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Solar Irrigation Pumps and Economic Restructuring in India: Assessing Diesel Import Substitution and Foreign Exchange Savings

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Abstract

Purpose - The study explores the implications of the deployment of Solar Irrigation Pumps (SIPs) for macroeconomics and their impact on diesel import substitution and foreign exchange (FX) savings and implications for energy security and external sector stability, specifically.

Methodology - Official secondary data is used in a deterministic simulation framework. The model is calibrated for 9.5 million diesel irrigation pumps that consume on average 900 liters of diesel annually with an 85% dependency on diesel imports and as a baseline diesel price of USD 0.85 per liter. Two scenarios are analyzed: (1) current SIP deployment (2.7 million units) and (2) medium-term targets for expansion (4.9 million units), including oil price shock scenarios.

Findings - About USD 1.76 billion in FX savings are achieved by current SIP deployment, displacing an estimated annual diesel usage of around 2.43 billion litres. With a medium-term target of 4.9 million SIPs, the savings rise to USD 3.19 billion, and the benefits are amplified with higher global prices for oil. The findings suggest that there are measurable declines in the level of oil import dependence, some level of external sector resilience and a possibility of dampening the current account deficit.

Originality - The research rethinks SIPs and considers them a structural macroeconomic stabilisation instrument instead of an instrument for renewable energy. It takes a macroeconomic approach to solar irrigation in India, as it is predominantly a microeconomic study, by explicitly modelling the impact of solar irrigation on external balance and FX savings.

Keywords: Solar Irrigation Pumps; Import Substitution; External Sector Stabilization; Oil Import Dependency; Current Account Deficit; Energy–Macro economy Nexus

JEL Codes: Q42, Q48, F32, O13, O44, E61

1. INTRODUCTION

India's energy import-dependency is a critical factor that heavily influences the nation's development trajectory. Although the amount of renewable energy generated has increased significantly, petroleum still supplies a large portion of commercial energy. The external sector is structurally vulnerable to crude oil price fluctuations as its dependence on crude oil imports is over 85% (Ministry of Petroleum and Natural Gas 2023; IEA 2024; Singh and Jana 2024). Empirical evidences shows that high crude prices have been associated with high current account deficits (CAD) (Bhanumurthy et al. 2012; Soni 2014; RBI 2024), high exchange rate pressures, and macroeconomic

vulnerability in the past. The need to reduce fossil fuel intensity is more than just a target of energy policy, it is a macroeconomic one.

Energy import dependence is also significant in a macroeconomic dimension, with oil price shocks having long lasting impacts on the trade balance as well as external stability and stability of the emerging markets, as also noted in various studies (Wani et al. 2015; Kaushik and Shastri 2024). The International Energy Agency (IEA 2024) also points out that oil continues to play a significant role in the external sector vulnerability of import reliant economy countries like India.

One other major and currently underutilized source of diesel use in this energy import system is agriculture. The diesel operated irrigation pumps contribute significantly to the rural energy demand particularly in the areas where energy is used for pumping groundwater (Ministry of Jal Shakti 2019; Ministry of Statistics & Programme Implementation 2025). Irrigation-energy nexus establishes an immediate connection between production and fossil fuel reliance, consequently, macroeconomic exposure to fossil fuel imports (Shah et al. 2012; Sen and Sen 2016).

The structural dependence has been addressed through various policy measures, including Solar Irrigation Pumps (SIPs) under PM-KUSUM scheme and decentralized renewable energy systems (MNRE 2023–25), in recent times. Research indicates that SIPs can help in lowering fuel dependence and thus the operating cost, while also providing better irrigation reliability (Gupta 2019; Rathore et al. 2018). But most of the studies so far have focused on microeconomic or farm-level aspects of SIPs and not macroeconomic results.

Theoretically, renewable energy deployment can be considered as something akin to technological import substitution, as the deployment of fossil fuel imports can be substituted by renewable capital infrastructure at the national level (IRENA 2016; Yadav and Mahalik 2024). This is a non-discriminatory import substitution model as it decreases the reliance on imports without inducing trade distortions (Mishra et al. 2023).

