CHAPTER 4

ASSESSMENT OF SWP SYSTEM WITH INTEGRATION OF EV CHARGING

4.1 Introduction

4.1.1 Background

In the preceding chapter (Chapter 3A), the focus was on assessing rooftop solar (RTS) and ground-mounted solar (GMS) systems to ascertain their potential when either fed to the grid or consumed locally. One critical observation arising from that discussion was the underutilization of solar photovoltaic water pumping (SWP) systems during non-irrigation periods, during which they often remain idle and generate surplus electricity that remains untapped. This scenario highlights the importance of devising mechanisms for effectively harnessing any excess solar power to enhance overall system efficiency and viability. Building upon these findings, the present chapter explores the feasibility of harnessing this surplus electricity to support additional applications such as electric vehicle (EV) charging. Furthermore, in the broader agricultural context, SWP solutions confront competition from diesel water pumps (DWP) and grid-based electric water pumps (EWP). These alternatives, despite their drawbacks, are often favoured by farmers due to entrenched practices, inconsistent energy pricing, or the initial cost barriers of solar-based systems. Hence, the present chapter seeks to evaluate the techno-economic feasibility of SWP systems not only for irrigation but also for potentially utilizing surplus generated electricity, thereby building upon the insights gained in Chapter 3A and extending them to address the comparative advantages and limitations of DWP and EWP.

4.1.2 Agricultural landscape

Agriculture in India faces multiple challenges, primarily stemming from low levels of crop production and higher input costs, leading to inadequate revenue from agricultural outputs. These issues are compounded by technological transitions and their environmental impact [1, 2]. The extent of impact varies from region to region due to climate, soil, cultural differences, and varying land-holding patterns. Small and marginal farmers are particularly affected due to the smaller size of their cropland and the unaffordable cost of inputs [3, 4]. Introduction and circumstances of subsequent withdrawal of farm laws [5] in recent times have highlighted the socio-political issues faced by crop-producing farmers in India.

There are various approaches taken by the government, research institutes, and crop producers to increase farm income through sustainable utilization of farm resources [6]. The government provides direct subsidies, and minimum support prices (MSP) and encourages the development of technologies [7, 8] to reduce the hassles of farmers. Research and academic circles address key issues to find farmer-friendly solutions [9, 10, 11]. Various successful examples of research outcomes for the betterment of crop production have been applied in crop variety [12], machinery [13, 14], farm practices [15], irrigation [16], crop care [17] and post-harvest [18]. The current study is an attempt to promote sustainable and economical options for irrigation.

Irrigation plays a critical role in crop production and has significant implications for the economy and sustainability of crop farms. In India, irrigation coverage extends to approximately 50% of the net crop area. However, there is considerable regional variation in irrigation status, with Assam having only 13% of its net sown area under irrigation, contrasting with more productive regions like Punjab (99%), Haryana (90%), and Andhra Pradesh (46%) [19]. This inadequate provision of irrigation has adversely affected crop production in Assam.

Agriculture is a vital sector of Assam's economy, covering about 54% of the total geographical area [20]. Over 80% of the state's population depends on agriculture, including plantation crops, with rice being the primary staple food crop [21]. Despite its agro-based economy, Assam's rice yield (2.15 t/ha) is 18% less than the national average yield (2.64 t/ha) and 47% less than Punjab's yield (4.13 t/ha) [19]. The productivity analysis of rice cultivation in India classifies Assam in the medium to very low productivity group, with over 50% of rice cultivation in low productivity zones and 40% in medium-low productivity zones [22]. Inadequate irrigation is identified as one of the primary reasons for these low productivity levels and reduced crop intensity in Assam [23].

The Indian government has introduced financial assistance and subsidies to promote renewable energy sources as part of its Intended Nationally Determined Contributions (INDC) target, which aims to achieve 175 GW of renewable energy capacity by 2022 and 450 GW by 2030 [24, 25], aligned with Sustainable Development Goals 7 and 13. Efforts are being made to demonstrate the viability of SWP systems not only in terms of their economic advantages but also their energy and environmental benefits [26]. Several studies have examined the effects of irrigation policies [27-31]. Various policies for energy subsidies exist, and there are also instances of providing subsidies on irrigation pumps. Some of these are listed in **Table 4.1** below, with specific reference to Assam.

Table 4.1: Irrigation schemes in Assam, India

Name of Scheme	Year	Description
Command Area Development and Water Management (CADWM) Programme	1974 onwards	This scheme focuses on improving agricultural productivity through better water management practices and the development of irrigation infrastructure [32].
Minor Irrigation Programme (MIP)	1986 onwards	This program aims to create new minor irrigation facilities such as shallow tube wells, low lift pumps, and dug wells to support small and marginal farmers [33].
Accelerated Irrigation Benefit Programme (AIBP)	1996 onwards	This scheme aims to enhance the irrigation potential of the state by constructing new irrigation projects and restoring existing irrigation systems [34].
Pradhan Mantri Krishi Sinchai Yojana (PMKSY)	2015 onwards	This scheme aims to improve water use efficiency in the agriculture sector through the development of new irrigation systems, restoration of old systems, and efficient water management practices [35].
Rural Infrastructure Development Fund (RIDF) scheme	2016 onwards	This credit-linked scheme by the National Bank for Agriculture and Rural Development (NABARD) provides financing for rural infrastructure development, including irrigation projects [36].
Pradhan Mantri Kisan Urja Suraksha evam Utthan Mahabhiyan (PM-KUSUM)	2019 Onwards	This scheme has three components: Component-A focuses on setting up decentralized grid-connected renewable energy power plants, Component-B aims to install stand-alone solar agriculture pumps, and Component-C focuses on solarizing grid-connected agriculture pumps [37].

The irrigation water supply to fields depends on various options, including different technologies, energy sources, and pumping methods [38, 39]. The three distinct choices are SWP, DWP, and EWP. In India, DWP is commonly used in remote and rural areas, but it comes with concerns related to fossil fuel depletion, negative environmental impact [40], and maintenance issues. On the other hand, EWP relies on grid electricity, making them unreliable in remote areas during power failures. As an alternative, solar energy is a viable option for providing stable energy for pumping irrigation water in off-grid areas, where access to power and maintenance services is not guaranteed. However, the relatively high initial investment costs of SWP systems require creative financing mechanisms or subsidies, especially for small-scale farmers.

While several studies have explored the effects of irrigation policies, limited research focuses on the intricacies caused by technological and economic factors influencing the choices of irrigation practices among the three options. Ideally, SWP is the preferred choice due to its renewable energy source and minimal operational cost, which becomes even more significant as the country aims to increase its energy consumption from renewable sources by 50% and reduce the emissions intensity of its GDP by 45% by 2030 [41].

Efforts have been made in the past to improve irrigation practices in Assam, including the implementation of shallow tube well systems and the recent introduction of SWP systems. Although there were efforts to extend electrical systems for irrigation, widespread success and adoption in the region remain a challenge. The cost-effectiveness of different pumping options for irrigation remains uncertain, with various issues to address, such as groundwater availability, financial barriers, and uncertainties surrounding resources like pumps, prime movers, and the availability of solar radiation, electricity cost, and diesel [42, 43]. The complexity of the system is further compounded by the varying marginal benefits in terms of increased yield and net revenue [44].

The current Chapter aims to identify and contrast the existing irrigation system with alternative options, considering practical crop rotation schedules, and focusing on the representative case study area of Assam. The research will evaluate the factors influencing the profitability and benefits of irrigation, particularly in the context of the PM-KUSUM scheme, a recent government initiative supporting irrigation in India. The specific objectives of this study are: (i) to provide valuable insights into sustainable and efficient irrigation practices by comparing different pumping options, (ii) to understand their economic and environmental implications, (iii) to promote the adoption of suitable irrigation methods for enhancing agricultural productivity and sustainability in regions like Assam and similar areas, and (iv) to evaluate the feasibility of utilising surplus solar energy generated during non-irrigation periods for grid integration or alternative productive uses such as EV charging, thereby improving energy efficiency and revenue generation.

4.2 Materials and Methods

The procedure for the comparative assessment of SWP, DWP, and EWP is illustrated in **Fig. 4.1**, which includes key input parameters and calculated variables. By considering input parameters such as crop data and irrigation methods, the demand of water demand for irrigation is calculated. This, along with the groundwater status, is used to determine the appropriate pump size and fuel input type, whether solar, diesel, or grid electricity. After determining the pump power, the economic and environmental assessments of the considered pumps are evaluated for ranking.

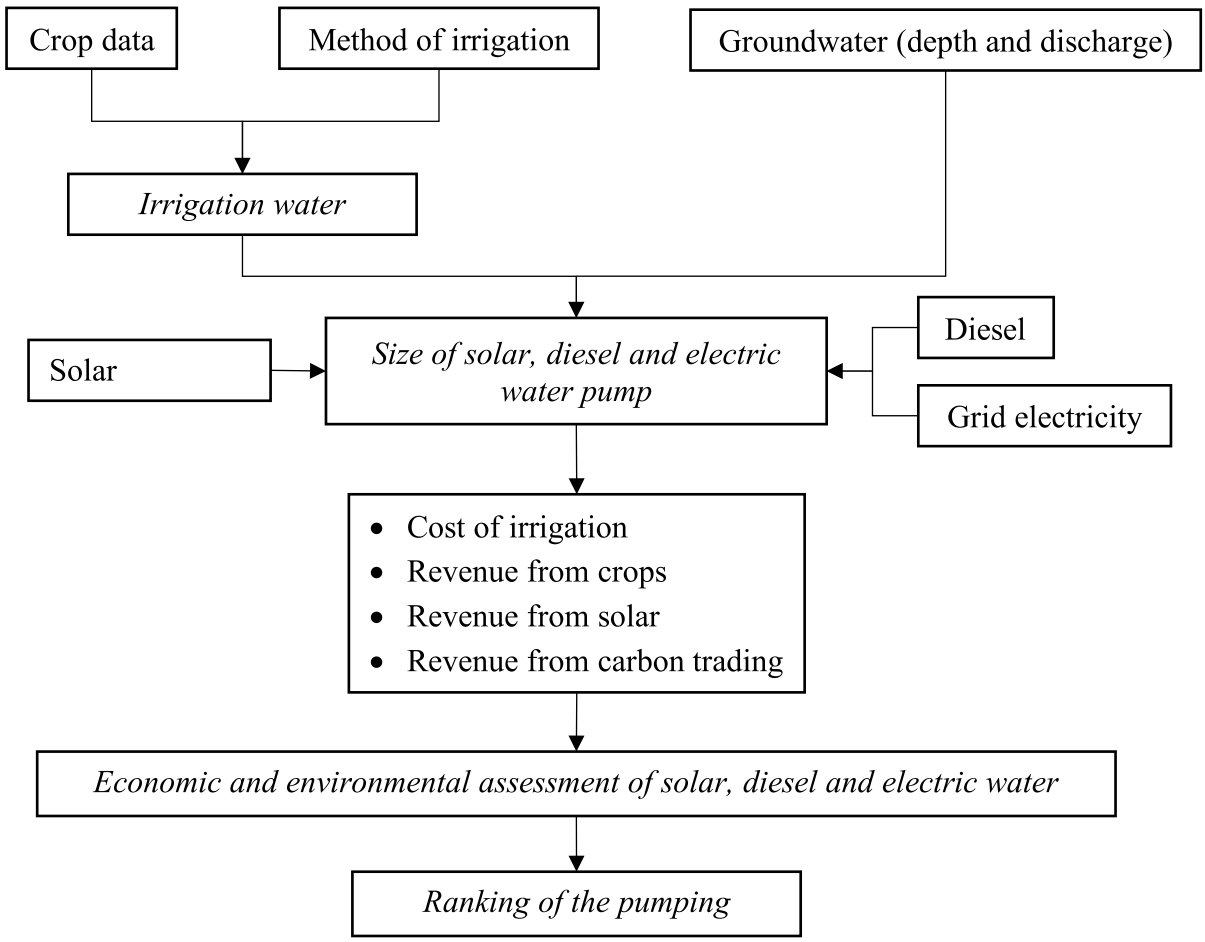

Fig. 4.1: Flowchart for the comparative assessment of SWP with DWP and EWP

4.2.1 Selection of study area

A representative study area, Jhawani-3 village, located within the Bihaguri development block of Sonitpur District, Assam has been selected for the analysis. This village is situated on the banks of the river Brahmaputra, as illustrated in **Fig. 4.2.** The analysis considers one hectare to evaluate different pumping options for irrigation. Two critical factors are considered in this assessment: groundwater status and solar radiation availability. These factors play a pivotal role in evaluating and determining the suitability of various irrigation methods.

