহ সরকারপাড়া	কামুল্লাহ সরকারপাড়া	বুড়োইল	নন্দীগ্রাম	বগুড়া	৭.৫	জিএইচইএল-২	চলমান
5860GHL03001	তালপুকুরা	তালপুকুরা	বুড়োইল	নন্দীগ্রাম	বগুড়া	৫	জিএইচইএল-৩	চলমান
5860GHL03021	কৈরপাড়া, কুন্দরহাট	কৈরপাড়া, কুন্দরহাট	বরইল	নন্দীগ্রাম	বগুড়া	১১	জিএইচইএল-৩	চলমান
5860GHL03023	দোলাসিংড়া, উচাপাড়া, বিরপলি	দোলাসিংড়া, উচাপাড়া, বিরপলি	গোহাইল	নন্দীগ্রাম	বগুড়া	১১	জিএইচইএল-৩	চলমান

Appendix C: List of suppliers under IDCOL Solar Irrigation Program

Sl.	Name of the suppliers	Address	Equipment brand	
			Pump	Controller
1.	**Rahimafrooz Renewable Energy Ltd. (RREL)**	Rahimafrooz Renewable Energy Ltd. 260/B, 5th floor, Tejgaon I/A, Dhaka-1208	Lorentz	Lorentz
2.	**Electro Solar Power Ltd (ESPL)**	Electro Solar Power Limited House # SW(B)/20 A Road # 08,Gulshan 1,Dhaka	Schenzhen Solartech Co. Ltd.	Schenzhen Solartech Co. Ltd.
3.	**Energypac Electronics Ltd.(EEL)**	Energypac Electronics Ltd. Novo Tower 270, Tejgaon I/A, Dhaka-1208	Grundfos	Grundfos
4.	**Sherpa Power Engineering Ltd. (Sherpa)**	Sherpa Power Engineering Ltd. Road No # 2, House # 42-43 Janata Housing, Adabar, Mohammadpur, Dhaka-1207	Sherpa (Manufactured by Shakti Pumps Ltd, India)	Sherpa (Manufactured by Shakti Pumps Ltd, India)
5.	**MAKS Renewable Energy Company Ltd. (MAKS)**	MAKS Renewable Energy Company Ltd. House No # 30 (3rd floor), Road No # 9 & 10, Block # G, Banani, Dhaka	Lorentz	Lorentz
6.	**Sunkoji Power Development Ltd. (Sunkoji)**	Sunkoji Power Development Ltd. House # 21, Block # A, Jaleshwar, Savar, Dhaka	Grundfos	Grundfos
7.	**Karben Solar Energy Ltd. (Karben)**	Karben Solar Energy Ltd. House #8A(5th floor), Road # 8, Gulshan - 1, Dhaka - 1212, Bangladesh	Grundfos	Grundfos
8.	**Bangla Trac Engineering Ltd (BTEL)**	Bangla Trac Engineering Ltd. Corporate Office: 4, Amtoli, Mohakhali, Dhaka-1212	Grundfos	Schneider Electric
9.	**Solargao Ltd. (Solargao)**	Solargao Ltd Suite 501, House 24,Road 14, Block G, Niketon, Dhaka-1212	HCP	Schneider Electric
			Pedrollo,	Schneider Electric
			Lorentz	Lorentz
10.	**Solar E Technology (Solar E)**	Sahid Robiul Islam Road (East side of Registry Office) Chuadanga-7200, Bangladesh	Hebei prime pump	Setec
11.	**Greenergy Solutions Ltd. (GSL)**	Greenergy Solutions Ltd. 1B, House 58, Road 7/A,Block H, Banani,Dhaka-1213	HCP	Vacon
12.	**Navana Renewable Energy Co. Ltd (NREL)**	Navana Renewable Energy Co Ltd, Navana Toyota 3S Center,2nd floor Tejgaon Industrial Area Dhaka-1208	Grundfos	ABB

SL	Name of the suppliers	Address	Equipment brand	
			Pump	Controller
13.	**UDDIPAN Energy Ltd (UEL)**	UDDIPAN Energy Limited Corporate Office: 840-841 Baitul Aman Tower (5th Floor) Ring Road, Adabor, Mohammadpur Dhaka-1207.	Franklin Electric	Schneider Electric
14.	**Samaj Unnayon Palli Sangstha (SDRS)**	House # 549, Road # 10, Baitul Aman Housing Society, Adabor, Dhaka-1207.	Sherpa	Sherpa
15.	**Greentek Ltd (GTL)**	House # 14, Road # 12, Block-KHA, PC Culture Housing Society, Shekertec, Adabor, Mohammadpur,	Sherpa	Sherpa
16.	**JSF Technology Pvt Ltd (JSF)**	House # 39, Road # 12, Shekertec, Adabor, Mohammadpur, Dhaka-1207	Duke Plasto Technique Pvt Ltd	Hermes Technologies Pvt. Ltd
17.	**Power Utility Bangladesh Ltd.**	Bengal House,75, Gulshan Avenue,Gulshan-1 Dhaka: 1212	Nanfang Pump Industry Ltd (CNP)	ABB
			NASTEC	NASTEC
18.	**Superstar Renewable Energy Ltd. (SREL)**	Baitul View Tower (17 Floor), 56/1,Purana Paltan, Dhaka-10000	SSG Solar	SSG Solar

Appendix D: Multicollinearity and the Marginal Effect Tests for the Models Used in the Study

Table D1: VIF of the Logistic Regression Model

Variables	VIF	1/VIF
AGE	2.17	0.46
EDU	1.58	0.63
OLH	1.15	0.87
LP	1.17	0.85
CI	1.72	0.58
IPR	1.20	0.83
GD	1.27	0.79
SWPI	1.19	0.84
LAI	1.29	0.78
VSIP	1.31	0.76
Mean VIF	1.41	

Table D2: Parameter Estimates of the Model, Marginal Effects

Explanatory Variables	Marginal Effects, dy/dx	Std. Error	z-value	p-value
Age	-0.019*	0.011	-1.73	0.084
Education	0.021***	0.008	2.62	0.009
Size of operational landholding	0.198**	0.083	2.39	0.017
Number of land parcels	-0.36	0.79	-.455	0.65
Cropping intensity	0.48	0.58	0.828	0.41
Investment plan for renting	0.279***	0.091	3.066	0.002
Groundwater depth	0.221	0.203	1.09	0.275
Satisfaction with present irrigation setting	-0.185**	0.078	-2.371	0.018
Loan for agricultural investment	0.029**	0.014	2.071	0.038
View on solar irrigation pumps	0.025***	0.009	2.777	0.0055

*Source: Author's calculation from field survey, 2019; ***, ** and * indicate the level of significance at 1%, 5% and 10%*

Appendix E: Some Visited SIPs

A visited solar irrigation pump in Nandigram, Bogra.

A visited solar irrigation pump in Badarganj, Ragnpur

A visited solar irrigation pump in Birganj, Dinajpur