Solarisation in agriculture in Tamil Nadu: A first principles evaluation

Susan Das Renuka Sane Ajay Shah*

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Abstract

Shifting agriculture away from the grid may help address fiscal challenges faced by the Tamil Nadu state government. The paper presents a cost-benefit analysis of implementing solarised irrigation pumps in Erode district, Tamil Nadu. The analysis is based on underlying assumptions on climatic conditions, cropping patterns and irrigation requirements in the district. The results suggest that the state and discom can benefit from the solarisation of agriculture if they can sell surplus power to commercial and industrial (C&I) consumers or in the power exchange market. The paper also performs cost-benefit analysis with the assumption of reduction in solar panel costs in future and finds that the discom would continue to gain net positive benefits. The paper also recommends formalising higher feed-in tariffs, supporting capital cost through subsidies, and exploring alternative procurement approaches.

JEL classification: Q, H2, H53
Keywords: Electricity, Tamil Nadu, agriculture, solar pumps, tariffs, subsidies

*Susan Das and Renuka Sane are Research Fellow and Research Director, respectively, at TrustBridge Rule of Law Foundation. Ajay Shah is co-founder and Senior Research Fellow at XKDR Forum. We thank Akshay Jaitly for inputs into this work. We also thank Martin Scherfler, Anas Rahman and the participants at the XKDR Forum - TrustBridge Rule of Law Foundation Conference titled 'Improving Investibility in Tamil Nadu's Power Sector' (13 October 2023; Chennai), for their feedback and comments. All errors remain our own.

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1 Introduction

The Indian power sector, especially in states such as Tamil Nadu, struggles with poor financial health of discoms, electricity theft and payment delays to power generators. Despite Tamil Nadu performing well on lower AT&C losses on a national scale, the state discom has accumulated a deficit of INR 1,25,222 crores, the highest among all discoms (PFC, 2023). This deficit is addressed through state government-backed borrowings. In FY 2022, Tamil Nadu government spent INR 1.17 per unit of power sold solely on interest payments contributing to a high average cost of supply (ACoS) for power, making Tamil Nadu's ACoS the highest in the country. The prevalence of a subsidy culture in Tamil Nadu's power sector, driven by political economy challenges, further widens the ACoS-ARR gap[1] for TANGEDCO (Tamil Nadu Generation and Distribution Corporation Limited). Subsidies create a revenue gap, burdening the state government's budget. Over the last five years, the government's subsidy payments to the power sector have nearly doubled, rising from INR 8312 crores in 2018-19 to INR 16750 crores in 2022-23 (TNERC, 2022). The accumulated losses of TANGEDCO contribute to more than 20% of the revenue expenditure by the state government on power sector subsidies and interest payments alone. Additionally, 70-90% of the outstanding guarantees by the state government is attributed to the power sector. This can potentially in future lead to fiscal crisis in Tamil Nadu and impede the non electricity non-interest expenditure by the state government.

Free power is the major contributor to the fiscal crisis in the state power sector. Electricity to agriculture is wholly subsidised by the state. The tariff rate for agriculture is set at Rs 4.60/kWh against the average cost of supply of Rs 8.35/kWh. Around one-fifth of total power sales by TANGEDCO are to agriculture consumers (TNERC, 2022). These are official estimates at best. The actual power usage is not known due to lack of metering of agriculture connections, and is estimated to be between 20-25 percent of total energy consumption.

Given the political economy challenges around increasing electricity tariffs for agriculture, several states in India have started experimenting with the idea of moving agriculture to solar energy. This serves two purposes - increasing farmers' income while assuring a reliable power supply and reducing the subsidy burden on discoms from agriculture. There have been four main schemes: Surya Raithi scheme in Karnataka, Suryashakti Kisan Yojana (SKY) in Gujarat, solar BLDC pump scheme in Andhra Pradesh and PM KUSUM-C scheme initiated by the Union government. The various pilot schemes in the states as well as Kusum-C, have had limited success. The reasons range from lack of trust between the farmers and the state, low feed-in tariffs that do not set the right incentives, high capital costs of the panels, and delays in payment of subsidies by the state.

In this paper we build on the learning from past solarisation attempts to arrive at the net benefit to a discom if a pump solarisation scheme was to be implemented in the Erode district in Tamil Nadu. Erode experiences generally scanty rainfall and dry climatic weather, except for a brief monsoon period in June- September. This makes it a suitable location for studying the financial benefits of a solarised irrigation scheme in Tamil Nadu, as the climate pattern reveals that the district requires irrigation along with natural rainfall-fed agriculture. We assume that the state pays a feed-in tariff to farmers for injecting surplus power to the grid, and fully bears the capital cost for pump solarisation.

[1] ACoS-ARR gap refers to the difference between the average cost of supply (ACoS) of power for the discom and average revenue realised (ARR) from revenue collection of electricity bills.

We conduct a ground-up assessment of actual irrigation requirement of farmers in the district based on their landholding size. This helps us to arrive at a rough estimate of average annual power consumption of farmers for each category of landholding (small & marginal, semi medium, medium and large farmers). We evaluate the potential benefits to the state under four scenarios: i) the discom sells the surplus energy to C&I customers at the current (higher) tariff rate, ii) the discom sells the surplus power to domestic customers, iii) discom avoids incurring the variable cost of power purchase by refraining from buying the power previously consumed by agricultural consumers, and (iv) there is a higher feed-in-tariff paid to the farmers relative to the baseline scenario.

We find selling surplus power generated from solarised pumps to commercial and industrial (C&I) consumers would benefit the discom. Even with a higher feed-in tariff for the farmers, the discom would still experience a net positive outcome from the scheme. We also perform cost-benefit analysis with the assumption of reduction in solar panel costs in future and find that the discom would continue to gain net positive benefits even if it sells the surplus power to only domestic consumers. Based on this analysis, we make recommendations on the design of feed-in tariffs, and the importance of setting up reliable payment mechanisms to incentivise farmers to opt-into the scheme. The analysis in this paper is focused on one district, and provides a framework to evalute the cost-benefit for each district in the state.

India has committed to achieve 50 percent of its cumulative installed electricity capacity from non-fossil fuel based energy resources by 2030 (Government of India, 2022). Currently the share of non-fossil fuel energy sources is 35.80% of total installed capacity in India (CEA, 2023). Current capacity addition plans fall short of the target of 50 GW annual capacity addition from solar and wind. To incentivise further RE capacity addition, it is necessary to fix the financial health of discoms. Moving agriculture consumers to solar is one way of doing so.

The paper is organised as follows. Section 2 provides an overview of the existing solarisation schemes related to agriculture. Section 3 describes our methodology, while section 4 presents the results. Section 5 discusses the path to implementation.

2 Example of solarisation schemes in agriculture

There have been four attempts in the country. The "Surya Raithi" in Karnataka, the Suryashakti Kisan Yojana (SKY) in Gujarat, the solar BLDC pump scheme in Andhra Pradesh and the PM KUSUM-C scheme initiated by the Union government. Table 1 provides the necessary information regarding the duration of PPA, feed-in-tariff rates, allocation of capital costs for the stakeholders, loan duration, etc., for pump solarisation schemes.