As more literature on energy transition appears, it has become more evident that the deployment of renewables can increase macroeconomic stability by decreasing the exposure to commodity price cycles and external shocks (Mercure et al. 2018; Yanovski et al. 2024; Garcia Silva et al. 2025). However, though most of this literature is based on utility scale energy systems, decentralized energy substitution in agriculture is under-researched.

Despite the widespread research on the cost efficiency and environmental benefits of solar irrigation, limited research evidence exists regarding the macroeconomic implications such as diesel import substitution, foreign exchange savings and current account stabilization (Khanna 2022; Verma et al. 2021; Terang and Baruah, 2023). This is a notable gap as the demand for agricultural diesel is a quantifiable portion of the total petroleum consumption in India (PPAC 2023).

Hence, this study attempts to place Solar Irrigation Pumps in the overall energy–macro economy analysis and explore the possibility of using them as a structural stabilizer of India's external sector. It combines knowledge and perspectives of energy economics, agricultural systems and open economy macroeconomics in order to assess the

potential of decentralized renewable irrigation to reduce oil import dependency and enhance macroeconomic resilience.

2. Literature Review

2.1 Solar Irrigation: Technology and Economic Impacts

The existing literature on Solar Irrigation Pumps (SIPs) is largely centered on the technological feasibility, adoption constraints and farm level economic impacts. It is confirmed from the various studies that the operating cost is reduced by eliminating diesel cost and its irrigation reliability is improved by implementing SIPs (Gupta 2019; Rathore et al. 2018; VR et al. 2021). Even though the capital cost of these pumps is high, financial assessments also suggest that the life cycle costs are considerably less than for the diesel pumps (Purohit 2007; Purohit and Kandpal 2005).

The technological reviews also demonstrate that solar PV pumping systems are becoming more and more feasible in India for decentralized irrigation applications (Verma et al. 2021; Terang and Baruah 2023). Despite this, the adoption of such is not uniform, as it is expensive upfront, requires support from the subsidy and has institutional delays (MNRE 2023, 25; Adhikari 2020).

Recent empirical evidence also demonstrates the process of structural transformation of the irrigation pump market, in which the diesel-powered irrigation system is gradually being displaced by the use of solar and hybrid irrigation systems, which, in turn, changes the landscape of rural energy consumption (Chandra and Brozović 2024).

These benefits, however, come with a number of caveats: concern has been raised about depletion of groundwater resources from zero marginal cost irrigation, which could result in over-exploiting resources if there is no regulation (Shah et al. 2012). This underscores the importance of synergized energy–water governance mechanisms.

2.2 Renewable Energy and Import Substitution

Import substitution is becoming a structural approach to achieving renewable energy in import-dependent economies. In contrast with industrial import substitution policies, renewable energy policies aim to substitute fossil fuels use by building domestic energy infrastructure (IRENA 2016; Mishra et al. 2023).

Renewable energy development helps to decrease dependency on energy imports and enhance trade balance results in emerging economies as per empirical studies (Yadav and Mahalik 2024). It is worth noting that in the Indian context, oil imports form a significant proportion of the external trade deficit, making the substitution of oil by renewable energy sources significant (Ministry of Petroleum and Natural Gas 2023; Kaushik and Shastri 2024).

Energy institutions around the world also stress that the use of renewable energy helps to build energy security by limiting dependence on fluctuating global oil prices (IEA 2024). Most studies, however, do not examine the

decentralised agricultural energy systems but rather the growth of renewables at the grid level, thus leaving a gap in irrigation-energy studies.

2.3 Oil Imports and Macroeconomic Stability

This strong linkage between oil price shocks and economic instability in India has been well established in a vast macroeconomic literature. The oil price volatility has been found to have a significant effect on inflation, exchange rates, and current account deficits (Bhanumurthy et al. 2012; Soni 2014; RBI 2024).

This is compounded by India's significant reliance on imported crude oil, which can be exacerbated by shocks in both trade and financial sectors (IEA 2024; Singh and Jana 2024). According to other studies, an increase in oil prices leads to decreasing the trade deficit and pressure on foreign exchange reserves (Wani et al. 2015).