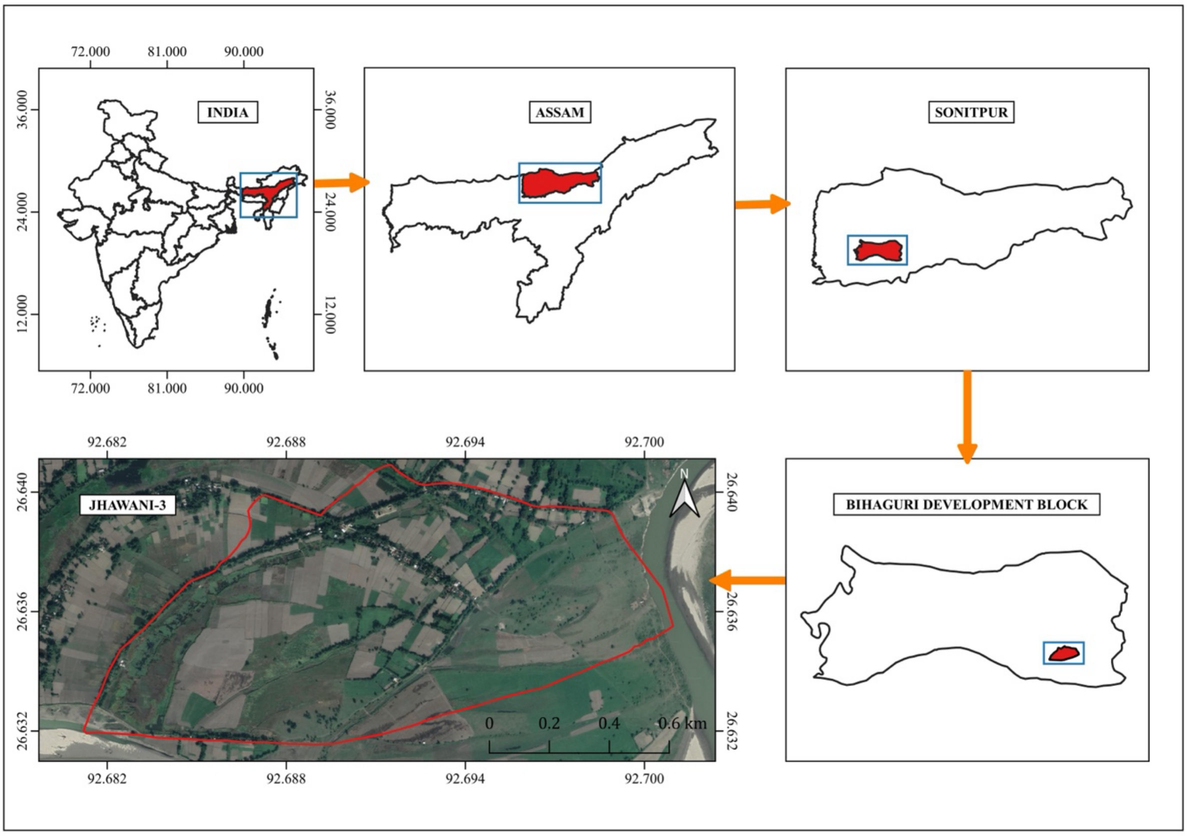

Fig. 4.2: Location map of the study area

4.2.2 Crop data considered for the analysis

The study considers two crop rotation viz., CR1, CR2; to assess the performance of the pumping options. Also, it enables an accurate comparison, accounting for variability in water use as well as the timing of water demand across different cropping patterns. Details for the analysis are presented in **Table 4.2** [45-47].

Table 4.2: Crop selection for the analysis

Crop rotation	Name of crop	Variety	Date of Sowing	Date of Harvest	Duration, days
		CR1			
Crop 1	Sali Rice	Swarna Sub-1	01-Jul	15-Nov	137
Crop 2	Strawberry	Winter Dawn	24-Nov	25-Feb	90
Crop 3	Ahu Rice	Lachit	01-Mar	29-Jun	120
		CR2			
Crop 1	Sali Rice	Swarna Sub-1	01-Jul	15-Nov	137
Crop 2	Mustard	TS-36	20-Nov	18-Feb	90
Crop 3	Boro Rice	Bina Dhan 11	25-Feb	20-Jun	115

4.2.3 Method of irrigation and water requirement

Based on the crop selection, two types of irrigation methods are required, namely (i) basin irrigation **Fig. 4.3** and (ii) furrow irrigation **Fig 4.4.** These two methods are used to calculate the required water volume for irrigation using the standard volumetric method. The area of the field has been considered as one hectare, which has a dimension of 100 m length × 100 m width. Based on the package of practices and related literature for the crops considered, a standing water height of 0.05 m for rice, 0.08 m for strawberry, and 0.06 m for mustard has been considered for one irrigation cycle [45-47].

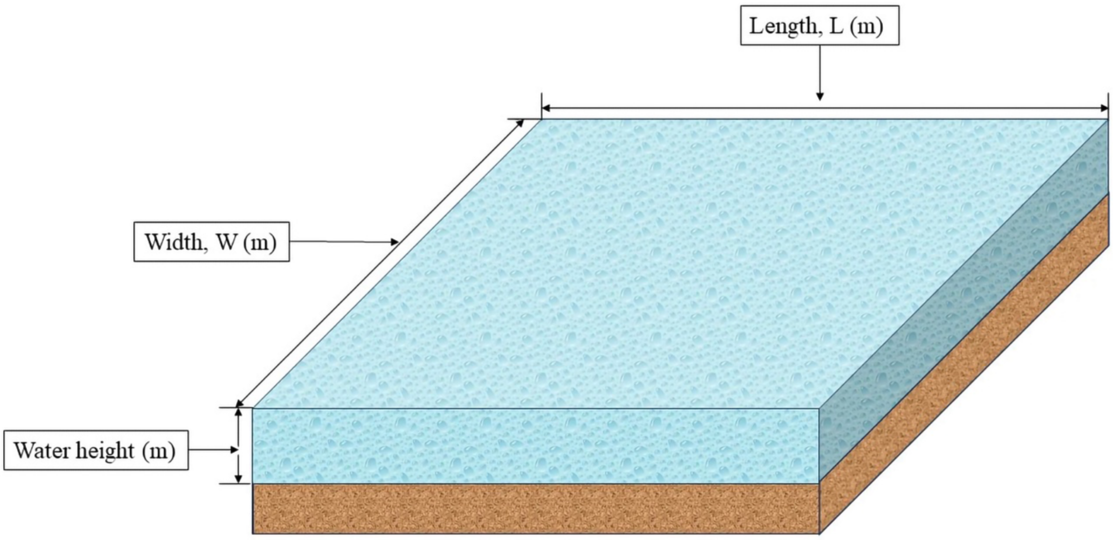

Fig. 4.3: Basin irrigation

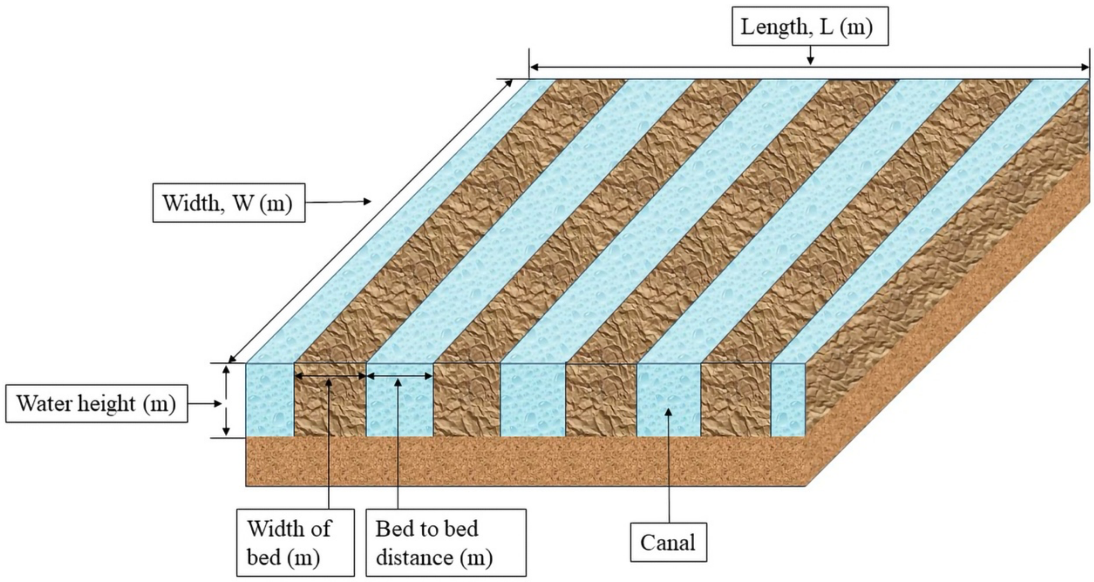

Fig. 4.4: Furrow irrigation

The volume of water required for one irrigation are estimated based on the unit farm area, which corresponds to the total land area under consideration [48].

For the basin irrigation process (rice and mustard),

$$Water\ Volume = Required\ water\ height \times Area \tag{4.1}$$

For the furrow irrigation process (strawberry),

$$Water\ Volume = Required\ water\ height \times W \times Bed\ to\ bed\ distance \times No.of\ canals \tag{4.2}$$

where, $$No.of\ canals = \frac{L - Bed\ to\ bed\ distance}{(width\ of\ bed + Bed\ to\ bed\ distance)} + 1 \tag{4.3}$$

W is the width and L is the length of the field.

4.2.4 Groundwater availability

The availability of groundwater varies with geographical location and season. Accurate analyses necessitate information on the groundwater status to determine the required pump power, considering groundwater depth and allowable discharge. This prevents over-exploitation of groundwater while fulfilling crop water needs [43]. Groundwater status information is obtained from groundwater prospect maps by the National Remote Sensing Centre [49]. The study area features an Alluvium (Sand and silt Dominant) aquifer type. For detailed groundwater status, refer to figure **Appendix 4A** and table **Appendix 4B**.

4.2.5 Pump selection

In this study, three types of pumps, viz., SWP, DWP, and EWP, are chosen based on the water requirements of the crops under consideration and the groundwater status. For SWP, solar data under standard test conditions (STC) for hours of peak sun radiation is taken into account [50]. These hours of peak sunshine are utilized to estimate the potential operational hours of SWP in a day, although the actual operational duration may vary. The flow chart presented in **Fig. 4.5** illustrates the complete pump selection process. The following approach is employed to approximate pump power and determine the optimal pump size.