These schemes have long-term PPA provisions between individual farmers/farmer cooperatives and the respective DISCOMs. The PPA duration ranges between 20-25 years, providing certainty for the stakeholders to invest in solarised pumps. Further, various incentives were in place for farmers to encourage and promote the adoption of solarised irrigation pumps. For example, Gujarat and Karnataka had generation-based incentives of Rs 3.50 and Rs 1.00 for every unit of power injected into the grid from solarised pumps. Similarly, attractive tariff incentives were in place for the DISCOMs to participate in the schemes since the successful implementation of solar pump schemes is contingent

Table 1 Characteristics of pump solarization schemes

This table presents details regarding the capital cost structure, tariff incentives, loan duration, equity share of stakeholders for the pilot schemes and PM KUSUM-C

Particulars	PM KUSUM 'C'	SKY	BLDC Pump Scheme	Surya Raitha
Launched year	2019	2018	2018	2018
PPA Duration	25 years	25 years	25 years	20 years
Feed-in-Tariff (Rs/kWh)		3.50	1.50	6.00*
GBI (Rs/kWh)		3.5 (for 7 years by state)		1.00
Farmer Upfront Contribution (in %)	10*	5	0 percent	
Share of DISCOM		35 percent	100 percent	Rs 408342
MNRE Contribution	30%	30%		Rs 162000
State govt. Contribution	30%	30%		Rs 58000
Total cost of the system (Rs)	458790	51500/KW	400000 (5HP)	678342
Target of the scheme	15 lacs SIPs	175 MW capacity	216 pumps (3HP and 5HP)	223
Solar PV Panel size (KW)	11.19	1.25 KW/HP	5	5.595
Total cost of the project (Rs crores)	14798 (by Centre)	900	9.3	23.029602
Loan Repayment Period	5-6 years	7 years	15 years	12 years

*3 percent hike on Rs7.20/kWh for 20 years; **30 percent bank loan to farmers

upon discoms. Gujarat and Karnataka had high feed-in-tariffs of Rs 3.50 and Rs 6.00 that the state government would provide to discoms for the surplus power injected into the grid.

The feed-in-tariff structure was supposed to help discoms service the loans taken by them for the implementation of solarised pump schemes. The capital cost structure of the solarised pumps in PM KUSUM-C is such that MNRE and respective state governments share the financing burden in equal proportion (30% each), and the rest is to be funded by either the farmers or the discom on behalf of the farmers. SKY and Surya Raitha's scheme had the same capital structure for sharing the financing between MNRE, the state government, and the discom. In the case of Andhra Pradesh, since the initiative was entirely initiated by the APEPDCL (the state discom), the financing cost was wholly borne by it.

Finally, the loans the discoms took in these pilot projects were short-to-medium duration loans. The tenure for loan repayment ranges between 7 to 15 years. However, in KUSUM-C, the provision for the loan repayment period is shorter than that for the pilot projects, which could be one of the factors leading to slower uptake.

By the end of March 2023, the Kusum-C component had achieved only 1 percent of sanctioned capacity. While the Surya Raithi reduced farmers' dependence on the grid, the feeder was a net importer of electricity instead of injecting surplus power into the grid, on account of the indiscriminate pumping of groundwater by the farmers. The SKY scheme had incremental gains for farmers and the discoms (Shah & Rai, 2021), but was discontinued in December 2020. This decision was prompted by the failure of the MNRE to disburse the capital subsidy, leaving discoms to bear 65% of the capital cost through a loan from NABARD (National Bank for Agriculture and Rural Development). When PM KUSUM-C was introduced, it alleviated the financial burden on discoms by providing 30% of the capital subsidy, ultimately leading to the discontinuation of the SKY scheme. The solar BLDC pump scheme was also discontinued owing to low enthusiasm and hesitation on part of the farmers. The reason behind it was that the BLDC pump sets could hamper the power supply to farmers in off-peak seasons as farmers could not draw power from the grid.

Maharashtra adopted a different model with the Chief Minister's Solar Agriculture Feeder Policy (Mukhyamantri Saur Krushi Vahini Yojana, MSKVY) in June 2017. MSKVY scheme was a precursor to the PM KUSUM-A scheme launched in 2019. Under MSKVY, large scale solar PV plants of capacity 2-10 MW were to be installed within a 5km radius of agriculture dominated sub-stations. It differed vastly from other solarisation pilot projects and schemes such as described in Table 1. Instead of focusing on generation of solar power for individual farmers, it prioritised large-scale generation. For example, a 2 MW solar plant can supply reliable day-time power to 700 5-HP pumps (Government of Maharashtra, 2023). In this scheme, the private landowners and farmers have to lease their land to the state government at Rs 1,25,000/ha with 3% annual hike, which will then setup the solar plant on its own or will invite bids from private developers for the same. There are also several other financial incentives in place for participating villages for exporting surplus power and monetary reward to Gram Panchayats. Although the scheme seeks to reduce the subsidy burden on the state, by providing large incentives it has the possibility to create additional fiscal burden on the state.

Similarly the inspiration for the Suryashakti Kisan Yojana (SKY) came from Dhundi village, where the world's first solar farmers' cooperative has been operating successfully since 2015 (Shah & Rai, 2021). With the help of the International Water Management Institute (IWMI) and Tata Water Policy project , Dhundi Saur Urja Utpadak Sahakari Mandali (DSUUSM) was setup in 2015 with six farmer members. Dhundi is the first example of private initiative for setting up solarised irrigation pumps for individual farmers, recognising the potential benefits inherent in the model. The organisation purchased solar irrigation pumps and combined them to create a micro-grid, which the DSUUSM cooperative then set up to run on behalf of the members. Madhya Gujarat Vij Company Limited (MGVCL), granted the cooperative a 25 year solar power purchase contract for 4.63/kWh. In exchange, the cooperative members gave up their right to request for 25 years of subsidised power (at Rs 0.60/kWh). Over time, this scheme has experienced growth by demonstrating profits for the stakeholders. The majority of the financing was through the Tata Water Policy project, however, the farmers also had significant equity contribution. The successful participation of farmers despite the high equity cost was due to the attractive feed-in-tariff, which made this investment worthwhile for the farmers. This could offer an alternate pathway for states to focus on providing attractive feed-in-tariff, and let the private initiative bear the responsibility of capital costs for pump solarisation.

3 Methodology

Erode district is situated at between 10° 36"N and 11° 58"N and between 76° 49"E and 77° 58"E in the northernmost corner of Tamil Nadu bordering Karnataka. Erode experiences generally scanty rainfall and dry climatic weather, except for a brief monsoon period in June- September. It is marked by dry climate throughout the year with heat peaking from March-May (Government of Tamil Nadu, n.d.). This makes it a suitable location for studying the financial benefits of a solarised irrigation scheme in Tamil Nadu, as the climate pattern reveals that the district requires irrigation along with natural rainfall-fed agriculture.

To understand the fiscal gains for the state through pump solarisation, we focus on three crucial parameters:

1. Annual self-consumption of power by farmers.
2. Determination of the size and capacity of solarised pumps.
3. Estimation of the excess power that farmers might inject into the grid.

Once the solarised irrigation pump capacity is determined, we calculate the total annual energy generated. We then calculate the surplus power exported to the grid by subtracting the annual power self-consumed by farmers. We factor in the feed-in-tariff payments to farmers from the discom as a means to incentivise them not to overuse power consumption. This allows us to determine the total feed-in-tariff that the state pays for the surplus power injected into the grid.

Following this, we compute the revenue gain from selling surplus power, as well as the power formerly consumed by farmers to other consumers. Additionally, we calculate the cost savings realised by avoiding power purchases to meet previous agriculture demand.

Ultimately, we compute the net annual benefit for TANGEDCO and the state by using the following formula:

$$\textbf{Annual Benefit} = \textbf{Revenue Gain} - \textbf{Total Feed-in-Tariff} \quad (1)$$

Finally, we evaluate the net present value of the overall benefit over 25 years from pump solarisation scheme to the state.

3.1 Estimating parameters for panel and pump requirements

The first step in the exercise is to estimate the size of solar pumps that farmers will need. This requires an estimate of the irrigation requirement for crops.

1. **Net Irrigation Requirement** -Net irrigation requirement pertains to the amount of water necessary to meet the specific needs of a crop per unit of land area.

   We choose the three major principal crops grown in the district that have a single growing season - paddy, groundnut and maize for our analysis (Kapur & Subramanian, 2022). The Food and Agriculture Organization (FAO) provides the formula for calculating crop water needs that takes into account crop characteristics and weather patterns. The FAO methodology is widely used in agriculture to estimate the irrigation requirements of crops. This value is determined through the following calculation process:

   (a) *Theoretical Water Requirement of Crops*: This entails estimating the total water demand of the crops cultivated within a given geographical region, such as the district of Erode. It involves assessing the collective water needs of the various crop types grown in the district, considering factors like crop type, growth stage, local climate, and soil characteristics. Details of the calculation are provided in Appendix A.2, where Table A.2 presents the values for each type of crop.