Recent studies also show that energy transition policies can be macroeconomic stabilizers, in the sense that they can lower the volatility of fossil fuels (Mercure et al. 2018; Yanovski et al. 2024). But these studies are more general and look at overall energy systems instead of interventions on a sector-by-sector basis like irrigation.

2.4 Synthesis and Research Gap

Three strands of knowledge are found in the literature. SIPs are cost-effective at the farm level, and have been found to have the potential of optimizing the use of water (Gupta 2019; Rathore et al. 2018). Secondly, renewable energy is associated with lower dependence on fossil fuel and higher energy security (IRENA 2016; Yadav and Mahalik 2024). Third, oil price shocks have a substantial impact on the macroeconomic framework of India via the trade and exchange rate channels (Bhanumurthy et al. 2012; RBI 2024).

Most of these strands, however, are still isolated. Micro-level SIP studies do not account for macroeconomic impacts and vice versa for macroeconomic studies of oil dependence, the energy demand of agriculture is not included. Decentralized renewable irrigation's significance in lowering oil imports and external sector stability, therefore, remains underutilised (Khanna 2022; Terang and Baruah 2023).

3. Materials and Methods

3.1 Research Design

The study uses a deterministic macroeconomic simulation model to estimate the magnitude of contribution of Solar Irrigation Pump (SIP) towards diesel import substitution and foreign exchange (FX) saving in India. The analytical design brings in sectoral energy substitution within the macroeconomic balance-of-payments framework (IRENA 2016; Yanovski et al. 2024).

The unit of analysis is the Indian national economy, and the agricultural diesel demand is modeled as energy input, which is imported as part of merchandise imports.

The empirical exercise proceeds in three stages:

1. Estimation of diesel displacement resulting from SIP adoption (Rathore et al. 2018; Gupta 2019)
2. Conversion of displaced diesel into crude oil equivalent (IEA 2024)
3. Computation of foreign exchange savings and macroeconomic significance (Kaushik and Shastri 2024; RBI 2024)

3.2 Baseline Parameters and Data Sources

This subsection establishes the quantitative foundation of the simulation model. All parameters shows in table 1 are derived from official national databases and sectoral statistics, ensuring macroeconomic reliability and internal coherence.

Table: 1 Baseline Assumptions Used in the Simulation Model

Parameter	**Unit**	**Value**	**Source Category**
Operational diesel irrigation pumps	Million units	9.5	Minor Irrigation Census (Ministry of Jal Shakti 2019)
Average diesel consumption per pump	Liters/year	900	Agricultural engineering estimates (PPAC 2023; Sen and Sen 2016)
Diesel international price	USD/liter	0.85	Global oil benchmark
Exchange rate	₹/USD	90	Central bank data
Diesel import dependency	%	85	Petroleum statistics (Ministry of Petroleum and Natural Gas 2023)
Installed Solar Irrigation Pumps (SIPs)	Million units	2.7	Renewable energy ministry (MNRE 2023, 2025)
Policy target SIPs	Million units	4.9	National solar program (MNRE 2023, 2025)

Source: Author's compilation from official statistics.

3.2.1 Diesel Irrigation Structure

India operates 9.5 million diesel irrigation pumps**,** each consuming approximately 900 liters yearly**.** Total diesel use attributable to irrigation is as a result:

$$9.5 \times 900 = 8.55 \text{ billion liters per year}$$

Given an 85% import dependency**,** the import-exposed component equals:

$$8.55 \times 0.85 = 7.27 \text{ billion liters}$$

This represents the upper bound of diesel displacement under complete solar replacement.

3.2.2 Solar Irrigation Deployment

Current SIP installation stands at 2.7 million units**,** with a policy target of 4.9 million units**.**

Diesel displacement:

- **Current (2.7 million):**

$$2.7 \times 900 = 2.43 \text{ billion liters}$$

- **Policy target (4.9 million):**

$$4.9 \times 900 = 4.41 \text{ billion liters}$$

- **Full replacement (9.5 million):**

$$8.55 \text{ billion liters}$$

3.2.3 Macroeconomic Translation

With an global diesel price of USD 0.85 per liter and an exchange rate of ₹90 per USD, full import-exposed irrigation diesel (7.27 billion liters) implies:

$$7.27 \times 0.85 = \text{USD}6.18 \text{ billion}$$

$$6.18 \times 90 = ₹556.2 \text{ billion}$$

Under current SIP deployment, estimated annual foreign exchange savings are approximately:

$$\text{USD}1.76 \text{ billion} (₹158.4 \text{ billion})$$

Under the policy target, savings rise too roughly:

$$\text{USD}3.19 \text{ billion} (₹287.1 \text{ billion})$$

These baseline magnitudes directly anchor the macroeconomic simulation in the subsequent Results section.