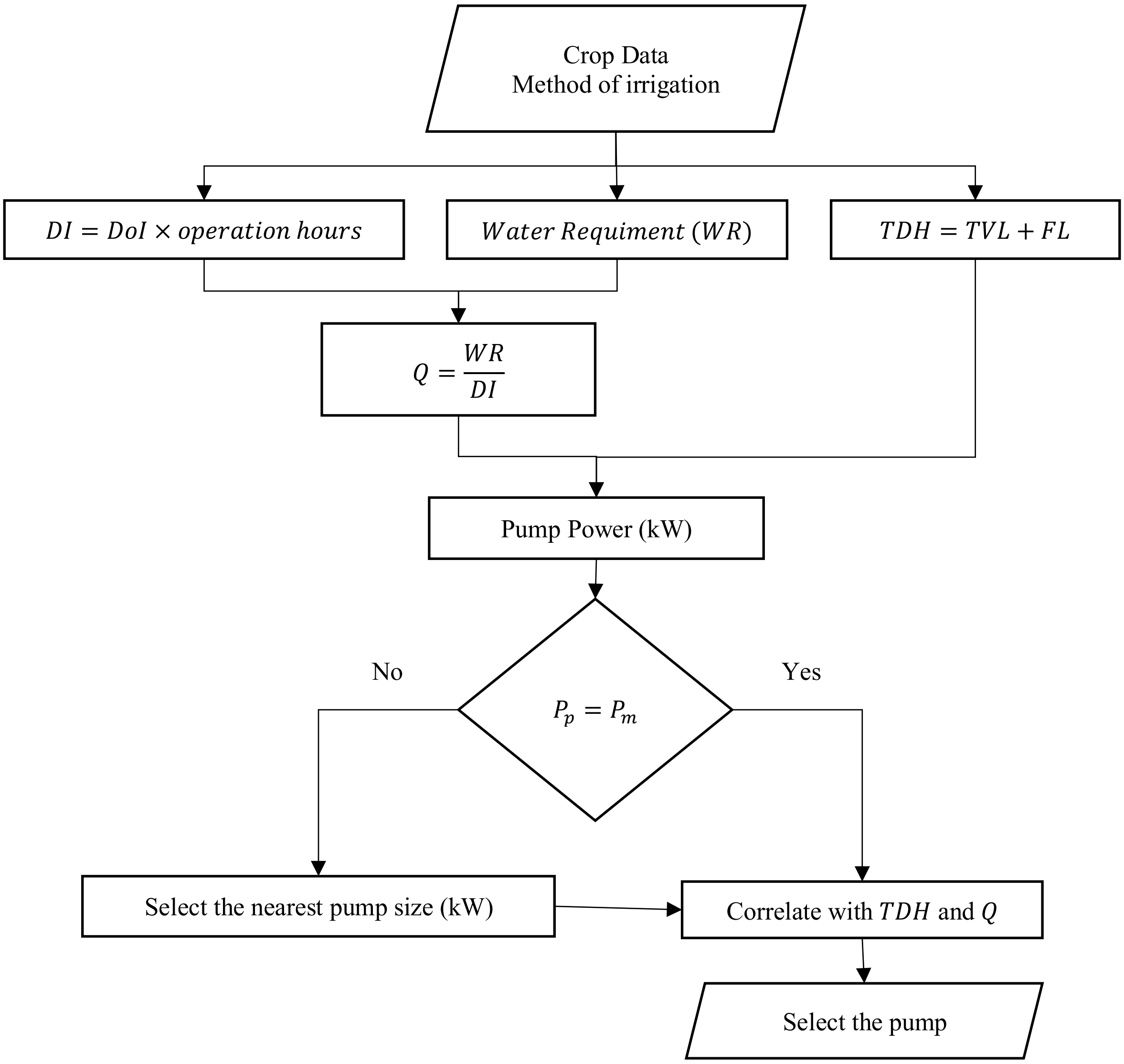

Fig. 4.5: Flowchart for selection of pump

[DI – Duration of irrigation (h), DoI – Days of irrigation (days), FL – Frictional lift (m), P_m – Pump available in market (kW), P_p – Pump power (kW), Q – Discharge (lps), TDH – Total dynamic head (m), TVL – Total vertical lift (m).]

4.2.6 Solar radiation data

The solar irradiation data for the study area is depicted in **Fig. 4.6**. This data is derived from a 5-year average spanning from 2017 to 2021 and is used to compute the seasonal availability of average radiation for the crop rotations. For CR1, the seasonal averages are 4.35, 3.81, and

4.64 kWh/m^2/day for the three crops, respectively. For CR2, the seasonal averages are 4.35, 3.78, and 4.64 kWh/m^2/day for the respective crops.

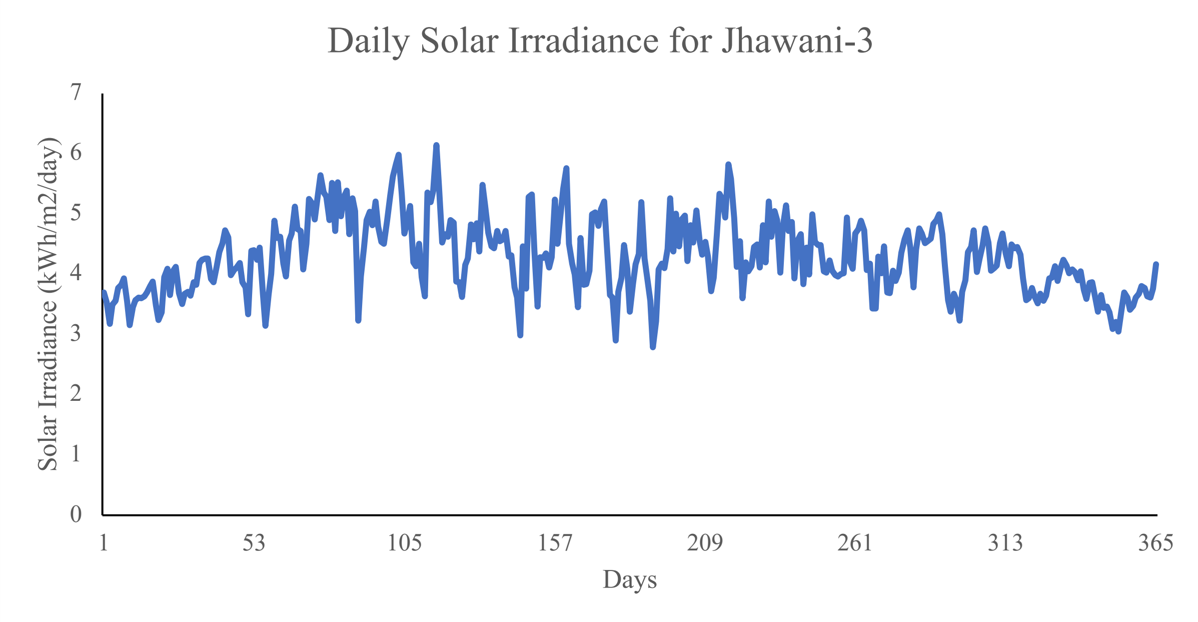

Fig. 4.6: Daily incident solar insolation in Jhawani-3 village [51]

4.2.7 Cost calculation and assumptions

The costs associated with the pumping options are estimated. Assumptions made during the calculation of costs are also discussed in detail.

a) Capital cost: The cost of procuring the machinery including installation and commissioning cost.

b) Ownership cost: Ownership cost includes depreciation, interest, and insurance. Depreciation accounts for the machine's wear and age, while interest represents the opportunity cost of using funds. The estimated costs of depreciation, interest and insurance are added together to find the ownership cost which assesses the long-term value of the purchase.

c) Operation and maintenance cost: Operation and maintenance cost comprises repair and maintenance, operator wage, and energy cost. The SWP system may have higher repair costs due to its complexity and specialized maintenance equipment. Regular cleaning of solar panels adds to the maintenance cost. DWP and EWP systems are easier to maintain, resulting in lower repair costs. Operator wage is calculated by multiplying the labour wage rate by the number of days worked. Energy cost includes diesel and electricity expenses at prevailing rates, but SWP has no energy cost. The estimated repair and maintenance cost, operator wage, and energy cost are combined to determine the operation and maintenance cost. Land ownership and tractor input costs are not considered in the economic analysis as they are expected to be consistent across the pumping options. **Table 4.3** summarizes the related cost and assumptions for the analysis.

Table 4.3: Cost calculation and assumptions for the pumping options

<table>
<tr><th colspan="2">Cost components</th><th colspan="3">Pumping system</th><th>Reference</th></tr>
<tr><td colspan="2"></td><td>Solar photovoltaic water pump (SWP)</td><td>Diesel water pump (DWP)</td><td>Electric water pump (EWP)</td><td></td></tr>
<tr><td colspan="2">Capital cost</td><td>MNRE Benchmark cost*</td><td>Prevailing market price</td><td>Prevailing market price</td><td>[52-54]</td></tr>
<tr><td rowspan="3">Ownership cost</td><td>Cost of depreciation</td><td>Straight line depreciation method is used with 50% as salvage value for the SPV unit and 10% for the pumping unit **</td><td colspan="2">Straight line depreciation method with 10% salvage value</td><td>[55]</td></tr>
<tr><td>Interest rate</td><td colspan="3">8% of the capital cost</td><td>[56]</td></tr>
<tr><td>Insurance</td><td colspan="3">2% of the capital cost</td><td>[57]</td></tr>
<tr><td rowspan="3">Operation and maintenance cost</td><td>Repair and maintenance cost</td><td>1%</td><td>5%</td><td>1%</td><td>[58]</td></tr>
<tr><td>Operator wage</td><td colspan="3">Prevailing daily wage rate (unskilled worker)</td><td>[59]</td></tr>
<tr><td>Energy cost</td><td>nil</td><td>Prevailing market price of diesel</td><td>Prevailing rate as fixed by power distributor</td><td>[60]</td></tr>
</table>

* Two cases viz., one with PM-KUSUM scheme implemented by Ministry of New and Renewable Energy (MNRE) providing (80%) subsidy and another without subsidy is considered

** Based on the field survey, 90% of the total cost is attributed to the SPV unit whereas the remaining is for the pump

4.2.8 Estimation of CO_2 emission

The environmental aspect of the three options of pumping is evaluated by considering the potential CO_2 emissions into the atmosphere due to the various energy sources used to operate the pumps. Solar, being a renewable source, provides an assessment of the environmental impacts from a systems perspective, taking into account the detailed input and output parameters within the designated system boundaries. For PV power plants, most of the GHG emissions occur upstream during materials and module manufacturing. The emission factor for DWP is derived from [61], but it may vary depending on the characteristics of both the engine and the fuel [62]. For EWP, the power source obtained from grid electricity is attributed to a user guide based on the database for the Indian power sector [63]. The emission factors for the different energy sources used for pumping are shown in **Table 4.4** below.

Table 4.4: Emission factors for the energy sources for pumping options

Source of energy	CO_2 Emission Factor (EF)	Reference
Solar PV	0.085 kg/kWh	[64]
Diesel	3.130 kg/kg fuel	[61]
Grid electricity	0.830 kg/kWh	[63]

The CO_2 emission is estimated by the following method:

For SWP

$$Solar\ PV_{emission} = Operation\ hours \times Pump\ power\ rating \times EF \tag{4.4}$$

For DWP

$$Diesel_{emssion} = Operation\ hours \times Pump\ power\ rating \times Fuel\ consumption \times EF \tag{4.5}$$

For EWP

$$Grid_{emission} = Operation\ hours \times Pump\ power\ rating \times EF \tag{4.6}$$

4.2.9 Revenue calculation

A comprehensive evaluation of revenue generation is essential to assess the economic feasibility of different pumping options. For SWP, revenue streams include agricultural yield, surplus electricity generated from PV systems, and earnings from carbon trading. In contrast, DWP and EWP generate revenue solely from agricultural production, as they do not benefit from surplus energy sales or carbon credit incentives.

4.2.9.1 Revenue from crops

The revenue from crop production is calculated by multiplying the estimated crop yield per hectare under optimal growing conditions by the market price of the crop. For this study, the Minimum Support Price (MSP) set by the government for each of the crops in CR1 and CR2 was considered [65, 66]. This parameter reflects the maximum achievable yield for a given crop and is used in the revenue calculation process.

4.2.9.2 Revenue from PV unit

The solar panels in the SWP system can be connected to the grid by opting for net metering with distribution companies. This enables the surplus energy generated during non-operational hours of the pumping system to be sold back to the grid. To calculate this revenue, the estimated electricity generation from the PV unit is multiplied by the feed-in tariff (FiT) rate. The estimated electricity generation is determined based on the installed capacity of the solar panels and the solar insolation in the region. The formula from Eq. 3.14 estimates the electricity generated [67].

4.2.9.3 Revenue from carbon trading

The revenue from carbon trading for SWP is calculated by estimating the carbon emission reduction, which quantifies the amount of fossil fuel energy replaced by solar energy in the irrigation process. This reduction in carbon emissions is then multiplied by the prevailing market price of carbon credits. However, it is essential to consider that the actual revenue from carbon trading can vary based on several factors. These factors include the prevailing market price of carbon credits, the actual amount of emissions reduced by each pumping option, and the demand for carbon credits in the market. As the carbon market is subject to fluctuations, the price of carbon credits can vary over time. Presently, emission reduction credits are priced between ₹414 and ₹580 per ton of CO_2 in the carbon markets. Industry experts predict that the price of carbon credits is likely to remain below ₹828 per ton of CO_2 for the foreseeable future [68]. In the calculations, the maximum value of the current market price is considered to provide a conservative estimate of the potential revenue from carbon trading.