   (b) *Proportion met through rainfall*: This refers to the fraction of the total water requirement for crop irrigation that is supplied by natural rainfall. This proportion can vary significantly based on the local climate, seasonal variations, and the specific water needs of different crops. The detailed calculation is in Appendix A.3, where Table A.4 presents the effective rainfall data for each month.

   (c) *Proportion met through irrigation*: This refers to the fraction of the total water requirement for crop irrigation that is to be met through irrigation sources. This determines the power consumption required for meeting the water demand of crops. We calculated the net irrigation requirement for crops in Erode in Appendix A.4.

2. **Average size of landholding:** The average size of a landholding is used to estimate the daily volume of water required for irrigation in a month. This estimation is based on the assumption that the water requirement for irrigation is relatively constant on a daily basis in a particular month. In Erode, majority of the landholdings are small & marginal (refer to Table A.5 in Appendix A.5).

3. **Actual crop irrigation requirement:** Based on the average size of landholding, we derive the daily volume of crop water requirement for each month in Table A.6 in Appendix A.6. There may be losses in the irrigation method, which are taken into account to arrive at final volume of water that needs to be pumped for crop irrigation. Figure 1 illustrates the monthly irrigation water requirements for different landholding sizes. This is based on the formula provided in the equation 7 in Appendix A.6. The demand for irrigation is highest from August to December, after which it decreases significantly. The demand for irrigation is almost nil between April to July based on crop planting season and rainfall values in Erode.

4. **Annual power consumption:** The annual power consumption for pumping the required water is estimated by considering two main factors: the head of the groundwater in the district and the number of operational hours for pumping. This estimation helps determine the electricity consumed to pump the required volume of water for irrigation. The following assumptions were made in order to calculate the annual power consumption requirement for irrigation in Erode:

   (a) **Source of irrigation:**
   The primary source of irrigation in the district of Erode is dug wells, as established by the Minor Irrigation Census data (Ministry of Jal Shakti, 2019).

   (b) **Average head for dug well irrigation:**
   We assume an average head of 30 meters for dug well irrigation. This assumption is based on the distribution of dug well depths within the district, as inferred from the Minor Irrigation Census data (Ministry of Jal Shakti, 2019).

   (c) **Number of operational hours:**
   We assume that agricultural pumps are operational for a duration of 8 hours. This assumption reflects the typical operational schedule for irrigation pumps in the district.

   Details regarding the calculation and estimate of annual self-power consumption of farmers in Erode based on the landholding size are provided in Appendix A.7.

5. **Solar insolation data:** Solar insolation represents the amount of solar energy a specific area receives and is typically measured using solar irradiance, which tells us how much solar energy is available per unit area. This data helps us understand how much solar energy the solar panels in the Erode district can capture. By analyzing the solar insolation data for the Erode district,

Figure 1 Monthly crop irrigation requirement in Erode

This figure depicts the daily volume of irrigation requirement for each month based on the category of average landholding size in the Erode district.

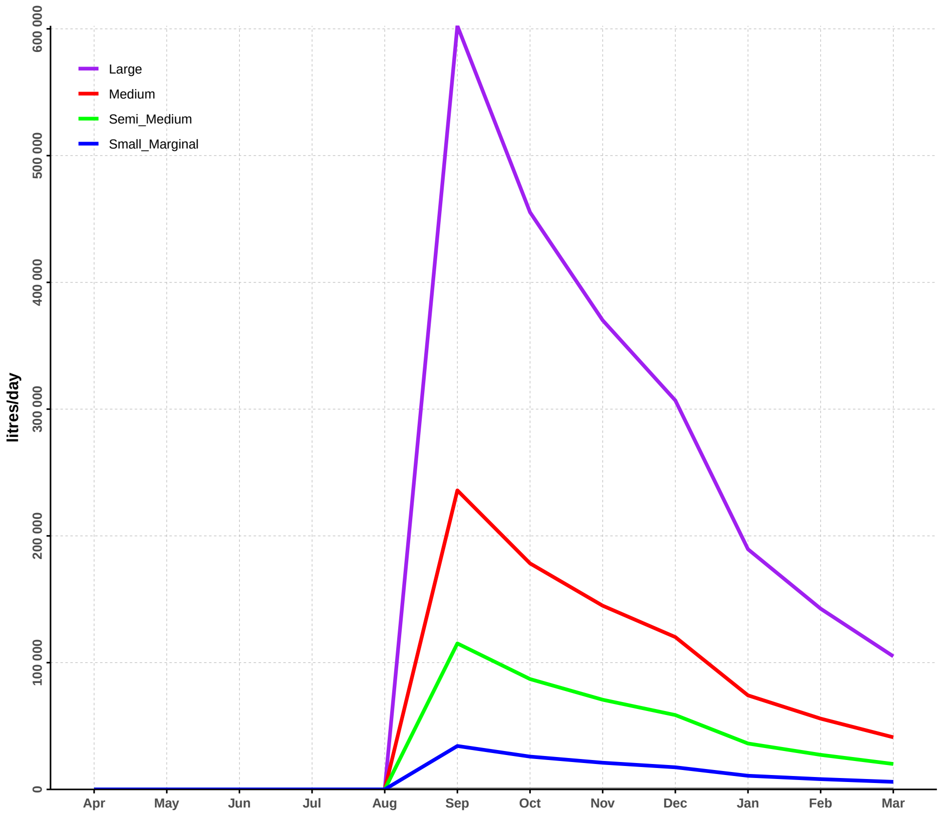

Table 2 Solar Pump Model Selection

This table presents the pump capacity (column 1), and solar panel capacity (column 2) along with the pump model (column 3) for each category of the landholding.

Size of Holding	(1) Pump Capacity (HP)	(2) Pump Model	(3) Panel Capacity (KW)
Small & Marginal	2	Model 2 (AC submersible)	3.6
Semi-medium	5	Model 7 (AC surface)	9.6
Medium	7.5	Model 10 (AC surface)	13.5
Large	20	Model 25 (AC surface)	36

we determine the right size for the solar-powered irrigation system, ensuring it meets the water requirements of the agricultural crops in Erode. For further details refer to Appendix A.8.

6. **Solar irrigation pump sizing:** MNRE has established guidelines for selecting the appropriate irrigation pump and solar panel capacity based on specific standard conditions related to solar insolation, pumping head, and the volume of water discharged (MNRE, 2023). These guidelines take into account the values of solar insolation, the water requirement of crops, the pumping head, and the type of irrigation used in the Erode district.

   We choose the appropriate irrigation pump model and the corresponding solar panel capacity to ensure efficient and sustainable irrigation practices in the Erode district.

   These guidelines help optimise the use of solarised irrigation pump systems for irrigation purposes, taking into account the local conditions and requirements. Table 2 gives the details regarding the pump and solar panel capacity and the model of solarised irrigation pumps that were chosen for each category of farmers based on power consumption, irrigation requirement and solar insolation data. Our findings on capacity and sizing of SIPs match with the results obtained from a recent portal setup by MNRE to recommend pumps for PM KUSUM-C scheme (MNRE, n.d.).

3.2 Cost-Benefit scenario analysis

Cost-benefit scenario analysis is essential to evaluate the financial benefits for TANGEDCO resulting from the adoption of solar-powered pumps. The analysis considers various scenarios, each offering a different perspective on the financial impact:

1. **Baseline Scenario - selling to C&I consumers**
   In the baseline scenario, surplus energy generated by the solar panels is procured by the discom. TANGEDCO then sells this surplus energy, in addition to the power that was earlier consumed by farmers from the grid, to commercial and industrial (C&I) consumers at a rate of Rs 7.65/kWh. C&I consumers are the high paying consumers for the discom. Thus selling the surplus power to the C&I consumers will ensure profitability, since the feed-in-tariff for power purchase is only Rs 2.28/kWh. The feed-in-tariff is lower than the average variable cost of power purchase for the discom (Rs 3.60/kWh). C&I consumers constitute around 30% of the power sales by TANGEDCO (TNERC, 2022), thus providing a sizeable market for selling the additional power.