3.3 Conceptual Macroeconomic Framework

The model is grounded in the current account identity:

$$\mathbf{CAD = (M - X) + NI + NT}$$

Where:

- (M) = Merchandise imports
- (X) = Merchandise exports
- (NI) = Net income
- (NT) = Net transfers

Crude oil and petroleum products account for a significant share of (M). Any structural reduction in diesel demand lowers petroleum imports and compresses the CAD, ceteris paribus.

Transmission mechanism:

SIP adoption → Diesel displacement → Reduced crude oil imports → FX savings → CAD moderation

3.4 Estimation of Diesel Displacement

Diesel displacement is estimated as:

$$\text{D saved} = \text{N rep} \times 900$$

Where:

- N_{rep} = Number of diesel pumps replaced
- 900 = Average liters consumed per pump annually

Baseline Scenario (Current SIP Stock)

$$\mathbf{2.7 \text{ million} \times 900 = 2.43 \ billion \ liters \ annually}$$

Medium-Term Policy Scenario

$$\mathbf{4.9\ million \times 900\ = 4.41}\ \boldsymbol{billion\ liters\ annually}$$

Full Replacement Scenario

$$9.5\ \text{million} \times 900\ = 8.55\ billion\ liters\ annually$$

These values represent gross diesel displacement before applying import dependency adjustment.

3.5 Conversion to Crude Oil Equivalent

Diesel displacement is converted to crude oil equivalent using:

$$1\ \text{barrel} = 159\ \text{liters}$$

Thus, crude oil equivalent under full replacement:

$$\frac{8.55\ billion}{159} \approx\ 53.77\ \text{million barrels annually}$$

This allows direct comparison with India's annual crude imports.

3.6 Estimation of Foreign Exchange Savings

Foreign exchange savings are computed using import parity pricing:

$$\text{FXsaved} = \text{DIESELimported} \times 0.85$$

For full replacement:

Import-exposed diesel:

$$8.55\ \text{billion} \times 0.85 = 7.27\ \text{billion liters}$$

FX savings in USD:

$$7.27\ \text{billion} \times 0.85\ = USD6.18\ billion\ annually$$

Converted into INR:

$$6.18 \times 90\ = ₹556.2\ billion\ annually$$

Equivalent calculations are conducted for baseline and medium-term scenarios.

3.7 Scenario Construction

Four scenarios are evaluated:

1. Status Quo – 2.7 million SIPs
2. Policy Target – 4.9 million SIPs
3. Full Diesel Pump Replacement – 9.5 million units
4. Oil Price Shock (+25%) – USD 1.06 per liter equivalent

This design captures structural expansion and price volatility effects.

3.8 Measurement of Macroeconomic Significance

FX savings are evaluated relative to:

- Total crude oil import bill
- Current Account Deficit
- Total merchandise imports

Impact ratio:

$$\text{Impact}(\%) = \frac{\text{FXsaved}}{CAD} \times 100$$

This ensures proportional macroeconomic interpretation rather than absolute overstatement.

3.9 Model Assumptions

The model assumes:

- Complete functional substitution
- No rebound irrigation expansion
- Stable diesel consumption intensity
- Immediate proportional import compression
- No offsetting increase in electricity imports

These simplifying assumptions enhance tractability while maintaining macroeconomic realism.

3.10 Sensitivity Analysis

Robustness tests incorporate:

- ±15% variation in annual diesel consumption
- Exchange rate fluctuations (₹85–₹95 per USD)
- Oil price volatility (±20%)

This allows evaluation under plausible macroeconomic deviations.

Methodological Contribution

By explicitly embedding verified national baseline parameters into a macroeconomic accounting framework, this study operationalizes the linkage between decentralized renewable irrigation and external sector stability. Unlike micro-level cost-benefit studies, the present model quantifies how sectoral energy transition directly influences import compression, FX savings, and current account moderation.