4.2.10 Economic analysis

4.2.10.1 Net present value (NPV)

Evaluating the economic feasibility of different pumping options requires a robust financial analysis, with NPV serving as a key metric. A discounted cash flow approach is employed to estimate future cash flows over the operational lifespan of each pumping system. To determine the present value of these future cash flows, NPV calculations incorporate an appropriate discount rate. If the investment is covered within the first year, the estimated discount rate is 8%, while for payments covered by annuities, the discount rate is 10% [29]. In this analysis, the economic lifespan of a pump set is assumed to be 10 years, while solar photovoltaic (PV) modules have an operational lifespan of up to 25 years. To reflect this disparity, 50% of the initial cost of the PV system is retained as salvage value and included in the cash flow at the end of the 10-year analysis period. The NPV is computed using a standard equation widely adopted in previous studies [69, 70], ensuring methodological consistency in assessing the financial viability of each pumping alternative.

$$NPV = \left[\sum_{t=1}^{n} \frac{R_t}{(1+r)^t}\right] - I \quad (4.7)$$

In the above equation, R_t represents the annual net cash flow in year t, r is the discount rate, n is the total number of years, and negative I is the initial investment cost. A project's viability is largely determined by its NPV value, and from an economic and financial standpoint, a project with a positive NPV value is considered feasible. However, in this analysis, the calculated NPV is used for comparative economic analysis among the prevailing pumping options. The results are expected to assist farmers in making informed decisions about adoption.

4.2.10.2 Payback period (PBP)

The PBP determines the time needed for an investment to recover its initial cost and reach the break-even point. It's a straightforward metric for investment assessment, aiding quick decision-making and comparison among options. However, PBP doesn't account for time value of money, risk, or long-term profitability. It is equal to the cost of the investment, I, divided by the annual net cash flow, R_t, as described in Equation [70].

$$PBP = \frac{I}{R_t} \quad (4.8)$$

4.2.10.3 Ranking of pumping options

Pumping options are compared using a ranking based on NPV, PBP, and the cost of irrigation by annual net cash flow (CoI/R_t). The cost of irrigation encompasses operational expenses, while annual net cash flow deducts this from generated revenue. Rankings are determined by the least CoI/R_t, indicating greater financial favourability. The process helps identify the most economically viable and efficient pumping option for farmers.

4.2.10.4 Sensitivity analysis

The sensitivity analysis in this study focuses on two key parameters: the subsidy rate for the capital and ownership costs of SWP to match DWP and EWP. A range of subsidy rates is examined covering a realistic spectrum of values based on existing policies and expert opinions, offering insights into financial viability and competitiveness. The capital and ownership costs of SWP are adjusted accordingly for each subsidy rate while keeping the costs of DWP and EWP constant. This analysis identifies subsidy levels for SWP to be on par with other options.

4.3 Results and Discussion

4.3.1 Irrigation water requirement

The water requirements for the considered crops are estimated based on their standard values for a single irrigation cycle: 500 m^3 for rice, 383 m^3 for strawberries, and 600 m^3 for mustard. Agricultural experts and field data indicate that these water requirements can be supplied within 5 days. These figures provide a guideline for irrigation scheduling, considering variables like climate and soil. Regular assessment is advised for optimal yield and water efficiency. Detailed irrigation scheduling is provided in **Appendix 4C**.

4.3.2 Pump selection

The SWP system size is determined to irrigate one hectare in the study area. The nearest pump size for SWP is selected from MNRE’s PM-KUSUM scheme [71]. Previous sizing used an average daily radiation of 7.15 $kWh/m^2/day$, while **Fig. 4.6** showed 4 - 4.5 $kWh/m^2/day$ for the selected study area location in Assam. Therefore, the pump discharge is adjusted to the location radiation for optimum operation. DWP and EWP options are chosen based on power needs, discharge, and dynamic head. Calculated values determine required pump operation hours using **Fig. 4.5**'s methodology. The three technological options of pumping considered are described in **Table 4.5**. Brief technical discussions are provided.

Table 4.5: Description of pumping options considered

Description	SWP	DWP	EWP
Power (kW)	3.73	3.73	3.73
Discharge (lps)	11	11	13
Type	A.C. Induction Motor Pump Set	Single-cylinder, water-cooled, four-stroke cycle engine	Monobloc Pump set
Price (₹)	3,34,100	31,500	33,553

US$ 1 ≈ ₹82.88 Indian Rupees (₹)

4.3.3 Cost of irrigation

To assess the economic viability of various pumping options, multiple costs related to pump ownership and operation are taken into account. Ultimately, the annual cost of irrigation per hectare is obtained by summing up ownership, operation, and maintenance costs. The pumping-related costs for crop rotations CR1 and CR2 are detailed in Table 6.

4.3.3.1 SWP with subsidy

The national subsidy program provided by the MNRE has been considered for evaluating the financial feasibility of the SWP system. The capital cost for the SWP system is based on the MNRE benchmark cost for 2021, and the subsidies/incentives provided for the North-eastern states are taken into account. The subsidies include central financial assistance (CFA) of 50%, a 30% subsidy from the State Government, and the remaining 20% is borne by the farmer. Therefore, only 20% of the capital cost for the SWP system is considered for cost evaluation in the case of a subsidized SWP system [72].

4.3.3.2 SWP without subsidy

The financial analysis of the SWP system is also carried out without considering any subsidies or incentives from the government. In this scenario, the total capital cost for the SWP system is considered without any reduction.

SWP has the highest capital cost among all pumping options as shows in the **Table 4.6**. However, the SWP (Subsidised) option has a significantly lower capital cost due to subsidies. Ownership costs for SWP and SWP (Subsidised) are higher due to higher capital costs, resulting in higher annual depreciation and interest charges. EWP has the lowest operation and maintenance cost, while SWP and SWP (Subsidised) have no energy cost but higher operator, repair and maintenance costs. Overall, EWP has the lowest annual cost of irrigation, followed by SWP (Subsidised). Despite higher costs, SWP offers sustainability and environmental benefits with its use of solar energy compared to non-renewable sources in DWP and EWP.

Table 4.6: Annual cost of irrigation (₹)

Items	SWP	SWP (Subsidised)	DWP	EWP
Capital cost	3,34,100	66,820	31,500	33,553
Ownership cost	48,110	12,295	5,985	6,375
CR1				
Operation and maintenance cost	30,659	30,659	39,571	19,938
Annual cost of irrigation	78,769	42,954	45,556	26,313
CR2				
Operation and maintenance cost	20,903	20,903	27,458	13,743
Annual cost of irrigation	69,013	33,198	33,443	20,118

4.3.4 Estimated CO_2 emission

The estimated CO_2 emissions for each pumping option are calculated based on the energy consumption and associated emission factor for an area of one hectare, and the results are shown in **Table 4.7** below.

Table 4.7: Estimated CO_2 emission of the pumping options (kg/y/ha)

CO2 emission (kg/y/ha)	CR1			CR2		
	SWP	DWP	EWP	SWP	DWP	EWP
	91	689	609	66	493	437

SWP system had the lowest estimated CO_2 emissions due to the energy consumption of the pump and the associated carbon footprint of the manufacturing and installation of the solar panels. In contrast, the DWP system had the highest estimated CO_2 emissions due to its high energy consumption from diesel fuel. The results indicate that the SWP system is the most environmentally friendly option in terms of CO_2 emissions, followed by EWP, while the DWP system is the least environmentally friendly option. These findings highlight the importance of considering the environmental aspects of irrigation systems when making decisions about irrigation infrastructure.

4.3.5 Revenue calculated

4.3.5.1 Revenue from crops

Derived from the potential yield of each crop the revenue for CR1 is ₹41,87,680 for all three crops. Similarly, for CR2, the combined revenue from the three crops is ₹2,72,780.

4.3.5.2 Revenue from PV unit

The revenue generated from the sale of surplus electricity is calculated using the FiT rate set by the state electricity board. In Assam, the FiT rate for solar power is ₹3.50 per kWh for grid-connected solar power projects with a capacity of up to 500 kW. For the installed PV array capacity of the SWP system annual electricity generation capacity is 8444 kWh. The average electricity generation per year during non-irrigation periods is calculated to be 6639 kWh for CR1 and 7136 kWh for CR2. The description of SWP and estimation of revenue from the PV unit during non-irrigation periods are presented in **Table 4.8**.

Table 4.8: Specifications and considerations of SWP

Description of item	Value
PV array capacity (kWp)	4.80
Motor pump-set capacity (kW)	3.73
Panel area (m^2)	48
Total incident radiation (kWh/m^2/year)	1,564
Revenue for non-irrigation periods for crop rotation 1 (₹)	23,238
Revenue for non-irrigation periods for crop rotation 2 (₹)	24,977

4.3.5.3 Revenue from carbon trading

Revenue from carbon trading for the SWP system is estimated based on the carbon emission reduction achieved through solar energy use in irrigation. It compares the emission reduction of SWP with DWP, which has higher carbon emissions. Estimated reductions are 598 kg of CO_2 per year for CR1 and 427 kg of CO_2 per year for CR2 compared to DWP. Revenue from carbon trading is estimated at ₹347 per year for CR1 and ₹248 per year for CR2. This highlights the potential of SWP systems for sustainable agriculture, carbon emission reduction, and additional revenue through carbon trading. **Table 4.9** provides the annual carbon credit values for the pumping options.

Table 4.9: Estimated value of CO_2 emission for the pumping options

	CR1			CR2		
	SWP	DWP	EWP	SWP	DWP	EWP
Carbon credits (₹)	53	400	353	38	286	254

4.3.5.4 Total revenue

The total revenue generated from the different pumping options is presented in **Table 4.10**. It can be seen that the revenue generated from the SWP system is higher than that generated from DWP and EWP, making it a more economically viable option for irrigation in terms of revenue. The revenue from the sale of surplus electricity and carbon trading is an additional source of income for SWP. This additional revenue can help to offset the higher capital cost of the SWP system in the long term.

Table 4.10: Revenue per year for different pumping options

Parameters	SWP	SWP (Subsidised)	DWP	EWP
CR1				
Revenue from crop (₹)	41,87,680	41,87,680	41,87,680	41,87,680
Revenue from solar (₹)	23,238	23,238	0	0
Revenue from carbon trading (₹)	347	347	0	0
Total revenue (₹)	42,11,265	42,11,265	41,87,680	41,87,680
CR2				
Revenue from crop (₹)	2,72,780	2,72,780	2,72,780	2,72,780
Revenue from solar (₹)	24,977	24,977	0	0
Revenue from carbon trading (₹)	248	248	0	0
Total revenue (₹)	2,98,005	2,98,005	2,72,780	2,72,780

4.3.6 Economic analysis

4.3.6.1 Net present value

The results demonstrated that the NPV of the SWP (Subsidised) system is higher than that of DWP and EWP, indicating its superior profitability. This is primarily attributed to factors such as no energy cost, increased revenue from selling surplus electricity, and revenue from carbon trading. The NPV for SWP without subsidy is lower despite higher revenue generation due to its higher initial cost. The NPV analysis provides valuable insights into the financial viability of pumping options, aiding decision-making and investment planning for farmers and other stakeholders in the agricultural sector. The NPV for pumping options calculated is presented in **Table 4.11** below.

Table 4.11: Net Present Value for 10 years

Parameters	SWP	SWP (Subsidised)	DWP	EWP
		CR1		
Net present value (₹)	2,51,17,546	2,55,57,495	2,54,21,272	2,55,37,537
Rank	4	1	3	2
		CR2		
Net Present Value (₹)	11,32,210	15,72,159	14,40,334	15,20,241
Rank	4	1	3	2

The positive NPV values for all options indicated that they are financially viable. However, the SWP (Subsidised) had the highest NPV for both CR1 and CR2, indicating that it is the most economically profitable option irrespective of different crop rotations. Therefore, it can be concluded that the SWP (Subsidised) is the most financially feasible and profitable pumping option for the study area.

4.3.6.2 Payback period

Table 4.12: The payback period for pumping options

Pumping options	Investment (₹)	Annual net cash flow (₹)	Payback period (Years)	Rank
		CR1		
SWP	3,34,100	41,32,495	0.0808	4
SWP (Subsidised)	66,820	41,68,311	0.0160	3
DWP	31,500	41,42,124	0.0076	1
EWP	33,553	41,61,367	0.0081	2
		CR2		
SWP	3,34,100	2,28,992	1.4590	4
SWP (Subsidised)	66,820	264808	0.2523	3
DWP	31,500	239337	0.1316	1
EWP	33,553	252662	0.1328	2

In **Table 4.12** the ranks column represents the ranking of each pumping option based on their payback period. Option DWP has the shortest payback period and is ranked first, followed by EWP and SWP (Subsidised), which are ranked second and third. SWP has the longest payback period and is ranked fourth for both crop rotations.