   Transitioning from the baseline scenario, we delve into alternative scenarios:

2. **Scenario 1: Selling to domestic consumers**
   In scenario 1, the surplus power generated by the panels is sold to the domestic consumers at a rate of Rs 4.60/kWh instead of C&I consumers. This also includes the power supplied to the agriculture consumers. This scenario is considered because a lot of C&I consumers in Tamil Nadu are currently shifting away from the grid by opting for captive power (Garg et al., 2022). Thus the surplus power generated can be utilised to meet growing demand of domestic residential consumers.

3. **Scenario 2: Savings on power purchase cost**
   In Scenario 2, the focus shifts to TANGEDCO's cost-saving measures. The discom avoids incurring the variable cost of power purchase, which stands at Rs 3.60 per kWh, by refraining from buying the power previously consumed by agricultural consumers. Instead, a Power Purchase Agreement (PPA) is established with TEDA (Tamil Nadu Energy Development Agency) to procure the surplus power generated from the fields of the farmers. This surplus power is utilised to fulfill TANGEDCO's power supply obligations.

   This scenario is particularly relevant in cases where the demand for electricity is not growing rapidly, and the existing demand can be satisfied through the scheme. By adopting this approach, TANGEDCO can realise significant cost savings through the price differential between average variable cost of power purchase and the feed-in-tariff.

4. **Scenario 3: Increase in Feed-in-Tariff paid by TANGEDCO for surplus power**
   Scenario 3 maintains assumptions similar to the baseline scenario, but it involves an increase in the feed-in-tariff paid by TANGEDCO for surplus power to Rs 3 per kWh. This scenario considers increasing the feed-in-tariff to incentivise farmers for adopting the scheme by offering a more remunerative price. However, the increased feed-in-tariff should be lower than the average variable cost of power purchase of Rs 3.60/kWh, to ensure discom continues to realise savings on price differential.

Table 3 displays assumptions for all these scenarios, containing information on feed-in-tariff, tariff for consumers, avoided variable cost of power purchase, tariff for agriculture consumer, etc. We also assumed an inflation rate of 4% for calculation of the net present value of benefit to TANGEDCO over next 25 years.

4 Results

4.1 Baseline Scenario

In the baseline scenario, the discom procures surplus energy generated by the solar panels located in the fields of farmers in the Erode district at a feed-in-tariff of Rs 2.28 per kilowatt-hour (kWh). The surplus power, in combination with the electricity previously consumed by farmers, is then sold to commercial and industrial (C&I) consumers. The net gain from this transaction determines the annual benefit to TANGEDCO.

We calculate the capital cost to the state for implementing the solarisation scheme in Table A.8 in Appendix A.9. It determines the number of SIP systems from individual number of holdings and their

Table 3 Assumptions on input parameters

This table represents certain basic assumptions for all 4 scenarios used for cost-benefit analysis of pump solarization in Erode for TANGEDCO.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Avoided Variable Cost of Power Purchase (Rs/kWh)	0	0	3.60	0
Tariff paid by Farmers (Rs/kWh)	4.60	4.60	4.60	4.60
Feed-in-Tariff paid by Discom (Rs/kWh)	2.28	2.28	2.28	3.00
Inflation (%)	4%	4%	4%	4%
Consumer Category Tariff (Rs/kWh)	7.65	4.60	7.65	7.65

Table 4 Annual Net Benefit to TANGEDCO

This table presents the annual net benefit to TANGEDCO (column 4) which we calculate by finding the difference between benefit to discom from selling power to C&I consumers (column 1 and 2) and cost to the discom for feed-in-tariff payments (column 3).

Benefit		Cost	Net Benefit - TANGEDCO (Rs Crores)
(1)	(2)	(3)	(1) + (2) - (3)
Power farmers are not consuming sold to C&I (Rs Crores)	Excess power generated sold to C&I (Rs crores)	Payment to farmers for excess power (Rs Crores)	
59.75	853.86	301.34	612.27

costs based on benchmark cost of the panels determined by the TNERC (TNERC, 2020). With the entire equity burden borne by the state, the cost arrives at Rs 3681.81 crores. Further the state would save about Rs.42.54 crore in Erode annually by not having to pay the subsidy for agriculture (refer to Table A.9 in Appendix A.9).

Finally to estimate the annual net benefit to TANGEDCO from implementing the scheme, we calculate the surplus power injected into the grid by the farmers in Table A.10 in Appendix A.9.

The surplus power is then sold to TANGEDCO, which has to purchase it at the feed-in-tariff of Rs 2.28/kWh. As per the baseline scenario, this is sold to the commercial and industrial (C&I) consumers at Rs 7.65 per kWh. Similarly, the power that was previously supplied to farmers is now redirected to meet the demand of C&I consumers seeking reliable and high-quality power supply. This shift in power distribution brings added benefits to TANGEDCO.

Table 4 describes the annual net benefit to TANGEDCO, from the power sold to C&I consumers (including power previously supplied to farmers) and cost from feed-in-tariff payments.

Table 5 Cost-Benefit to State from pump solarisation

This table presents the benefits, savings and cost to the state from pump solarisation and finally the net benefit to state from it. We calculated these values for all the 4 scenarios.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Benefit to TANGEDCO /State (Rs Crores)	6353.82	2573.80	-2718.10	5366.28
Savings by State on Power subsidy (Rs Crores)	563.40	563.40	563.40	563.40
Cost to State of Solarised Pumps (Rs Crores)	3681.81	3681.81	3681.81	3681.81
Net Benefit to the State (Rs Crores)	3235.41	-544.61	-5836.51	2217.87

We calculate the net present value (NPV) of the annual benefit to TANGEDCO by considering the annual benefits over a 25-year duration. The present value of annual benefit over 25 years for all the scenarios is provided in Table A.11 in A.9. We sum up the values for each year to determine the overall NPV of the annual benefit, which amounts to Rs 6353.815 crores.

Additionally, the state realises annual savings of Rs 42.54 crores in tariff subsidies due to the pump solarization scheme. When accounting for inflation over the next 25 years, the NPV of these savings for the state totals Rs 563.40 crores.

4.2 Scenario analysis result based on BAU scenario

Table 5 presents the net benefit to the state under different scenarios from implementing the solarisation scheme at full scale in the district of Erode. It includes benefit to state for sale of excess power, savings from recurrent power subsidies, and capital cost of solarised irrigation pumps to the state. The annual benefit to TANGEDCO from the sale of power under different scenarios is given in Annexure-2.

The state gains Rs 3235.41 crores if the discom is able to sell the surplus power along with previous agriculture demand to the C&I consumers over the duration of 25 years, which is the baseline scenario. In scenario 1(power is sold to domestic instead of C&I consumers) and scenario 2(in which the discom avoids purchasing excess power), the scheme will cause losses to the state and its state-owned entity TANGEDCO. However, even if the feed-in-tariff is increased to Rs 3.00/kWh to further incentivise the farmers (Scenario 3) with other underlying assumptions in baseline scenario, then also the state stands to gain net benefit from implementing the scheme over 25 year duration.

4.3 Scenario analysis result based on future cost reduction in solar panels

Over the last two decades, there has been a significant reduction in the costs of solar panels, primarily driven by rapid innovation and the learning-by-doing rate. Additionally, there is a growing emphasis on expanding domestic manufacturing of solar panels, which has the potential to lead to even more cost reductions. Therefore, a scenario analysis based on cost considerations has been conducted for

Table 6 Cost-Benefit to State from pump solarisation: cost reduction scenario

This table presents the benefits, savings and cost to the state from pump solarisation and finally the net benefit to state from it. We calculated these values for all the 4 scenarios based on the additional assumption of 30% reduction of solar panel costs.

	Baseline	Scenario 1	Scenario 2	Scenario 3
Benefit to TANGEDCO /State (Rs Crores)	6353.82	2573.80	-2718.10	5366.28
Savings by State on Power subsidy (Rs Crores)	563.40	563.40	563.40	563.40
Cost to State of Solarised Pumps (Rs Crores)	2577.27	2577.27	2577.27	2577.27
Net Benefit to the State (Rs Crores)	4339.95	559.93	-4731.97	3352.46

all four previously mentioned scenarios.