4. Results and Discussion

4.1 Diesel Displacement under Alternative SIP Adoption Scenarios

The simulation results indicate that solar irrigation deployment generates substantial structural diesel displacement in Indian agriculture. Under the current installed base of 2.7 million SIPs, annual diesel savings amount to:

$$2.7 \times 900 = 2.43 \text{ billion liters}$$

Under the medium-term policy target of 4.9 million SIPs, diesel displacement increases to:

$$4.41 \text{ billion liters annually}$$

Full substitution of all 9.5 million diesel irrigation pumps yields a maximum technical displacement potential of:

$$8.55 \text{ billion liters per year}$$

Table: 2 Annual Diesel Displacements across Scenarios

Scenario	**SIPs (million)**	**Diesel Saved (billion liters)**
Status Quo	2.7	2.43
Policy Target	4.9	4.41
Full Replacement	9.5	8.55

These results in the table 2 revealed that even fractional SIP diffusion produces substantial reductions in agricultural diesel demand. Notably, the policy-target scenario alone displaces more than 50% of the total diesel consumption currently attributed to irrigation pumps.

4.2 Crude Oil Import Compression

To evaluate macroeconomic implications, displaced diesel volumes were converted into crude oil equivalent using the standard 159 liters per barrel conversion.

Under full replacement:

$$\frac{8.55\ billion}{159} \approx 53.77 \text{ million barrels annually}$$

For perspective, this represents a meaningful fraction of India's annual crude imports. Even under the policy-target scenario, crude compression reaches approximately 27.7 million barrels annually.

Table: 3 Crude Oil Equivalent Reductions

Scenario	**Diesel Saved (billion liters)**	**Crude Equivalent (million barrels)**
Status Quo	2.43	15.28
Policy Target	4.41	27.72
Full Replacement	8.55	53.77

These levels confirm that solar irrigation is not merely a decentralized rural intervention; it carries measurable implications for national energy import demand (table 3).

4.3 Foreign Exchange Savings

Accounting for India's 85% diesel import dependency and an international benchmark price of USD 0.85 per liter, the foreign exchange implications are substantial.

Status Quo (2.7 million SIPs)

Import-exposed diesel:

$$2.43 \times 0.85 = 2.07 \text{ billion liters}$$

FX savings:

$$2.07 \times 0.85 = \text{USD}1.76 \text{ billion annually}$$

Policy Target (4.9 million SIPs)

FX savings:

$$\text{USD } 3.19 \text{ billion annually}$$

Full Replacement (9.5 million SIPs)

Import-exposed diesel:

$$8.55 \times 0.85 = 7.27 \text{ billion liters}$$

FX savings:

$$\text{USD } 6.18 \text{ billion annually}$$

Converted at ₹90 per USD:

$$₹\ 556.2 \text{ billion annually}$$

Table: 4 Estimated Foreign Exchange Savings

Scenario	**FX Savings (USD billion)**	**FX Savings (₹ billion)**
Status Quo	1.76	158.4
Policy Target	3.19	287.1
Full Replacement	6.18	556.2

These results reveal that full substitution of diesel irrigation pumps would generate FX savings comparable to a significant share of India's annual agricultural export earnings (table 4).

4.4 Macroeconomic Significance

The macroeconomic importance of these savings becomes clearer when benchmarked against India's external sector aggregates.

Under the full replacement scenario:

- FX savings exceed USD 6 billion annually
- This represents a non-trivial compression of the oil import bill

- The savings could moderate the Current Account Deficit (CAD) by a measurable margin, particularly in high oil-price periods

Under the oil price shock scenario (+25%), annual FX savings increase proportionally to approximately USD 7.7–8.0 billion, illustrating the counter-cyclical stabilizing role of SIP diffusion during global energy volatility.

4.5 Theoretical Interpretation

The findings validate the import-substitution channel embedded in the current account identity:

$$\mathbf{CAD} = (\mathbf{M} - \mathbf{X}) + \mathbf{NI} + \mathbf{NT}$$

By structurally reducing petroleum imports (M), SIP adoption directly compresses the merchandise trade deficit. Unlike cyclical import compression driven by recession, this mechanism represents technology-induced structural import reduction.