The payback period calculation focuses solely on the cost of irrigation and does not consider other associated costs such as land ownership, input expenses, labour, and machinery. These additional factors can significantly impact the actual payback period of an irrigation system. The calculation provides a valuable perspective on the recovery of the initial investment specifically related to irrigation costs. However, it should be understood that the true payback period may be longer when considering the comprehensive financial implications of agricultural operations. Factors such as crop yields, market prices, input costs, and operational efficiency can vary and influence the overall profitability and payback period. Therefore, while the presented payback period calculation is informative for assessing the irrigation investment in isolation.

4.3.6.3 Ranking based on annual cost of irrigation (CoI) by annual net cash flow (R_t)

The ranking based on the CoI by R_t provides valuable insights into the financial performance of considered pumping options. The results indicate that the EWP option ranks first due to its lower CoI demonstrating its financial attractiveness followed by the SWP (Subsidised) option. The DWP option ranks third and finally, the SWP option without subsidy ranks fourth. The SWP (Subsidised) option also performs well in terms of annual net cash flow, indicating its financial viability. This ranking aids farmers and stakeholders in informed irrigation decisions. The ranking is presented in **Table 4.13**.

Table 4.13: Ranking based on CoI by R_t

Ranking	CR1		CR2	
	Pumping options	CoI/R_t	Pumping options	CoI/R_t
1	EWP	0.63	EWP	0.80
2	SWP (Subsidised)	1.03	SWP (Subsidised)	1.25
3	DWP	1.10	DWP	1.40
4	SWP	1.91	SWP	3.01

4.3.7 Sensitivity analysis

The results of the sensitivity analysis highlight the importance of subsidy rates in promoting the adoption of SWP. Based on the findings shown in Fig. 4.7, it is observed that by increasing the subsidy rate to 90%, the capital cost of the SWP system can be similar to that of the DWP and EWP options. This indicates that a higher subsidy rate can significantly reduce the upfront investment required for implementing SWP, making it more comparable to conventional pumping options in terms of capital cost.

Furthermore, Fig. 8 reveals that when a subsidy rate of 95% is applied to the SWP system, the ownership cost becomes equivalent to that of the DWP and EWP options. This suggests that a higher subsidy rate can offset the higher ownership costs associated with the SWP system, such as depreciation charges, interest rates, and insurance costs, making it more financially competitive with other pumping options.

By revising and increasing the subsidy rates, policymakers and stakeholders can potentially make the capital and ownership costs of SWP more comparable to conventional pumping options, thereby incentivizing farmers to transition towards sustainable and environmentally friendly irrigation practices.

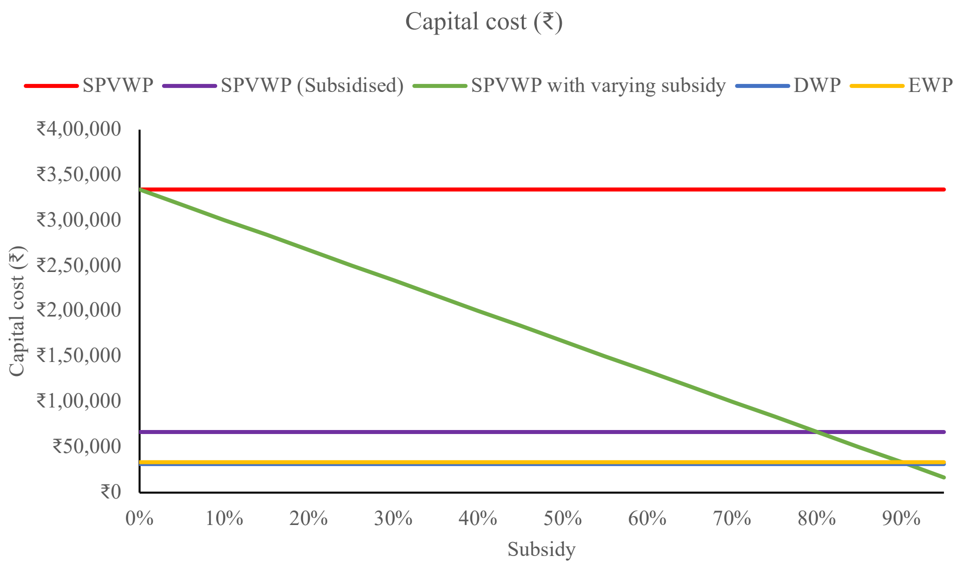

Fig. 4.7: Rate of subsidy for SWP to match the capital cost of DWP and EWP

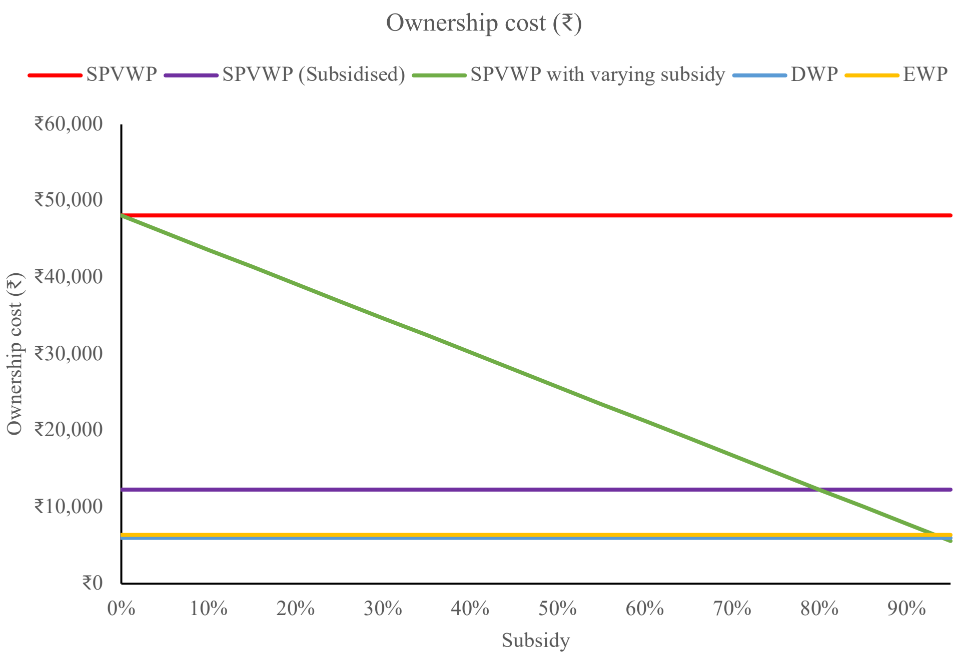

Fig. 4.8: Rate of subsidy for SWP to match the annual ownership cost of DWP and EWP

4.3.8 Variation of discharge with radiation

The study also examines the relationship between solar radiation and the discharge rate of SWP systems. Solar radiation significantly impacts the energy output of the PV unit, affecting the pumping capacity and discharge. The discharge is influenced by varying solar radiation throughout the day and across seasons. Higher solar radiation leads to increased electricity generation, resulting in higher pump output and discharge. Conversely, lower solar radiation leads to reduced pump output and discharge. Modelling this relationship involves using appropriate equations and empirical data, such as the power-voltage characteristics of the PV unit. The discharge refers to the volume of water flowing through the pumping system against the hydraulic head (H) to the receiving area in a given time. The hydraulic head (H) represents the height level that the water must work against, representing the available mechanical energy. The total energy required can be determined using the provided equation:

$$E_h = \rho g H \int_0^t Q(\tau) d\tau \tag{4.9}$$

The incident solar energy is converted to electrical energy to power the water pump and overcome the hydraulic head. The relevant energy equations are as follows. The pump's electrical energy requirement can be expressed as:

$$E_e = \int_0^t V(\tau) \times I(\tau) d\tau \tag{4.10}$$

and the current generated from solar cell is given by:

$$I(\tau) = I_L - I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right] \tag{4.11}$$

where I_L is the light-generated current which is given by:

$$I_L = qAG(\tau)\left(L_n + L_p + W\right) \tag{4.12}$$

where $G(\tau)$ is the carrier generation rate (atoms/cm^3/s), A is the area of a solar cell, q is the charge on an electron, L_n and L_p are the diffusion lengths of the electrons and holes and W is the width of the depletion layer. V is the voltage generated across the load connected, n is the ideality factor, k is the Boltzmann constant and T is the temperature of the solar cell. I_0 is the leakage current that flows through the cell under non-illuminated conditions due to recombination.

The relationship between solar radiation and the performance of the SWP system is essential. Higher radiation leads to increased current and power output, enabling more hydraulic energy for water pumping and resulting in a higher discharge. Factors such as pump efficiency, transmission losses, and system configuration also influence the discharge. Analysing this relationship allows for optimizing operations, improving water efficiency, reducing energy consumption, and enhancing crop productivity. Farmers and system operators can make informed decisions and adjust irrigation schedules based on this knowledge. By maximizing the benefits of solar radiation, the SWP system can achieve optimal performance and contribute to sustainable agricultural practices.

4.3.9 Solar irrigation-based microgrid

The integration of the PV unit of the SWP system as a microgrid for solar irrigation presents several advantages and opportunities. By leveraging the surplus electricity generated by the PV unit, it becomes possible to supply power to other energy consumers within the agricultural community. This can include powering other irrigation systems, agricultural machinery, storage facilities, or even nearby households. The use of a microgrid allows for greater energy self-sufficiency and resilience, reducing dependence on the main grid and the associated costs. It also opens up the potential for energy trading within the community, where surplus electricity can be sold to neighbouring farms or businesses. Furthermore, a solar-based microgrid contributes to the overall sustainability and environmental benefits, as it reduces reliance on fossil fuels and lowers carbon emissions. However, the implementation of a solar irrigation microgrid requires careful planning, including system design, storage capacity, and grid management to ensure reliable and efficient operation. Policy and regulatory frameworks also play a crucial role in supporting the development and adoption of such microgrids in the agricultural sector. Overall, the use of the PV unit of the SWP as a microgrid holds great promise for enhancing energy access, promoting renewable energy integration, and fostering agricultural sustainability.

4.4 Feasibility analysis for electric vehicle charging

The SWP system operates only when water is required in the field. During the periods when irrigation is not needed, the excess energy generated by the SWP system can be efficiently utilized for charging EVs or fed into the grid [73, 74].

The energy generated by the SWP system on a typical day is determined using eq. 3.14 and is represented as below:

$$E_{SWP}(i) = \eta_{PV} \times A_{SWP}(i) \times PR \times E_{sol} \quad (4.13)$$

Where $E_{SWP}(i)$ is the total energy generated by the SWP system on a day (kWh/day)
On irrigation days the generated energy from SWP system is utilized for water pumping as shows:

$$E_{pump}(i) = E_{SWP}(i) \quad (4.14)$$

where $E_{pump}(i)$ is the energy required for water pumping on an irrigation day (kWh/day)
The excess energy generated is calculated as:

$$E_{surplus}(i) = E_{SWP}(i) - E_{pump}(i) \quad (4.15)$$

where $E_{surplus}(i)$ is the excess energy available from SWP on non-irrigation days (kWh/day). On non-irrigation days the excess energy generated from SWP system can be fully used to charge EVs.
Since $E_{pump}(i) = 0$ on non-irrigation days, $E_{surplus}(i) = E_{SWP}(i)$

4.4.1 Load modelling for EV charging

The total load requirement for EV charging is calculated as:

$$L(i,j) = \frac{E_{req}}{t_c} \quad (4.16)$$

where $L(i,j)$ is the load requirement for EV charging at location i and time j (kW), t_c is the charging duration required (hours) to reach the battery's full capacity and E_{req} is the energy requirement of the battery in kWh.

The energy demand to charge the EV battery over the given charging period is represented below which can be calculated as:

$$E_{EV} = V_{batt} \times I_{batt} \times T_{charging} \tag{4.17}$$

where V_{batt} is the voltage of EV battery, I_{batt} is the current required for charging and $T_{charging}$ is the charging time in hours.

4.4.2 EV charging infrastructure development

The development of EV charging infrastructure utilizing surplus energy from SWP systems presents a technically viable and sustainable solution for optimizing renewable energy utilization while supporting electric mobility. SWP systems operate intermittently, often generating excess photovoltaic power during periods when water pumping is not required. By integrating bidirectional inverters, DC-DC converters, and maximum power point tracking (MPPT) controllers, surplus solar power can be efficiently redirected to EV charging stations. The deployment of such infrastructure requires optimized power electronics, including grid-interactive inverters and energy management systems (EMS), to ensure stable energy transfer, mitigate intermittency issues, and enhance charging reliability [75].