This analysis anticipates a substantial decline in solar panel costs, with an expected 30% reduction within the current decade. This projection aligns with findings from a sensitivity analysis conducted by Evro et al., 2023, indicating a positive trend toward more affordable solar panel technology.

The results in Table 6 demonstrate that pump solarisation would be beneficial for the state under all scenarios (the power is sold to C&I consumers with or without increase in the feed-in-tariff and power is sold to domestic consumer). It is not beneficial to the state only in scenario 2 in which the discom avoids purchasing excess power to meet its supply obligations. This indicates that even if C&I consumers transition away from the discom, the surplus power can still be utilised to meet the demand of domestic consumers, ensuring profitability for the discom. Furthermore, increasing the feed-in-tariff from the current rate of Rs 2.28/kWh to Rs 3.00/kWh would still make the scheme beneficial for the discom.

In summary, the scenario analysis from Table 5 and 6 emphasises the importance of effectively selling surplus power to C&I consumers or at power exchange, which is the key factor in achieving net positive financial benefit. The success of the solarisation scheme for agriculture relies on the ability of the discoms to sell the surplus power to the C&I category consumers at an optimum rate to achieve profitability over the 25 years.

5 The path to implementation

In the wake of growing concerns surrounding the financial sustainability of discoms due to agriculture subsidies, the implementation of solarised irrigation pumps emerges as a promising solution. The analysis of various cost-benefit scenarios and factors related to the adoption of solar pumps in agriculture reveals critical insights that can guide policymakers and stakeholders towards a sustainable and economically viable path for discom finances.

5.1 Selling surplus power

First and foremost, the financial viability of solarised irrigation pumps for both farmers and discoms hinges on the ability to sell surplus power to commercial and industrial (C&I) consumers. This is derived from our learning in the results provided in Table 5 & Table 6. Around 30% of the power demand in the state from TANGEDCO is constituted by C&I consumers. Without this revenue stream, the state and its state-owned entity, in this case, TANGEDCO, face losses. Hence, it is imperative to create a framework that encourages the efficient utilisation of surplus power.

Further in the month of October 2023, power exchange markets in India experienced shortages of power spanning for a week, in which despite high bids, there were no sellers (IEX, 2023). States like Karnataka had to resort to enforcing section 11 of the Electricity Act 2003, forcing private generators in the state to supply power to the ESCOMs (Sane, 2023). To reduce the chances of such exigencies occurring in near future, the solarised pumping systems can act as aggregator supply of power that TEDA can use to trade in the exchange market or meet urgent demand requirements in Tamil Nadu.

5.2 Design of feed-in-tariff

Feed-in tariffs determine the attractiveness of the program to the farmers and the viability to the discom. A low feed-in tariff may result in farmers exploiting groundwater resources and selling water in secondary markets at higher prices (Mukherji, 2022). The Surya Raithi scheme in Karnataka experienced low and non-operational feed-in tariffs at Rs 1/kWh, which failed to motivate farmers to export surplus power to the grid. Instead, it led to indiscriminate groundwater pumping, affecting the energy-water relationship in nearby areas. Additionally, beneficiaries of the scheme became net importers of power from the grid (Durga et al., 2021). In contrast, the Dhundi village pilot had a tariff design of Rs 4.63/kWh, which incentivised farmers to maximise surplus power export, thereby benefiting themselves (IWMI, 2018). A higher feed-in tariff is a more effective incentive for farmers to inject maximum surplus power into the grid, even when the state covers the entire capital cost. There is a need to develop a standard framework and methodology for the regulators to arrive at an optimum feed-in-tariff, taking into consideration the political economy of the State.

5.3 Metering of agriculture connections

In order to implement the pump solarisation scheme successfully such that all the stakeholders have positive gains as per our model, it is crucial to meter agriculture connections. Until the early 1970s, most states in India charged agricultural users for electricity based on metered consumption. However, in the 1970s and 80s, the political lobby advocating for subsidised power, resulted in a system of providing free electricity to agricultural consumers. This practice discouraged installing electricity meters for agricultural connections (Kale et al., 2018). Metering became a politically sensitive decision, and there was a lack of trust between agricultural consumers and discoms due to fears of subsidy removal.

Solarisation schemes present discoms with a valuable opportunity to incentivise metering among agricultural consumers through measures like feed-in tariffs (Viswamohanan et al., 2022). To foster trust between discom and farmers, proactive education on the benefits of metering is imperative before implementation. Metering is essential for the effective functioning of feed-in tariff mechanisms, preventing economic losses for both farmers and the discom. Additionally, it plays a pivotal role in continuous monitoring, allowing for scheme reassessment to ensure financial viability and promote groundwater conservation. The SKY scheme in Gujarat exemplifies the positive impact of metering on power consumption patterns and farmer behavior. Farmers with metered solarised pumps exhibited lower annual power consumption, showcasing intentional efforts to pump less water and export more electricity for additional income (Shah & Rai, 2021). Further there are two metering methods - unidirectional and bidirectional. Unidirectional metering, observed in the Andhra Pradesh scheme, faced limited adoption due to grid reliability concerns as farmer could not access power from the grid during generation shortages (Rahman et al., 2021). Conversely, bidirectional metering, while offering flexibility, requires awareness campaigns on sustainable groundwater management and optimal feed-in tariffs to mitigate the risk of over-extraction of groundwater (Durga et al., 2021).

5.4 Timely payments

Farmers involved in solarised pump projects need to receive their feed-in tariff payments in a timely and efficient manner. In the case of the Surya Raithi scheme, beneficiaries did not receive their share of feed-in tariffs and faced difficulties accessing them (Durga et al., 2021). In contrast, Gujarat's SKY scheme, succeeded in securing greater participation due to its timely and efficient disbursement of feed-in tariffs to farmers(Shah & Rai, 2021).

This is particularly important in Tamil Nadu for two specific reasons. First, as seen the previous section, there are significant benefits to be derived from metering agricultural consumers. At the same time there is a trust deficit between the consumers and the state as represented by the discoms. In the event that it can be credibly demonstrated to agricultural consumers that they will be paid promptly and that metering their connections is an necessary condition for this, it is more likely that they will accept metering. Secondly, financially distressed power utilities are bad pay-masters.

These problems can be solved by designing an appropriate payment mechanism, using a combination of technologies that are already available and in use in India. An IOT device can be placed on the meter of each agricultural connection, which will measure the units of electricity consumed and transmit the information to a central payments system established for this purpose. All units fed into the system within a specified time period, say a day or a week will trigger an immediate payment obligation on behalf of the power purchaser. The power purchaser will be required to fund an escrow account, administered by TEDA or a similar agency, with sufficient funds to cover the costs related to the power it is likely to purchase within that time period. Upon receiving the signal at the end of the day or week long cycle that a payment obligation has been triggered, a direct debit will be made from the escrow account into the bank account of the agricultural consumer in question. The farmer in question will receive a notification of payment through its bank application on a smart phone or an SMS using UPI or other payment platforms.

Here, it can be appreciated that the shorter the time period between feeding power into the grid and being paid, the greater will be the confidence of the farmer that they will in fact be paid. In the event that the account is not sufficiently funded, the supply of power to the purchaser can be turned off automatically. Many details will need to be worked out, including the number of days' of power payments that the escrow account should be funded for in advance etc., but in principle the system should inspire confidence and lead to wider adoption. Careful design and a well-conceived pilot project to demonstrate the payments system will also be required.

5.5 Financing mechanisms

The initial capital cost of solar panels can be a significant barrier for many farmers. The various pilot schemes offer subsidies to cover a portion of the capital cost. The schemes also often include an equity component, requiring farmers to contribute to the capital cost. This leads to hesitancy in adoption (Pasupalati et al., 2022; Rahman et al., 2023). Further, discoms are expected to take loans on behalf of the farmers and use the expected savings from the scheme to repay the loan. It increases the debt burden on the discoms. Therefore in our model, we assume that the state will provide full capital cost for the implementation of the scheme such that additional burden does not fall on the farmers and the already-crippled discom.

States can consider offering capital subsidies to farmers. A transition to solar can effectively reduce the consumption of subsidies in the state (Viswamohanan et al., 2022). The saving on the electricity subsidy for agriculture could help recover the capital subsidy.