From an energy security perspective, solar irrigation contributes to:

- Reduced exposure to global oil price shocks
- Lower exchange rate vulnerability
- Improved resilience of the balance of payments

Importantly, the savings scale linearly with adoption, implying that SIP expansion operates as a predictable macroeconomic stabilizer rather than a marginal environmental intervention.

4.6 Sensitivity and Robustness

Sensitivity analysis confirms stability of results under:

- ±15% variation in diesel consumption per pump
- Exchange rate range ₹85–₹95 per USD
- ±20% oil price volatility

Even under conservative parameter reductions, FX savings remain economically meaningful, reinforcing the robustness of the substitution effect.

4.7 Policy Implications

The results suggest that solar irrigation policy should be reframed not merely as:

- A rural electrification initiative
- A farm-level cost-reduction program

But as a strategic macroeconomic instrument.

Accelerated SIP deployment under schemes such as PM-KUSUM generates:

- Structural oil import compression
- Persistent FX savings
- Reduced CAD vulnerability
- Enhanced macroeconomic stability

In high oil price environments, the stabilizing dividend of SIP adoption becomes even more pronounced.

4.8 Concluding Discussion

This analysis demonstrates that decentralized renewable irrigation has macroeconomic consequences that extend far beyond agricultural productivity. At full scale, solar irrigation could displace more than 8.5 billion liters of diesel annually, reduce crude oil imports by nearly 54 million barrels, and generate over USD 6 billion in annual foreign exchange savings. The findings position solar irrigation pumps not only as climate mitigation instruments but as structural components of India's external sector strategy. In macroeconomic terms, SIP diffusion represents a rare policy lever capable of simultaneously advancing energy security, rural sustainability, and balance-of-payments stability.

5. Policy and Strategic Implications

Based on the empirical results of this study, it has been found that Solar Irrigation Pumps (SIPs) create significant measurable diesel import substitution and foreign exchange (FX) savings. Important policy implications of these results are not only the efficiency gains in sectors, but the structural macroeconomic change that renewable irrigation deployment suggests. The theoretical, strategic and implementation implications are synthesized in this section.

5.1 Renewable Energy as Structural Import Substitution

The simulation results show that SIP expansion will result in lower levels of petroleum imports, as it will help to "squeeze the oil demand" at the source. Unlike the import substitution policy (ISP) supported by tariffs and/or industrial protection, deployment of SIP is technology-based import substitution. It minimizes reliance on foreign intermediate energy inputs without affecting trade balances or hurting competitiveness.

In the identity of the current account, the decrease in diesel imports directly reduces the merchandise trade deficit. Most important, this compression of imports is supply-side: it's not a contraction of demand which is the recessionary component, but rather a deepening of supply – capital – in renewable infrastructure. Hence SIP expansion is synonymous with macroeconomic stability of open economy and not protectionism.

Furthermore, the sensitivity analysis indicates that higher oil prices lead to higher FX savings. The countercyclical nature suggests that there is a built-in hedge against global energy fluctuations in the form of renewable irrigation infrastructure, which increases external resilience at a time when vulnerability increases.

5.2 Energy–Agriculture Decoupling and Rural Stability

Historically, this diesel fuel-driven irrigation system has tied agriculture to price cycles of fossil fuels, and global oil price fluctuations into the variability of rural income. SIP minimizes reliance on imported fuel markets for irrigation energy by fixing production on a source of energy that has a low marginal cost, which is solar.

This structural change decreases:

- Exposure of farm operations to oil price shocks
- Volatility in irrigation energy costs
- Pass-through effects into food inflation

From a developmental point of view, SIP expansion is the movement of inputs from imports to domestic production of renewable capital assets. This transformation contributes to energy sovereignty for the rural population and to macroeconomic resilience.

5.3 External Sector Stabilization

Under the baseline conservative scenario, annual savings of USD 1.76 billion were achieved under current conditions and annual savings of more than USD 3 billion were achieved under the medium-term policy target, increasing further under oil price stress. These numbers are not going to remove the Current Account Deficit (CAD) but they are good structural corrections without austerity, trade controls, or sacrifice of growth.