To optimize the operational effectiveness of SWP-based charging infrastructure, smart charging station designs must be implemented, with each charging point capable of both slow and fast charging, depending on real-time surplus energy availability. This adaptive charging strategy requires IoT-enabled smart controllers for remote monitoring, predictive load management, and energy optimization. These controllers facilitate real-time adjustments based on surplus energy availability and user demand, ensuring efficient utilization of generated electricity and minimizing power wastage. Furthermore, dedicated e-rickshaw charging stations should be established near SWP installations to ensure efficient energy use, particularly in rural and semi-urban areas where e-rickshaws are a primary mode of transportation [76].

To further improve operational efficiency, battery swapping stations can be integrated into the system, allowing e-rickshaw drivers to replace depleted batteries quickly instead of waiting for conventional charging. This requires the implementation of modular battery packs, standardized connectors, and automated battery exchange mechanisms to facilitate seamless and rapid battery replacements. Additionally, the integration of EV charging infrastructure with an advanced EMS enables synchronization of charging schedules with surplus energy availability, reducing grid dependency and enhancing overall system resilience. Battery energy storage systems (BESS) can be employed to provide buffering capacity, ensuring a stable energy supply for EVs beyond peak solar hours and improving system reliability [77].

From a technical perspective, challenges such as harmonics mitigation, power quality management, and adaptive charging algorithms must be addressed to ensure stable and efficient operation. The implementation of predictive energy dispatch models and demand-response mechanisms can further optimize energy distribution and prevent localized grid overloading. Additionally, local community involvement is crucial for the long-term sustainability of SWP-integrated EV charging infrastructure. Training programs for farmers and local residents on station maintenance and operation can enhance system longevity, improve local technical expertise, and promote community ownership of the project.

Energy availability analysis

The analysis highlights the potential of using excess solar energy for EV charging infrastructure during two crop rotation scenarios:

For Crop Rotation 1, the total surplus energy available is 6,639.41 kWh/year, while in Crop Rotation 2, the surplus energy is 7,136.41 kWh/year. This shows that more surplus energy is available in Crop Rotation 2, which can be effectively utilized for EV charging, particularly during periods when the SWP system is not in use for irrigation.

4.4.3 Smart grid integration

Smart grid integration can help manage and distribute the generated electricity effectively. Implement an energy management system (EMS) to allocate electricity between irrigation needs and EV charging.

Priority of Utilization:

a) First priority is to charge the EV:

If $E_{surplus}(i) \geq E_{req}$, the EV is fully charged, and the remaining energy is fed into the grid:

$$E_{grid}(i) = E_{surplus}(i) - E_{req} \tag{4.18}$$

If $E_{surplus}(i) < E_{req}$, all $E_{surplus}(i)$ is used for EV charging.

b) Any remaining energy goes to the grid if EV charging demand is met. The smart grid model will then dynamically allocate this excess energy to other locations or charging stations, optimizing EV charging infrastructure. Alternatively, if $E_{SWP}(i) < E_{req}$, additional power may need to be sourced from the grid.

Inverter and Battery Storage

To maximize the utilization of excess energy generated from SWP systems for EVs charging, a bidirectional inverter and a battery storage system need to be installed. The bidirectional inverter converts DC power from the solar PV modules into AC power. The battery storage system stores the energy generated from the SWP system during peak sunshine hours for later use. This is particularly useful when solar energy is unavailable, such as during nighttime, which ensures a more reliable EV charging infrastructure.

4.4.4 EV Specifications and charging requirements

The charging capacity is determined based on the types of EVs in the community (in this case electric rickshaws, three-wheelers).

Perform a battery analysis to evaluate voltage, current, and power requirements for EV charging. Match the charging specifications with the capabilities of the SWP system during surplus generation hours. The battery specifications and energy requirements for EV charging is presented in **Table 4.14.**

Inverter Capacity P_{inv}: The inverter must handle the maximum output power generated by the solar panels. Therefore,

$$P_{inv} \geq P_{solar\_max}$$

Battery Storage Requirements ($E_{storage}$): To ensure consistent power availability for EV charging:

$$E_{storage} = E_{surplus} \times \eta_{storage} \tag{4.19}$$

where $\eta_{storage}$ is the efficiency of the battery storage system

Table 4.14: Battery specifications and energy requirements for charging

Parameter	Value
Battery Voltage	48 V

Current Required	30 A
Energy per Charge	2.5 kWh

4.4.5 Energy utilization efficiency

Energy utilization efficiency ($\eta_{charging}$) is a key parameter in assessing the effectiveness of EV battery charging. It is defined as the ratio of the energy successfully stored in the battery ($E_{charged}$) to the total energy supplied by the charging source ($E_{supplied}$), expressed as a percentage:

$$\eta_{charging} = \frac{E_{charged}}{E_{supplied}} \times 100\% \tag{4.2019}$$

This efficiency metric accounts for energy losses due to resistive heating, power conversion inefficiencies, and other parasitic losses within the charging system. Higher charging efficiency indicates reduced energy waste, leading to lower operating costs and improved overall sustainability of EV charging infrastructure. Optimizing $\eta_{charging}$ is essential for enhancing battery longevity, reducing grid demand, and improving the economic and environmental viability of EV adoption.

4.4.6 Potential of EV Charging

To estimate the potential of charging EVs from the excess energy of the SWP systems parameters includes battery capacity, average distance per charge and charging efficiency is considered. The battery capacity of the EV is 40 kWh, allowing it to cover a distance of 250 km on a single charge. The charging efficiency of the battery is considered 90%. Using these parameters, the number of EVs that can be fully charged annually during each rotation can be calculated as below:

$$\text{Number of fully charged EVs} = \frac{\text{Surplus Energy (kWh)}}{\text{Battery Capacity (kWh) / Charging Efficiency}} \tag{4.201}$$

For Crop Rotation 1, it is determined that 149 electric vehicles (EVs) can be fully charged using the excess energy generated. Similarly, for Crop Rotation 2, a total of 160 EVs can be fully charged. To effectively utilize the excess energy, it is important to establish charging infrastructure near the SWP installations. The infrastructure should include EV charging stations with compatible connectors to allow easy plug-and-play solutions for EV owners.

This analysis primarily estimates EV charging potential from a supply-side perspective, based on surplus electricity from SWP systems. However, limited data on EV ownership, usage patterns, and charging demand in rural Assam restricts detailed demand-side modeling. Qualitative insights indicate a gradual increase in rural EV adoption, particularly for two and three-wheelers.

A key challenge is the temporal mismatch between surplus solar generation during daytime and typical EV charging demand, often occurring in mornings or evenings. This issue highlights the importance of energy storage and smart grid integration to align supply and demand effectively. Future studies should incorporate detailed demand profiles to enable comprehensive EV charging feasibility assessments in rural contexts.

4.4.7 Optimized energy management strategies

In this section, an energy management framework is proposed to optimize the allocation of PV power, prioritizing SWP systems, followed by EV charging, and finally, grid export. The strategy ensures that the SWP receives sufficient power to meet irrigation needs, which are critical for agricultural productivity. Surplus solar energy is then dynamically diverted to EV charging stations, promoting sustainable transportation. Any remaining excess power is fed into the grid, enhancing grid stability and maximizing solar utilization. Real-time monitoring of solar generation and demand is implemented to ensure efficient operation, and demand-side management (DSM) strategies are incorporated to align EV charging with peak solar generation hours. This includes incentivizing EV charging during the day and optimizing irrigation schedules to coincide with high solar availability. The following algorithm encapsulates the proposed energy management strategy:

4.4.8 Energy management algorithm

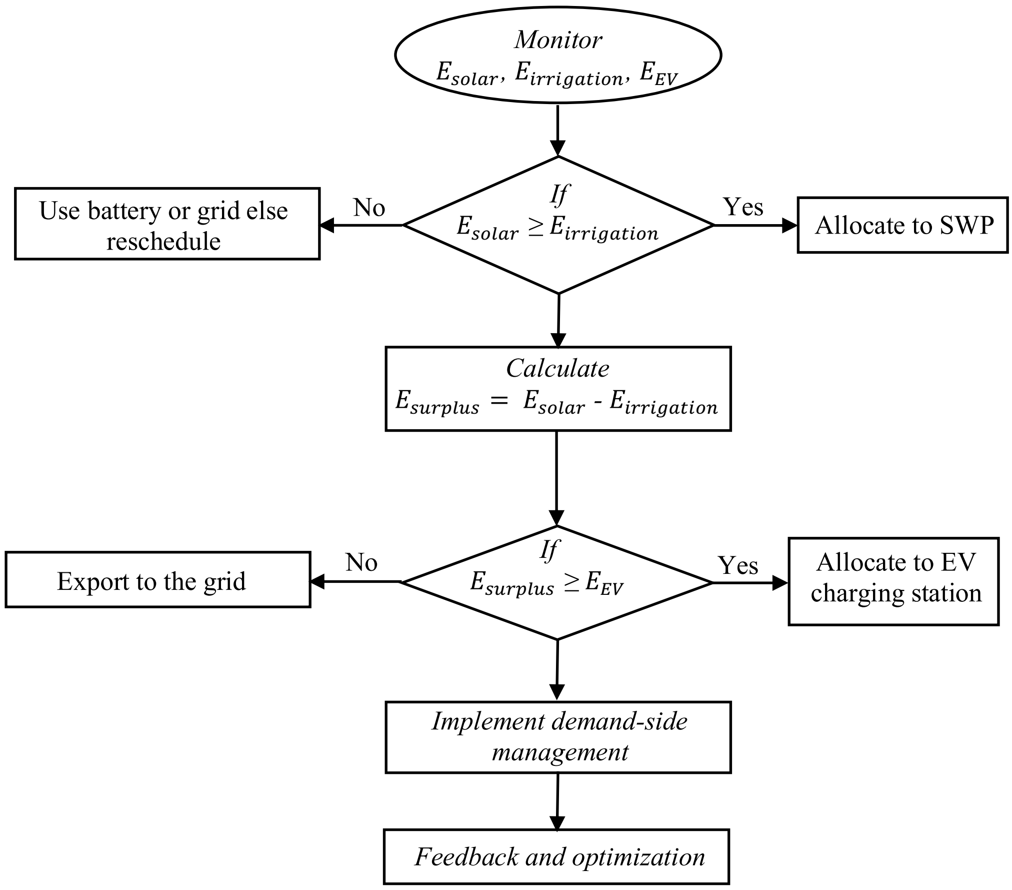

Fig. 4.9: Energy management algorithm

Monitor Solar Generation and Demand: Solar energy generation (E_{solar}) depends on irradiation, which fluctuates throughout the day, leading to variations in power output. Similarly, energy demand is not constant and varies based on irrigation requirements ($E_{irrigation}$) and EV charging (E_{EV}) station needs. By integrating real-time monitoring systems for both generation and consumption, the excess energy from SWP systems can be utilized more efficiently. Also, based on demand, energy can either be fed into or drawn from the grid, which will help in minimizing energy wastage.

Prioritize SWP: When solar energy generation (E_{solar}) meets or exceeds the irrigation energy requirement ($E_{irrigation}$), the necessary power should be allocated to the SWP system. If E_{solar} is lower than $E_{irrigation}$, the deficit can be supplemented using battery storage or grid, else irrigation can be rescheduled. When irrigation is required in the field, the first priority will be the SWP system, regardless of whether solar energy generation meets the irrigation energy requirement or not.

Allocate surplus power to EV charging: The surplus energy ($E_{surplus}$) is determined by subtracting the power required for irrigation ($E_{irrigation}$) from the total power generated by the solar system (E_{solar}), as shown by the equation:

$$E_{surplus} = E_{solar} - E_{irrigation} \quad (4.212)$$

Once surplus power is identified, it is allocated to EV charging stations. When the demand for irrigation is met or no longer required, the surplus power will be prioritized for use by the EV charging stations.

Export Excess Power to the Grid: When the demand at the EV charging stations is lower, any remaining surplus energy can be exported to the grid. This ensures that the excess power is utilized efficiently, which will reduce the wastage of energy.

Incorporate Demand-Side Management: One effective strategy is to notify EV users about the optimal charging times during peak solar energy generation hours. And also, dynamically adjust the irrigation schedules based on the solar energy forecast.

Feedback and Optimization: Continuously update allocations based on real-time conditions and refine schedules to enhance efficiency.