A separate state implementing agency could engage in bulk procurement of solarised pumps at negotiated prices. This approach streamlines the procurement process and allows for establishing payment security facilities ensuring that the benefits of the subsidy reach the intended recipients promptly.

For on-grid pumps, states could prioritise areas where pumps are used extensively, typically operating for over 700 hours per year (Rahman et al., 2023). By focusing on areas with high usage, states can avoid potential losses in subsidy expenditure and infrastructure support. Additionally, targeting unmetered farmers, likely to consume more power, could lead to increased savings and more efficient use of resources.

5.6 Operational & maintenance

One key factor influencing the feed-in-tariff calculation of electricity generated by solar pumps is the cost and lifetime of PV modules in the irrigation pump sets. These modules need to operate reliably and efficiently for their 25-year warranty period to justify their high capital cost. It is critical to maintain a low power degradation rate of not exceeding 0.8% per year to meet this warranty period (Jordan & Kurtz, 2013). Otherwise, it will cause a reduction in annual power generation, defeating the purpose of reducing agricultural power demand from the grid. This under performance of the solarised pump systems can then cause revenue shortfall for the discom, and affect the cost recovery for initial capital cost. These factors highlight the importance of proper monitoring and maintenance to ensure that solarised irrigation pumps operate effectively and efficiently over their lifetime (Aboagye et al., 2022).

Pasupalati et al., 2022 observed that in the pilot schemes implemented in Andhra Pradesh and Karnataka, discoms assumed the responsibility for the solar pump systems' operation and maintenance (O&M). However, in the case of Andhra Pradesh, this arrangement led to concerns and hesitancy among farmers. This hesitancy stemmed from issues related to equipment failures, indicating the need for improved maintenance and reliability in such schemes. Thus, the trust deficit between the farmers and discom could affect the scheme's uptake as farmers may not find the solar irrigation pumps reliable. Therefore, it is crucial to clearly define and assign responsibility for their operation and maintenance (O&M) right from the beginning of scheme implementation. If the discoms or third-party developers jointly bear the responsibility with the farmers for O&M, it would encourage the scheme's adoption. In addition, there is a need for capacity building among farmers to ensure they can effectively meet the O&M requirements of SIPs (Tiwary et al., 2021).

5.7 Monitoring & Evaluation

Monitoring and Evaluation (M&E) plays a critical role in assessing the effectiveness and impact of government schemes. In the various pilot schemes, the existing M&E information primarily focused on the installed capacity of solar PV and, in specific states like Gujarat and Karnataka, on the amount of solar energy injected into the grid (Pasupalati et al., 2022). One noteworthy exception is the pilot project in Dhundi, which conducted assessments covering these critical aspects (IWMI, 2018).

However, to fully understand the scheme's success and potential areas of improvement, a more comprehensive M&E framework is needed. This framework should go beyond just measuring installed solar capacity and energy generation and focus on capturing data related to water table levels, crop yields, and changes in farmer income. This comprehensive M&E framework can provide a more accurate and complete picture of the scheme's success and its alignment with its objectives.

In conclusion, the implementation of solarised irrigation pumps holds significant potential to transform power sector landscape in Tamil Nadu, offering benefits to farmers, discom, and the state. To unlock this potential fully, a well-designed feed-in-tariff, metering solutions, transparent operational practices, smart financing mechanisms, and a robust M&E framework are critical components. By addressing these aspects comprehensively, Tamil Nadu can harness the power of solar energy alleviate the fiscal stress on the discom.

5.8 Recommendations

1. Optimal and high feed-in-taiff should be set such that it incentivises the farmers while balancing the interests of the discom.
2. Adoption of bidirectional metering should be prioritised to ensure net-metering to allow farmers to both inject and withdraw power from the grid while raising awareness about sustainable groundwater management so that they limit self-consumption of power, reducing dependency on the grid.
3. The responsibility for the operation and maintenance of solarised irrigation pumps from the scheme's inception should be clearly defined and assigned, ensuring the involvement of discoms or third-party developers alongside farmers. It will ensure that the O&M burden does not fall solely on the shoulders of farmers.
4. To promote higher adoption of solarised irrigation pumps, full capital cost subsidies should be provided which can address the affordability concerns among farmers.
5. Alternative approaches towards solarising agriculture should be explored such as bulk procurement of SIPs by a state implementing agency to enhance affordability of the scheme by negotiating lower prices due to bulk purchase. Alternative models of solarisation should also be

explored that transfers the risks and costs of installation to third-party developers, ensuring equitable benefits for all stakeholders.

6. The scheme target should focus on areas with high pump usage as well as zones which fall under dry climatic conditions throughout the year dependent on irrigation to ensure economic feasibility of the scheme.
7. A robust M&E framework should be developed to comprehensively assess the scheme's impact, including parameters related to the water table, power consumption and farmer income, allowing for more evidence based decision-making and adaptation of the scheme.
8. Selling of surplus power to C&I consumers or high paying consumers is important for the financial viability of the scheme. Thus, TEDA should act as aggregator of power supply from SIPs installed and either sell it to C&I consumers at prices lower than current tariff rates or trade in the exchange markets to ensure higher returns.

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A Appendix

A.1 The Institutional framework of PM KUSUM-C

Table A.1 Details of PM KUSUM Scheme Components

	Mechanism	Financing	Incentives
Component A	Solar power plants ranging from 500 kW to 2 MW to be setup by individual or group of farmers, Panchayats, Farmer Producer Organisations, Cooperatives, Water User Associations. In case the specified entities cannot arrange equity, they can choose to develop solar power plants through developers or local DISCOMs by leasing of land.	Solar power generated through the plants to be purchased by the DISCOMs at feed-in-tariff (fiT) approved by the SERCs, which will be used to recover the capital investment. In case of private developers setting up plants, the farmers will receive lease rent for leasing out the land to develop solar power plants and the developers will recoup their investments through selling power to the DISCOMs.	Procurement based incentive for the DISCOM @ Rs 0.40 per unit of power purchased or Rs. 6.6 lacs per MW of capacity installed whichever is less, for a period of five years from the COD.
Component B	Individual farmers will be supported to install standalone solar pumps of capacity up to 7.5 HP in off-grid areas, where grid supply is not available.	30% of the benchmark or tender cost, whichever is lower will be provided through CFA and State govt. will provide atleast a subsidy of 30%. The remaining 40% of the cost will be borne by the farmers out of which for the 30% farmers can avail bank loans and only 10% in equity has to be provided upfront by the farmers.	Farmers get access to reliable and quality power supply in off-grid areas and irrigation facilities.
Component C - IPS	Individual farmers will be supported to solarise their grid-connected pumps of capacity up to 7.5 HP, although farmers can solarise beyond this capacity, but CFA will be for upto 7.5 HP.	30% of the benchmark or tender cost, whichever is lower will be provided through CFA and State govt. will provide at least a subsidy of 30%. The remaining 40% of the cost will be borne by the farmers out of which for the 30% farmers can avail bank loans and only 10% in equity has to be provided upfront by the farmers.	Farmers receive feed-in-tariff for surplus power exported to the grid from the individual solar power plants.
Component C - FLS	In this model instead of solarisation of individual pumps, states will solarise the agriculture feeder.	In case of where agriculture feeders are not separated, loans for feeder separation can be availed through NABARD,REC, PFC or RDSS scheme. Central Financial Assistance of 30% on the cost of installation of solar power plant (up to Rs. 1.05 Cr/MW) will be provided.	Farmers receive access to the day-time reliable power supply at lower tariffs.

A.2 Crop Water Need Calculation

The specific water needs of the crop is determined based on its type, growth stage, and local conditions. We calculate the daily crop water requirement using the average daily crop evapotranspiration[2] (ET_c)

[2]Crop water use, also known as evapotranspiration (ET_c), represents soil evaporation and the water used by a crop for growth and cooling purposes. This water is extracted from the soil root zone by the root system, which represents transpiration and is no longer available as stored water in the soil. Consequently, ET_c is used

Table A.2 Reference Crop Evapotranspiration (ET_c) and Crop Coefficient (K_c) values

This table presents the reference crop evapo-transpiration values for the Erode district in column 1 and crop coefficient values for paddy, groundnut and maize in column 2, 3, and 4 respectively.