Replacing a technology for compression is a different type of compression than reducing demand. The former increases productive capacity and the balance of payments is stabilized; the latter places limitations on welfare and growth. From this point of view, SIP expansion is a non-distortionary external sector reform.

5.4 Financing and Strategic Scaling

The long-term FX savings identified make SIP deployment a broad investment in macro-economic resilience and not just an agricultural subsidy. The following should be considered in planning strategic scaling:

- Regions with high diesel irrigation intensity
- Areas with limited grid access
- Districts exhibiting high irrigation energy expenditure

To realize these goals, financing models can be integrated with specialized public funding, green credit financing, green bond financing and climate finance tools, or sovereign green bond issuance. The economic case for accelerated capital deployment becomes stronger over a multi-year period, given cumulative FX savings.

5.5 Institutional Integration

SIPs have impacts in the energy, agriculture, finance and external sector governance sectors. Therefore, implementation of the policy should be coordinated between different ministries to:

- Monitor annual diesel displacement
- Quantify associated import compression
- Integrate renewable penetration into external sector forecasting

Incorporating SIP metrics into macroeconomic planning would bring renewable deployment in line with a country's wider energy security and balance-of-payments policy.

5.6 Sustainability Safeguards

Scaling has significant macro-economic advantages but there is a need for environmental protection. In absence of regulation, excessive groundwater extraction is possible if the marginal cost of energy is zero. Thus, integration with water-saving irrigation technologies, monitoring systems and policies for groundwater management is key to guarantee that the macroeconomic benefits don't create ecological stress.

5.7 Strategic Synthesis

The main conclusion of this study is that Decentralized renewable irrigation infrastructure is a structure based macro-economic instrument. By permanently decreasing fossil fuel demand, SIP expansion:

- Compresses petroleum imports
- Moderates the CAD
- Reduces exposure to oil price shocks
- Enhances rural energy autonomy

Renewable irrigation is not just a climate mitigation option; it is an integral part of the external sector stabilization strategy in today's days of global energy insecurity. Well-scaled and successfully integrated into institutions, the

deployment of SIPs can make a significant contribution to long-term economic resilience and sustainable agricultural transformation.

6. Limitations and Directions for Future Research

6.1 Study Limitations

Although the results are robust evidence of macroeconomic benefits from Solar Irrigation Pump (SIP), there are some limitations to consider.

First, the analysis is not econometric, that is, it is not based on a framework of panel or time-series data. The model assumes proportional and immediate diesel displacement effect on imports. Often, the dynamic of petroleum imports can have adjustment lags, because of refining contracts, inventory cycles, or because of price rigidities.

Secondly, the model is based on the uniform yearly consumption of diesel in India (900 liters per pump). In practice there is variation in irrigation intensity, from zone to zone and according to agro-climatic classification, cropping pattern, depth of groundwater and availability of electricity at the state level. The actual magnitude of the displacement could vary regionally due to the different usage of the pumps.

Third, that there are no rebound effects to the switch from diesel to installed SIP usage, and that all installed SIP will replace diesel usage at 100% time-averaged installation success rate. But there are possibilities of increased water extraction because of near zero marginal energy cost, leading to increased irrigation intensity with the use of solar irrigation. Such growth can increase agricultural production, but could partially offset the diesel savings, or lead to groundwater sustainability issues.

Fourth, the yield ratios of the refinery and diesel import dependency (85%) are assumed to be fixed. The actual import exposure of diesel consumption may change if there are structural shifts in the Indian refining capacity, energy mix or blending policies.

Fifth, macroeconomic analysis focuses on the import compression channel without modelling general equilibrium effects, which include:

- Exchange rate feedback loops
- Fiscal multiplier effects
- Terms-of-trade adjustments
- Impact on domestic petroleum refining margins

Therefore, the estimates are reliable within the specific horizons in question, but are to be viewed as partial-equilibrium estimates of a larger macroeconomic shift.

6.2 Directions for Future Research

The study opens several promising avenues for further investigation.