4.5 Summary of findings

4.5.1 Summary

Energy efficiency and cost considerations

The findings of the study highlight several important factors influencing the choice and viability of different pumping options. Firstly, SWP stand out as the most energy-efficient option, as they incur no energy costs compared to DWP and EWP, which rely on diesel and grid electricity, respectively. DWP, in particular, incurs higher energy costs compared to EWP. DWP and EWP benefit from lower operator costs due to their continuous operation, while SWP operates only during peak sunshine hours, potentially increasing the number of operational days required to meet irrigation needs.

Capital and operational costs

One of the significant challenges faced by SWP is its higher capital cost, which includes depreciation and interest costs. While subsidies can mitigate this challenge to some extent, the ownership cost of an unsubsidized SWP remains high. Additionally, the variability in peak sunshine hours must be taken into account when considering SWP's performance. The reliance on solar energy makes it susceptible to fluctuations in weather conditions, affecting its efficiency. The study focuses on the SWP AC system as it offers comparable costs to the SWP DC system while providing slightly higher discharge capacity. However, it is worth noting that DC pumps may have advantages in certain scenarios but may also be more challenging to repair and maintain.

Revenue generation and financial viability

The benchmark cost for SWP systems is higher in North-eastern states like Assam, likely due to transportation costs, installation difficulties, and remote locations. In terms of revenue generation from the PV unit, it is dependent on the rate per unit of electricity, which can vary across regions based on regulatory frameworks. While consuming PV-generated electricity reduces reliance on the grid and can be economically beneficial, selling surplus electricity to the grid may not always result in significant financial gain. In some cases, lower tariffs for selling electricity to the grid compared to prevailing grid electricity rates in the Assam region can lead to financial losses.

To promote the adoption of SWP systems, subsidizing the capital cost is crucial, and this should be considered before calculating bank interest for subsidized projects. It is important to note that the analysis assumes a salvage value at the end of 10 years for SWP. However, considering the cost of electricity generation for the remaining useful life of the PV unit could potentially result in higher revenue estimates.

Integration with electric vehicle charging

The study also explores the feasibility of utilizing excess energy generated by SWP systems for EV charging. Since SWP systems operate intermittently based on irrigation needs, surplus solar energy is often available when irrigation is not required. Instead of letting this energy go to waste, it can be efficiently redirected to power EVs or be fed into the grid, contributing to both renewable energy optimization and sustainable mobility.

4.5.2 Policy implications

Cost-effectiveness and long-term benefits

From the perspective of farmers, the primary concern is to choose the most cost-effective pumping option. The analysis reveals that in terms of upfront investment such as capital cost, DWP is the cheapest, followed by EWP, subsidized SWP, and non-subsidized SWP. Sensitivity analysis is also conducted to examine the role and extent of subsidies.

In terms of long-term profitability assessed through Net Present Value (NPV) analysis, subsidized SWP emerges as the most financially viable pumping option, followed by EWP, DWP, and non-subsidized SWP. Crop rotation has minimal influence on the cost trends across all pumping options.

The study suggests that SWP is a sustainable option for long-term and large-scale farming, offering significant environmental benefits. However, for small-scale and short-term farming, the high investment costs of SWP may not be offset by cost savings compared to DWP or EWP, given the minimal energy consumption. Therefore, a thorough cost-benefit analysis and consideration of long-term advantages are crucial when making policy recommendations regarding the adoption of SWP.

Policy recommendations

The findings of this study have significant policy implications for promoting sustainable irrigation practices in Assam, India, and regions with similar conditions. Considering the current circumstances, the following policy recommendations are proposed:

- Targeted Subsidy Support: Given the low level of irrigation in Assam due to fragmented landholding patterns and the limited financial capacity of farmers, policymakers should consider providing targeted subsidies specifically for SWP systems. These subsidies can alleviate the upfront capital costs associated with SWP installations, making them more accessible and financially viable for small-scale farmers. By promoting the adoption of SWP systems, farmers can overcome the challenge of high diesel prices, ensuring a reliable and affordable source of irrigation.
- Investment in Irrigation Infrastructure: Recognizing the essential role of irrigation in enhancing crop production, policymakers should prioritize investment in irrigation

infrastructure. By developing and upgrading irrigation networks, farmers can access a steady supply of water, leading to increased agricultural productivity and overall economic growth.

- Promoting Cash Crops with Irrigation Support: To make agriculture a more lucrative venture and address unemployment, policymakers should promote the cultivation of cash crops like tea and strawberries. These crops have the potential to generate higher returns, but they require consistent and adequate irrigation support. Implementing irrigation schemes tailored to the specific water requirements of these crops can unlock their economic potential and attract more farmers to engage in cash crop cultivation.
- Strengthening Farmer Cooperatives: Encouraging the formation of farmer cooperatives can help address the issue of underutilized lands and enable collective investment in irrigation infrastructure. By pooling resources and expertise, farmers can share the costs of irrigation systems and collectively manage water resources. Strong farmer cooperatives can negotiate better prices for inputs, including irrigation services, further enhancing the financial viability of agriculture in the region.

EV charging infrastructure and sustainable energy

The successful deployment of SWP-integrated EV charging infrastructure offers multiple benefits, including increased energy self-sufficiency, reduced reliance on fossil fuels, and improved rural mobility. By leveraging surplus solar energy efficiently through smart charging stations, dedicated e-rickshaw hubs, and battery swapping solutions, this model contributes to the decarbonization of both the transportation and agricultural sectors. The integration of advanced power electronics, smart control systems, and energy storage solutions ensures a scalable and resilient charging infrastructure, fostering a more sustainable energy ecosystem.

Government support for electric mobility

The Indian government has been actively driving the transition to electric mobility through targeted policy interventions and financial incentives. One of the most notable initiatives is the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, which aims to promote EV adoption by offering subsidies and supporting infrastructure development. It emphasizes the expansion of public charging stations to enhance the accessibility of EV infrastructure. Alongside national efforts, several states have introduced their own incentives to make EVs more affordable.

References

[1] Agrawal, S., and Jain, A. Sustainable deployment of solar irrigation pumps: Key determinants and strategies. *Wiley Interdisciplinary Reviews: Energy and Environment*, 8(2):e325, 2019. DOI: https://doi.org/10.1002/wene.325

[2] Dwivedy, N. Challenges faced by the agriculture sector in developing countries with special reference to India. *International journal of rural studies*, 18(2):1-6, 2011.

[3] Malhi, G. S., Kaur, M., and Kaushik, P. Impact of climate change on agriculture and its mitigation strategies: A review. *Sustainability*, 13(3):1318, 2021. DOI: https://doi.org/10.3390/su13031318

[4] Singh, M. A. H. E. N. D. R. A. Challenges and opportunities for sustainable viability of marginal and small farmers in India. *Agricultural Situation in India*, 77(2):133-14, 2012.

[5] Tiwari, R. Explained: What farm law repeal means for farmers, govt, Opposition and PM. *The Indian Express*, 2021. https://indianexpress.com/article/explained/farmers-protest-farm-laws-repeal-7632011/ (Retrieved on 21 November 2021).

[6] Gupta, N., Pradhan, S., Jain, A., and Patel, N. Sustainable agriculture in India. Council on Energy, Environment and Water, 2021. https://www.ceew.in/.

[7] Kanika, M. List of agricultural subsidies given to farmers by the government of India, 2022. Retrieved on 24 February 2022 from https://krishijagran.com/agriculture-world/list-of-agricultural-subsidies-given-to-farmers-by-government-of-india/ .

[8] Salunkhe, H. The overview of Government subsidies to agriculture sector in India, 2022. Available at SSRN 4555039. DOI: https://doi.org/10.9790/2380-0154347

[9] Gangwar, D. S., and Tyagi, S.Internet of things connected smart farm solutions for sustainable agro-ecological and rural development. Int J Eng Future Technol, 14(2), 64-71, 2017. http://www.ceser.in/ceserp/index.php/IJEFT/article/view/4795.

[10] Garg, K. K., Wani, S. P., and Patil, M. D. A simple and farmer-friendly decision support system for enhancing water use efficiency in agriculture: tool development, testing and validation. *Current Science*, 1716-1729, 2016. DOI: https://doi.org/10.18520/cs/v110/i9/1716-1729

[11] Martis, J. E., Sannidhan, M. S., and Sudeepa, K. B. A farmer-friendly connected IoT platform for predicting crop suitability based on farmland assessment. *Internet of Things and Analytics for Agriculture*, Volume 3:247-272, 2022. DOI: https://doi.org/10.1007/978-981-16-6210-2_12

[12] Martey, E. Empirical analysis of crop diversification and energy poverty in Ghana. *Energy Policy*, 165:112952, 2022. DOI: https://doi.org/10.1016/j.enpol.2022.112952

[13] Baruah, D. C., and Bora, G. C. Energy demand forecast for mechanized agriculture in rural India. *Energy Policy*, 36(7):2628-2636, 2008. DOI: https://doi.org/10.1016/j.enpol.2008.03.030

[14] Mehta, C. R., Chandel, N. S., Jena, P. C., and Jha, A. Indian agriculture counting on farm mechanization. *Agricultural Mechanization in* Asia, Africa and Latin America, 50(1), 84-89, 2019. https://www.cabdirect.org/cabdirect/abstract/20193212856.

[15] Jung, Y., Jang, H., and Matthews, K. R. Effect of the food production chain from farm practices to vegetable processing on outbreak incidence. *Microbial Biotechnology*, 7(6):517-527, 2014. DOI: https://doi.org/10.1111/1751-7915.12178

[16] Knox, J. W., Kay, M. G., and Weatherhead, E. K. Water regulation, crop production, and agricultural water management—Understanding farmer perspectives on irrigation efficiency. *Agricultural water management*, 108:3-8, 2012. DOI: https://doi.org/10.1016/j.agwat.2011.06.007

[17] Garg, G., Gupta, S., Mishra, P., Vidyarthi, A., Singh, A., and Ali, A. CROPCARE: an intelligent real-time sustainable IoT system for crop disease detection using mobile vision. *IEEE Internet of Things Journal*, 10(4):2840-2851, 2021. DOI: https://doi.org/10.1109/jiot.2021.3109019

[18] Kumar, D., and Kalita, P. Reducing postharvest losses during storage of grain crops to strengthen food security in developing countries. *Foods*, 6(1):8, 2017. DOI: https://doi.org/10.3390/foods6010008

[19] Goliath, R. Handbook of Statistics on Indian States. Reserve Bank of India, 2021. Retrieved on 6 September 2022 from https://m.rbi.org.in/scripts/AnnualPublications.aspx?head=Handbook%20of%20Statistics%20on%20Indian%20States

[20] ENVIS Centre: Assam, 2015. Agriculture in Assam. Status of environment and related issues. Retrieved on 9 December 2022 from http://asmenvis.nic.in/Database/Agriculture_839.aspx

[21] Upadhyaya, T. P. Role of agriculture in economic development of Assam. *Cogniz. J*, 2:10-21, 2022. DOI: https://doi.org/10.47760/cognizance.2022.v02i06.002

[22] Ministry of Agriculture and Farmer's Welfare, Rice productivity analysis in India, In Directorate of Rice Development. Government of India, 2002. https://drdpat.bih.nic.in/.

[23] Department of Agriculture and Horticulture, Irrigation, Directorate of Agriculture, Government of Assam, 2022. Retrieved on 12 September 2021 from https://diragri.assam.gov.in/portlets/irrigation

[24] Department of Economic and Social Affairs. India plans to produce 175 GW of renewable energy by 2022, 2021. Retrieved on 17 December 2021 from https://sdgs.un.org/partnerships/india-plans-produce-175-gw-renewable-energy-2022

[25] Graham, N.T., Gakkhar, N., Singh, A.D., Evans, M., Stelmach, T., Durga, S., Godara, R., Gajera, B., Wise, M. and Sarma, A.K. Integrated analysis of increased bioenergy futures in India. *Energy Policy*, 168:113125, 2022.
DOI: https://doi.org/10.1016/j.enpol.2022.113125

[26] Hartung, H., and Pluschke, L. The Benefits and Risks of Solar Powered Irrigation-a global overview, 2018.