	(1)	(2)	(3)	(4)
	(ET_0) (mm/day)	Paddy (Kc)	Groundnut (Kc)	Maize (Kc)
Apr	1.37			0.6
May	2.55			
Jun	3.05			
Jul	2.95	1.05		
Aug	4.12	1.05		
Sep	4.01	1.2		
Oct	3.67	1.2		
Nov	2.95	0.9		
Dec	2.31	1.05	0.6	
Jan	0.88	1.13	1.15	0.35
Feb	0.63	1.2	1.15	0.6
Mar	0.54	0.9	0.6	1.2

value for a particular month and crop (corresponding to the growth stage and planting period). The crop water need value is used interchangeably with the crop evapotranspiration rate.[3]

Crop evapotranspiration is estimated as follows (FAO, n.d.-a):

$$ET_c = ET_0 \times K_c \tag{2}$$

where:

ET_c : Crop Evapotranspiration (mm/day)

ET_0 : Reference Crop Evapotranspiration (mm/day)

K_c : Crop Coefficient for a particular crop

Table A.2 gives us the reference crop evapotranspiration and the crop coefficient[4] values for paddy, maize and groundnut in Erode. The National Remote Sensing Centre dataset provided the evapo-transpiration values (NRSC, 2022). The crop coefficient values were collected from the FAO dataset based on soil condition and growth stage of the crops (FAO, n.d.-b).

We compute the crop evapotranspiration values of paddy, maize and groundnut for each month using equation 2. Table A.3 provides us the results from the calculation for ET_C values. We then select the

interchangeably with crop water use.

[3]The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of actively growing green, well-watered grass of uniform height.

[4]Crop coefficient incorporates crop characteristics and averaged effects of evaporation from the soil to predict evapo-transpiration.

Table A.3 Monthly Crop ET_c Values (mm/day)

The table presents the theoretical crop water requirement for paddy, groundnut and maize crops in Erode district in Column 1, 2 & 3. It also presents the maximum water requirement for any combination of crops in each month in Column 4.

	(1) Paddy ET_C	(2) Groundnut ET_C	(3) Maize ET_C	(4) Max ET_C
Apr	0.00	0.00	0.82	0.82
May	0.00	0.00	0.00	0.00
Jun	0.00	0.00	0.00	0.00
Jul	3.10	0.00	0.00	3.10
Aug	4.33	0.00	0.00	4.33
Sep	4.81	0.00	0.00	4.81
Oct	4.40	0.00	0.00	4.40
Nov	2.66	0.00	0.00	2.66
Dec	2.43	1.39	0.00	2.43
Jan	0.99	1.01	0.31	1.01
Feb	0.76	0.72	0.38	0.76
Mar	0.49	0.32	0.65	0.65

maximum value of ET_c for each month to accommodate for any combination of crops grown at any given point of time.

A.3 Effective Rainfall (P_e)

We assess how much of the crop water requirement is met by rainfall in the district. The term used to denote the amount of crop water requirement met by rainfall is called "effective rainfall". It is the total rainfall minus runoff, evaporation and deep percolation. It represents only the water retained in the root zone that can be used by the plants.

The formula for calculating effective rainfall is as follows (FAO, n.d.-a):

$$P_e = 0.8P - 25, \text{if } P > 75 \text{ mm} \tag{3}$$

$$P_e = 0.6P - 10, \text{if } P < 75 \text{ mm} \tag{4}$$

where,

P : Total Rainfall (mm/month)

P_e : Effective Rainfall (mm/month)

Table A.4 provides the data for total amount of rainfall received by Erode in each month. Further it provides the monthly values of effective rainfall(mm/day) for Erode which we calculate using equation 3 and 4.

Table A.4 Effective Rainfall Monthly Data

This table presents the effective rainfall data. Column 1 contains monthly rainfall values (mm/month) in Erode, which we use to calculate effective rainfall for each month in Column 2 using equation 3 and 4. Column 3 represents effective rainfall for each month in mm/day.

	(1) Total rainfall (mm/month)	(2) Effective Rainfall (mm/month)	(3) Pe (mm/day)
Apr	75.99	35.79	1.19
May	175.21	115.17	3.84
Jun	105.05	59.04	1.97
Jul	158.41	101.73	3.39
Aug	267.14	188.71	6.29
Sep	91.21	47.97	1.60
Oct	105.24	59.19	1.97
Nov	51.03	20.62	0.69
Dec	56.38	23.83	0.79
Jan	0.03	0.00	0.00
Feb	1.36	0.00	0.00
Mar	21.18	2.71	0.09

A.4 Net irrigation requirement

We then compute the net irrigation requirement for a specific month by finding the difference between the crop water need and the effective rainfall for that month. This value represents the amount of water that needs to be supplied through irrigation to meet the crop's water requirements. The net irrigation requirement is typically expressed in units of millimeters per day (mm/day). It helps in determining the volume of water required to support crop growth during the growing season. The formula for net irrigation requirement (mm/day) is given in equation 5 below:

$$\text{Net Irrigation Requirement} = ET_c - P_e \tag{5}$$

where:

$$ET_c : \text{Crop Evapotranspiration (mm/day)}$$
$$ET_0 : \text{Effective rainfall (mm/day)}$$

This gives the average daily depth of irrigation water required per unit area in a month. The net irrigation requirement values are provided in Table A.6.

A.5 Average size of landholding

Table A.5 provides data on the distribution of landholding in Erode district (Ministry of Agriculture and Farmer's Welfare, 2016). Average size of landholding is calculated across 4 broad categories of farmers - small & marginal (0-2 ha), semi-medium (2-4 ha), medium (4-10 ha) and large (>10 ha) farmers. The given table provides average size of landholding within each of the categories, and the number of individual holdings under these categories.

Table A.5 Average size of landholding category-wise (in ha)

The table represents the landholding pattern in the Erode district for each category of farmers based on their landholding size. Column 1 provides data regarding the average size of landholding for each category, while Column 2 provides data regarding the number of individual holdings for each category. Finally, Column 3 showcases the proportion of landholding for each category in Erode.

	(1) Average size of holding (in ha)	(2) Individual holdings	(3) % of Total Holding
Small & Marginal (0-2 ha)	0.80	162148	82.87
Semi-medium (2-4 ha)	2.69	26218	13.40
Medium (4-10 ha)	5.51	6860	3.51
Large (>10 ha)	14.07	445	0.23

Table A.6 Monthly Irrigation Water Requirement (litres/day)

This table represents the monthly irrigation requirement for Erode. Column 1 contains the net irrigation values (mm/day) which represents the irrigation requirement for each unit of land. Column 2, 3, 4 & 5 provides the monthly volume of daily irrigation water required (litres/day) for each category of landholding.

Month	NIR (mm/day)	Small & Marginal	Semi-Medium	Medium	Large
Apr	0.00	0.00	0.00	0.00	0.00
May	0.00	0.00	0.00	0.00	0.00
Jun	0.00	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00	0.00
Sep	3.21	25688.53	86377.69	176929.77	451797.08
Oct	2.43	19415.47	65284.51	133724.03	341469.52
Nov	1.97	15781.87	53066.53	108697.61	277563.58
Dec	1.64	13085.87	44001.23	90128.91	230147.68
Jan	1.01	8080.00	27169.00	55651.00	142107.00
Feb	0.76	6080.00	20444.00	41876.00	106932.00
Mar	0.56	4477.87	15056.83	30841.31	78754.48

A.6 Actual crop irrigation requirement

We then compute the daily volume of water required for irrigation purposes in a specific month for each of these categories using the following formula:

$$\text{Volume of water required (litres/day)} = \text{Net Irrigation Requirement} \times \text{Average size of holding} \quad (6)$$

Table A.6 contains values of daily irrigation requirement (litres/day) in Erode for each month.