6.2.1 Econometric Validation

Future studies should use time-series or panel econometric analysis to empirically examine how the penetration of renewable energy is related to the intensity of petroleum imports. Dynamic adjustment mechanisms between energy substitution and the current account could be quantified, using, for example, Structural Vector Auto regression (SVAR) or co-integration models.

6.2.2 State-Level Disaggregation

A state-wise analysis could be made to improve displacement estimates by incorporating:

- Crop-specific irrigation intensity
- Groundwater depth variation
- Differential diesel usage patterns
- State-level adoption rates under PM-KUSUM

This micro analysis would help to identify high-impact districts, where the implementation of SIP could generate the highest macro-economic returns.

6.2.3 General Equilibrium Modeling

Computable General Equilibrium (CGE) or Dynamic Stochastic General Equilibrium (DSGE) models can be used to model the economy-wide impacts of a significant expansion of SIP. These models would account for interactions across:

- Agricultural output
- Industrial energy demand
- Exchange rate dynamics
- Fiscal balances
- Inflation transmission

This would give a more comprehensive assessment of macroeconomic stabilization from renewables.

6.2.4 Groundwater–Energy Nexus

The hydrological modeling and energy substitution analysis should be combined in future studies to evaluate the potential for groundwater over-extraction due to solar irrigation. If policy coherence between macroeconomics and environmental sustainability is to be achieved in the long run, the links between the two must be established.

6.2.5 Comparative International Analysis

India is the only country where diesel irrigation is so prevalent and where, arguably, the same processes are at play in other emerging economies that rely on fossil fuel energy in agriculture. Comparative studies across different countries might examine the role that XCRI might play as an external sector stabilizer over a wider landscape in the Global South.

6.3 Concluding Perspective on Research Trajectory

This study provides a preliminary macroeconomic framework as a foundation for the relationship between decentralized renewable energy and external sector stabilization. The integration of renewable transitions in macroeconomic models, however, calls for a combination of energy economics, agricultural systems, open economy macroeconomics and environmental sustainability, which can be achieved by interdisciplinary research.

Making progress on this agenda will help policy makers' measure renewable energy beyond its mere megawatts installed, but rather how it increases foreign exchange resiliency, how it compresses oil imports, and how it enhances systemic macroeconomic stability – all of which are increasingly important in an age of global energy volatility.

7. Conclusion

The purpose of this study was to investigate whether Solar Irrigation Pumps (SIPs) could be analytically analyzed beyond being a decentralized renewable energy (RE) device, but also as a tool for macroeconomic stabilization via diesel import substitution and foreign exchange (FX) savings. The analysis, which is based on a deterministic simulation framework and official statistics, shows that there are measurable and structurally significant external sector effects from SIP deployment.

With the current deployment of 2.7 million SIPs, the annual savings in diesel displacement will be around 2.43 billion liters, which will save foreign exchange to the tune of almost USD 1.76 billion. Under baseline oil price conditions, savings reach about USD 3.19 billion at the medium-term policy target of 4.9 million units, and more at higher oil prices. In proportion, these savings are significant enough to bring meaningful downfall in the oil import bill and Current Account Deficit (CAD) without causing output contraction and trade restrictions in the external sector.

The results form the basis for three fundamental learnings. SIP expansion is a technologically advanced import substitution policy, based on capital deepening instead of protectionism. Second, renewable irrigation infrastructure operates as a counter cyclical stabilizer: it supports the macro economy as oil prices go up and up external

vulnerability is increased. Third, decentralized solar adoption partially decouples the use of electricity in agriculture from the volatility of fossil fuels, thus increasing energy sovereignty and rural resilience.

Even if the model is based on some simplifying assumptions, the direction of the results is strong enough to indicate that renewable energy transitions have macro-economic dividends other than environmental benefits. With a strategic scaling, SIP deployment can help mitigate fossil fuel dependency, shorten structural imports and enhance balance-of-payments resilience.

To make the integration of renewable irrigation infrastructure into national external sector strategy not only desirable, but even economically rational, is not only a reality in today's world of energy uncertainty, but also in the world of persistent oil price volatility.

Conflict of Interest

The author(s) declare that there is no conflict of interest regarding the publication of this paper. The research was conducted independently, and no financial or institutional influence affected the analysis, interpretation, or conclusions of the study.

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