[27] Closas, A., and Rap, E. Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. *Energy Policy*, 104:33-37, 2017. DOI: https://doi.org/10.1016/j.enpol.2017.01.035

[28] Lefore, N., Closas, A., and Schmitter, P. Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. *Energy Policy*, 154:112313, 2021. DOI: https://doi.org/10.1016/j.enpol.2021.112313

[29] Rathore, P. K. S., Das, S. S., and Chauhan, D. S. Perspectives of solar photovoltaic water pumping for irrigation in India. *Energy strategy reviews*, 22:385-395, 2018. DOI: https://doi.org/10.1016/j.esr.2018.10.009

[30] Senol, R. An analysis of solar energy and irrigation systems in Turkey. *Energy Policy*, 47:478-486, 2012. DOI: https://doi.org/10.1016/j.enpol.2012.05.049

[31] Yashodha, Y., Sanjay, A., and Mukherji, A. Solar irrigation in India: a situation analysis report (No. H050619),2021. *International Water Management Institute*. DOI: https://doi.org/10.5337/2021.217

[32] Command Area Development and Water Management (CADWM). Department of Water Resources, Government of Assam,1974. Retrieved on 14 September 2021 from https://irrigation.assam.gov.in/projects/cadwm-projects

[33] Minor Irrigation Programme (MIP). Department of Agriculture, Government of Assam,1986. Retrieved on 2 September 2021 from https://irrigation.assam.gov.in/projects/minor-irrigation-schemes

[34] Accelerated Irrigation Benefit Programme (AIBP), 1996. Retrieved on 5 September 2021 from https://indiawris.gov.in/wiki/doku.php?id=accelerated_irrigation_benefit_programme

[35] Pradhan Mantri Krishi Sinchayee Yojana (PMKSY). Irrigation, Government of Assam, 2015. Retrieved on 14 February 2023 from https://irrigation.assam.gov.in/portlets/pradhan-mantri-krishi-sinchayee-yojana-pmksy

[36] Rural Infrastructure Development Fund (RIDF). Department of Agriculture, Government of Assam, 2016. Retrieved on 14 February 2023 from http://assamagriculture.in/dashboard/index.html

[37] Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM). Ministry of New and Renewable Energy, 2019. Retrieved on 14 February 2023 from https://pmkusum.mnre.gov.in/landing.html

[38] Hilarydoss, S. Suitability, sizing, economics, environmental impacts and limitations of solar photovoltaic water pumping system for groundwater irrigation—a brief review. *Environmental Science and Pollution Research*, 30(28):71491-71510, 2023. DOI: https://doi.org/10.1007/s11356-021-12402-1

[39] Rathore, P. K. S., Das, S. S., and Chauhan, D. S. Perspectives of solar photovoltaic water pumping for irrigation in India. *Energy strategy reviews*, 22:385-395, 2018. DOI: https://doi.org/10.1016/j.esr.2018.10.009

[40] Boretti, A. Advantages and disadvantages of diesel single and dual-fuel engines. *Frontiers in Mechanical Engineering*, 5:64, 2019. DOI: https://doi.org/10.3389/fmech.2019.00064

[41] Press Information Bureau. Renewable Energy in India, Government of India, 2022. Retrieved on 9 September 2022 from https://pib.gov.in/FeaturesDeatils.aspx?NoteId=151141&ModuleId=2#:~:text=Increasing%20renewables%20capacity%20to%20500,)%20by%2045%25%20by%202030

[42] Campana, P. E., Li, H., Zhang, J., Zhang, R., Liu, J., and Yan, J. Economic optimization of photovoltaic water pumping systems for irrigation. *Energy Conversion and Management*, 95:32-41, 2015. DOI: https://doi.org/10.1016/j.enconman.2015.01.066

[43] Gao, X., Liu, J., Zhang, J., Yan, J., Bao, S., Xu, H., and Qin, T. Feasibility evaluation of solar photovoltaic pumping irrigation system based on analysis of dynamic variation of groundwater table. *Applied energy*, 105:182-193, 2013. DOI: https://doi.org/10.1016/j.apenergy.2012.11.074

[44] Agrawal, S., and Jain, A. Sustainable deployment of solar irrigation pumps: Key determinants and strategies. *Wiley Interdisciplinary Reviews: Energy and Environment*, 8(2):e325, 2019.

[45] Package of practice (POP) for horticulture crops. Assam Agricultural University, Jorhat and Department of Agriculture, Assam, 2015. Retrieved on 9 January 2023 from https://diragri.assam.gov.in/portlet-innerpage/package-of-practices

[46] Package of practice (POP) for Kharif crops. Assam Agricultural University, Jorhat and Department of Agriculture, Assam, 2015. Retrieved on 9 January 2023 from https://diragri.assam.gov.in/portlet-innerpage/package-of-practices

[47] Package of practice (POP) for rabi crops. Assam Agricultural University, Jorhat and Department of Agriculture, Assam, 2015. Retrieved on 9 January 2023 from https://diragri.assam.gov.in/portlet-innerpage/package-of-practices

[48] Khan, M. T. A. I., Sarkar, S., Hossain, S., Ahmed, A. U., and Pathik, B. B. The feasibility study of solar irrigation: Economical comparison between diesel and photovoltaic water pumping systems for different crops. In *2013 International Conference on Electrical Information and Communication Technology* (EICT) pages 1-5. IEEE, 2014.

[49] Ground Water Prospects Mapping. National Remote Sensing Centre, 2011. Retrieved on 9 January 2023 from https://www.nrsc.gov.in/readmore_geosci_grdwaterprospectmap?language_content_entity=en

[50] Solar water pumping systems (SWPS system design). System design, selection and installation guidelines, 2019. Retrieved on 10 April 2021 from https://watermission.org/wp-content/uploads/2019/10/System-Design-Selection-and-Installation-Guidelines.pdf

[51] [data set] NASA Langley Research Center, 2023. NASA POWER Data Access (Version 2.0.0). NASA Project. Retrieved on 30 January 2023 from https://power.larc.nasa.gov/data-access-viewer/

[52] DP cost, 2023. Kirloskar KOS-520+ 5 HP open well submersible pump price. Retrieved on 12 January 2023 from https://www.industrybuying.com/openwell-submersible-pump-kirloskar-PU.AG.OP.1415690/

[53] Kirloskar Varsha 4, 5hp Air Cooled Diesel Pumpset (Koel cost), 2023. Retrieved on 12 January 2023 from https://www.indiamart.com/proddetail/kirloskar-varsha-4-5hp-air-cooled-diesel-pumpset-23543007362.html

[54] Benchmark costs for off-grid and decentralized solar PV systems for the year 2021-22 (MNRE BC), 2021. Standard, Specification and Benchmark Cost. Retrieved on 3 February 2022 from https://mnre.gov.in/img/documents/uploads/file_f-1629354435111.pdf

[55] Ellis, R., Shockley, J., and Shepherd, J. Estimating the Economic Depreciation of Farm Assets, 2021. https://agecon.ca.uky.edu/ext-publications.

[56] Thanawala, H., 2023. FD rates go up: These banks offer up to 8% interest on three-year fixed deposits. Money Control. Retrieved on 25 April 2023 from https://www.moneycontrol.com/news/photos/business/personal-finance/fd-rates-go-up-these-banks-offer-up-to-8-interest-on-three-year-fixed-deposits-10300981.html

[57] Farm Power and Machinery, 2021. Retrieved on 25 April 2023 from http://www.eagri.org/eagri50/FMP211/lec16.html

[58] Pande, P. C., Singh, A. K., and Kumar, P. Solar PV pumping system for irrigation purpose and its economic comparison with grid-connected electricity and diesel operated pumps. *Indian Journal of Economics and Development*, 4(4):1-7, 2016.

[59] Minimum Wage Notifications (MWN). Commissionerate of Labour, Government Of Assam, India, 2022. Retrieved on 26 April 2022 from https://labourcommissioner.assam.gov.in/documents-detail/minimum-wage-notifications

[60] Assam Power Distribution Company Limited (APDCL), 2022. Retrieved on 20 June 2022 from https://www.apdcl.org/website/

[61] Gautam, Y., Singh, O. P., and Singh, P. K. Economic and environmental benefits of replacing diesel pumps with solar irrigation pumps in Jaipur, Rajasthan. *International Journal of Agriculture, Environment and Biotechnology*, 13(4):469-474, 2020. DOI: https://doi.org/10.30954/0974-1712.04.2020.12

[62] Jakhrani, A. Q., Rigit, A. R. H., Othman, A. K., Samo, S. R., and Kamboh, S. A. Estimation of carbon footprints from diesel generator emissions. In 2012 *International Conference on Green and Ubiquitous Technology*, pages 78-81, Indonesia, 2012.

[63] Satsangi, P., GS, S. B., and Saxena, A. K. Performance analysis of grid interactive solar photovoltaic plant in India. *Energy for Sustainable Development*, 47:9-16, 2018. DOI: https://doi.org/10.1016/j.esd.2018.08.003

[64] Mclntyre, J., Berg, B., Seto, H., Borchardt, S. WNA Report, comparison of lifecycle greenhouse gas emissions of various electricity generation sources. World Nuclear Association, 2011. Retrieved on 26 April 2023 from https://world-nuclear.org/

[65] MSP. Significant Hike in MSP for Kharif and Rabi Crops, 2022. Retrieved on 25 January 2023 from https://agricoop.nic.in/sites/default/files/Web%20copy_eng.pdf

[66] MSP RMS, 2022. Cabinet Approves Minimum Support Prices for All Rabi Crops for Marketing Season 2023-24. Retrieved on 20 January 2022 from https://www.pib.gov.in/PressReleasePage.aspx?PRID=1868760

[67] Saurenergy. Saur Energy International, 2016. Retrieved on 16 March 2022 from https://www.saurenergy.com/solar-energy-blog/here-is-how-you-can-calculate-the-annual-solar-energy-output-of-a-photovoltaic-system#:~:text=Globally%20a%20formula%20E%20%3D%20A,output%20of%20a%20photovoltaic%20system

[68] Bedana, D., Kamruzzaman, M., Rana, M. J., Mustafi, B. A. A., and Talukder, R. K. Financial and functionality analysis of a biogas plant in Bangladesh. *Heliyon*, 8(9):2022. DOI: https://doi.org/10.1016/j.heliyon.2022.e10727

[69] Ehrhardt, M. C., and Brigham, E. F. Corporate finance: A focused approach. South-Western Cengage Learning, 2011.

[70] Guno, C. S., and Agaton, C. B. Socio-economic and environmental analyses of solar irrigation systems for sustainable agricultural production. *Sustainability*, 14(11):6834, 2022. DOI: https://doi.org/10.3390/su14116834

[71] Specification for solar photovoltaic water pumping systems (SF SWP), 2023. Standard, specification and benchmark cost. Retrieved on 2 May 2023 https://mnre.gov.in/img/documents/uploads/file_s-1679652433646.pdf

[72] Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM Scheme). National Portal of India, Central financial assistance (CFA)/ state government support, 2023. Retrieved on on 3 May 2023 from https://www.india.gov.in/spotlight/pm-kusum-pradhan-mantri-kisan-urja-suraksha-evam-utthaan-mahabhiyan-scheme

[73] Barman, P., Dutta, L., Bordoloi, S., Kalita, A., Buragohain, P., Bharali, S., and Azzopardi, B. Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches. *Renewable and Sustainable Energy Reviews*, 183:113518, 2023. DOI: https://doi.org/10.1016/j.rser.2023.113518

[74] Nunes, P., Farias, T., and Brito, M. C. Day charging electric vehicles with excess solar electricity for a sustainable energy system. *Energy*, 80:263-274, 2015. DOI: https://doi.org/10.1016/j.energy.2014.11.069

[75] Lalitha, G., Kaliyaperumal, G., Nijhawan, G., Praveen, P., Tyagi, L. K., and Abood, A. S. Integration Challenges and Solutions for Solar-Powered Electric Vehicle Charging Infrastructure: From Panel to Battery. In *E3S Web of Conferences*, volume 505, pages 02001, South Africa, 2024.

[76] Sivasankar, C., Saravanan, G., Pradeepa, H., Arun, V., and Ganesh, E. N. Advancements in Sustainable Charging Infrastructure: Integrating Solar Energy and IoT for Smart E-Vehicle Charging Stations. In *2023 International Conference on Sustainable Communication Networks and Application* (ICSCNA) pages 311-315, India, 2023.

[77] Cui, D., Wang, Z., Liu, P., Wang, S., Dorrell, D. G., Li, X., and Zhan. Operation optimization approaches of electric vehicle battery swapping and charging station: A literature review. *Energy*, 263:126095, 2023. DOI: https://doi.org/10.1016/j.energy.2022.126095