The efficiency of the chosen irrigation method plays a pivotal role in computing the final crop irrigation requirement. In this specific scenario, we assume drip irrigation with an efficiency of 0.75 in the district of Erode. We then use equation 7 to compute the final volume of water required factoring in irrigation losses.

$$\text{Volume of water required (litres/day)} = \frac{\text{Net Irrigation Requirement} \times \text{Average size of holding}}{\text{Irrigation efficiency}} \quad (7)$$

A.7 Annual power consumption

In order to determine the size and capacity of solar-powered pumps for agricultural use, we calculate the annual power usage required by farmers. This calculation is a crucial step in designing a solar irrigation system that can provide sufficient energy for the pumps. The annual power usage of farmers, depends on factors like groundwater depth and the average operational hours of the pumps.

Pumping power

Pumping power refers to energy expended over a specified time in discharging given volume of a fluid from below the ground. The formula for pumping power is given by:

$$\text{Pumping Power} = \frac{V}{3600} \times \rho \times g \times h \quad (8)$$

where,

Pumping Power : Energy expended to discharge water over a specified duration. Expressed in Watts (W).

V : Volume of water discharged (m^3) – Maximum monthly water requirement

ρ : Density of water - 1000 kg/m^3

g : gravitational constant - 9.81 m/s^2

h : depth of dug well - 30 m

In the process of estimating the appropriate pump size, understanding the irrigation pattern, including the source and mode of irrigation, is crucial. In the district of Erode, the dominant source of irrigation is dug wells (Ministry of Jal Shakti, 2019). The assumptions made to calculate the pump size have been stated earlier in section 3.1.

We use equation 8 to get the daily power consumption by farmers in a specific month for each category of landholding. To get the volume of water discharged by the pump in equation 8, we use equation 7 to calculate the volume of water that needs to be discharged by the pump daily in a specific month.

Annual power consumption

We calculate the power consumption for each month for each category of farmers as follows:

$$\text{Monthly Power Consumption} = \frac{\text{Pumping power} \times \text{Operational hours} \times \text{No of days in month}}{1000} \quad (9)$$

where,

Monthly Power Consumption : Power consumption by farmers in a month (kWh)

Summing up the power consumption for every month, gives us the annual power consumption of farmers in the Erode district in Table A.7.

Table A.7 Annual Power Consumption in Erode district

This table presents the average annual power consumption by an individual farmer in each category.It represents the power usage for actual irrigation requirement. It does not factor in overwithdrawal of groundwater by farmers.

	Annual Power Consumption (kWh)
Small	302.83
Semi medium	1018.28
Medium	2085.76
Large	5326.08

Table A.8 Capital Cost to the State for Solarised Irrigation Pumps

This table represents the capital cost to the state for implementation of pump solarisation in Erode. Column 1 contains the capacity of solar panel for each category of landholding. Column 2 represents the benchmark cost of the solar panel as determined by TNERC. Column 3 then calculates the total cost of panel for individual holding and Column 5 calculates the total cost of panels for all landholdings in each category.

(1) Solar PV Capacity (KW)	(2) TNERC cost (Rs./KW)	(3) Total cost/panel (Rs.)	(4) No. of panels (No.)	(5) Total cost (Rs. cr.)
3.6	39000	140400	162148	2,276.56
9.6	39000	374400	26218	981.60
13.5	39000	526500	6860	361.18
36	39000	1404000	445	62.48
			Total	3,681.81

A.8 Solar insolation

Solar insolation, also known as solar irradiance, measures the amount of solar energy that is incident on a given area over a specified time period. It is often quantified in kilowatt-hours per square meter (kWh/m^2) per day, representing the average daily solar energy received.

We obtain the average solar radiation values for each month to determine the appropriate capacity of solar panels (NASA, 2022). The standard solar radiation value recommended in the Ministry of New and Renewable Energy (MNRE) guidelines for panel design is 7.15 kWh/m^2/day (MNRE, 2023). In Erode however, the solar insolation values typically range from 4.5-6 kWh/m^2/day. Given the lower value of solar insolation in Erode (around 4.5 kWh/m^2/day) compared to the MNRE standard of 7.15 kWh/m^2/day, we apply a factor of safety (FOS) of 2 to the solar PV array size to account for variations in weather conditions. This adjustment ensures that the solar panels are designed to produce sufficient energy even under less favorable weather conditions, considering the lower solar insolation levels in Erode compared to the standard guidelines.

Table A.9 Annual Sales and Revenue from Agriculture

This table represents the annual cost to the state from power subsidy for each category of farmers in Erode. Column 1 has annual power consumption data for an individual farmer of each category, and column 3 presents the total cost to the state from subsidy for each category of farmers which we calculated using equation 10.

	(1) Sale of power (kWh)	(2) No. of farmers	(3) Cost to State (Rs. Cr.)
Small	302.83	162,148	22.59
Semi medium	1,018.28	26,218	12.28
Medium	2,085.76	6,860	6.58
Large	5,326.08	445	10.90
		Total	42.54

A.9 Baseline scenario analysis

Capital cost to the state for solar pumps

The benefits from reduction in agricultural subsidy

We calculate the cost to the state from free power to agriculture as follows:

$$\text{Cost to the State} = \text{Sale of Power} \times \text{No. of farmers} \times \text{Agriculture tariff} \quad (10)$$

where,

Cost to the State : Cost to the state in terms of subsidy (Rs/kWh)

Sale of Power : Annual Power Consumption (kWh)

Agriculture tariff : Rs 4.60/kWh

The benefits from surplus power generation

We first calculate the annual power generated from the solarised pumping system as follows:

$$\text{Annual Energy generated (kWh)} = \text{Solar Panel Capacity} \times 365 \times 24 \times \text{C.U.F.} \times \text{Grid Availability Factor} \quad (11)$$

where,

C.U.F. : Capacity Utilisation Factor of Solar Panels (0.19)

Grid Availability Factor : Duration for which grid is available to rural areas (0.90)

We use equation 11 to arrive at Table A.10 which provides the quantum of surplus power that is sold to TANGEDCO, which then will sell it to the C&I consumers.

PV Annual Benefit to TANGEDCO

Table A.10 Annual Energy Generation by Solar PV Panels

This table presents excess power injected into the grid by each category of farmers from solarised pumps. In column 1 we calculate the power generated per farmer using equation 11, column 2 then computes the total power generated for each category of farmers, estimated by multiplying the per power generated per panel with the number of farmers. Column 3 then provides the excess power that will be sold to TANGEDCO - by finding the difference between annual power generated and annual consumption of power by the farmers (using Table A.9)

	(1)	(2)	(3)
	Power generated/farmer	Total Power Generated	Excess Power
	(kWh)	(MU)	(MU)
Small	5392.656	874.41	825.31
Semi medium	14380.416	377.03	350.33
Medium	20222.46	138.73	124.42
Large	53926.56	24.00	21.63
Total		1,414.16	1,321.68

Table A.11 PV Annual Net Benefit - TANGEDCO

Year	PV Annual Benefit (Rs Crores)			
	Baseline	Scenario 1	Scenario 2	Scenario 3
1	612.26	248.02	-261.92	517.10
2	559.45	226.62	-239.33	472.50
3	511.19	207.07	-218.68	431.74
4	467.10	189.21	-199.82	394.50
5	426.81	172.89	-182.58	360.47
6	389.99	157.98	-166.84	329.38
7	356.35	144.35	-152.44	300.97
8	325.62	131.90	-139.30	275.01
9	297.53	120.52	-127.28	251.29
10	271.87	110.13	-116.30	229.61
11	248.41	100.63	-106.27	209.80
12	226.99	91.95	-97.10	191.71
13	207.41	84.02	-88.73	175.17
14	189.52	76.77	-81.07	160.06
15	173.17	70.15	-74.08	146.26
16	158.23	64.10	-67.69	133.64
17	144.58	58.57	-61.85	122.11
18	132.11	53.52	-56.52	111.58
19	120.72	48.90	-51.64	101.95
20	110.30	44.68	-47.19	93.16
21	100.79	40.83	-43.12	85.12
22	92.10	37.31	-39.40	77.78
23	84.15	34.09	-36.00	71.07
24	76.89	31.15	-32.89	64.94
25	70.26	28.46	-30.06	59.34