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An adaptive staggered investment strategy for promotion of residential rooftop solar PV installations in India

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ABSTRACT

Rooftop solar PV in India has seen good progress in the commercial and industrial sectors, but the progress in the domestic sector is relatively slow due to the high initial installation cost. Thus, there arises the need for good market models for Rooftop Solar (RTS) implementation. This paper conducts a comparative study of workable RTS market models by employing the discounted cash flow method, as per the recent regulatory guidelines. Market models are formulated and tested for a typical residential high-rise apartment complex in India comprising 15 storied buildings with a combined maximum demand of 180kVA. The results suggest that the centralized community RTS model of 80kWp capacity with upfront financing is suitable when compared to the decentralized individual model, as it has the lowest levelized cost of 3.39 ₹/kWh and a payback period of 5.5 years. With the federal subsidy, the prosumer levelized cost reduces to 2.06 ₹/kWh with a payback period of 3.3 years. Thus grid parity is achieved for all tariff tier rates. With adaptive staggering strategy, this scheme is validated to be more attractive for the urban residential microgrids, as the solar installation of 80kWp and its cost can be staggered and even reduced over the planning period. The study result gives RTS stakeholders insight into selecting the most cost-effective market model to suit their requirements. The proposed analysis can be replicated for high-rise residential buildings, especially in cities with high electricity tariffs. With time, a decrease in solar PV installation price and an increase in grid price are expected; hence, the overall investment cost gets reduced and staggered.

Keywords

Rooftop solar PV;
Community Model;
Solar Financing;
Grid Parity;
LCOE;

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Abbreviations

AT&C – Aggregate Technical & Commercial losses
C-RTS – Community Rooftop Solar
CAPEX – Capital Expenditure
CUF – Capacity Utilisation Factor
DCF – Discounted Cash Flow
DISCOM – Distribution Company
EMS – Energy Management System
FIT – Feed In Tariff
G2H – Grid to Home Mode
GCRT – Grid Connected Rooftop
GHG – Green House Gas
GHS – Group Housing Society
I-RTS – Individual Rooftop Solar
LCOE – Levelized Cost of Electricity

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MD – Maximum Demand	PV – Photo-Voltaic
MNRE – Ministry of New and Renewable Energy	RE – Renewable Energy
NPV – Net Present Value	RTS – Rooftop Solar
O&M – Operation & Maintenance	RWA – Residential Welfare Associations
OCC – Overall Capital Cost	S2G – Solar to Grid Mode
OPEX – Operational Expenditure	S2H – Solar to Home Mode
PPA – Power Purchase Agreement	

1. Introduction

India is amongst the countries with vast solar potential. With nearly 3000 hours of sunshine every year, and 300 sunny days per year, India can theoretically produce annually 5000TkWh of clean and renewable solar energy [1]. India's enormous RE potential of 1097GW primarily includes a solar energy potential of 748GW, according to Energy Statistics 2021 published by the Ministry of Statistics and program implementation (MOSPI) [2]. In the past decades, India and most world nations have seen an increase in population, improved access to modern services and electrification rates, rapid growth in Gross Domestic Product (GDP), and thus an increase in electricity demand. This demand is presently being met primarily by fossil fuels such as coal, oil, and gas [3]. Thus, it has become necessary for India to harvest its abundant solar energy potential by introducing appropriate solar policies [4]. The percentage share of PV in the world's electricity generation mix is low. Cost and power intermittency are the primary reasons [5–8]. With the increase in the cost of energy from fossil fuels and the decrease in the cost of PV, many countries will soon achieve grid parity, which is considered the apex point for PV adoption [5].

For solar PV power generation to improve market penetration, its cost must become comparable to that of existing traditional coal-based power generation. In India, 36% of the installed capacity is from renewables. Among the renewables, 9.5% of the installed capacity is from solar PV. The optimal RE scenario for India in the year 2030 for minimum import dependency is formulated in [9], and the effect of RE on reducing imports is analysed.

Compared to utility-scale solar, RTS has benefits such as reducing AT & C losses, thus a more significant reduction in GHG emissions and low water and land requirements. Falling solar PV prices, favourable net metering regulations, federal subsidy schemes, and good utilization of rooftop space also create excellent opportunities for promoting RTS PV [10]. As reported by International Renewable Energy Agency (IRENA), solar energy can create the largest number of jobs per unit of energy investment [11]. Thus, along with meeting the clean energy targets, RTS also creates business models with high job creation potential.

However, most state-owned DISCOMs are yet to implement RTS on a large scale. The higher electricity tier charged at a higher tariff represents a significant share of DISCOM's revenue, will now be supplied by RTS. Capping restrictions limit RTS capacity to a fixed percentage of the local distribution transformer capacity or percentage of connected load per customer. Also, Indian RTS consumers face challenges such as high capital costs, limitations in technical know-how of feasibility studies, installation, O&M, and the proper competency assessment of the vendors.

LCOE-based studies are conducted to evaluate the techno-economics of grid-connected and off-grid renewables under varying market scenarios considering the life cycle cost. LCOE can compare the cost economics of renewables with conventional fossil fuel-based generation or diverse renewable sources [12]. In [13], LCOE-based economic analysis is conducted to compare an off-grid PV-battery DC microgrid system with grid price for a village in Jharkhand, India. In [14], LCOE is used to compare solar PV, grid extension, and diesel gensets for Sub-Saharan Africa. In [15], the authors conduct a techno-economic analysis of 10 major sites in Pakistan by computing the Net Present Value(NPV), Internal rate of Return(IRR) value, and payback period. For a given RE, LCOE is used to compare the cost economics of different market financial models. In [12], the solar financing model is considered an option to improve the cost-benefit of RE deployment in Africa. LCOE helps policymakers decide on the extent of financial subsidies for RTS to improve its market penetration [16]. LCOE-based grid parity check is used as the primary metric for evaluating the suitability of RTS in many countries [17–22].

Grid parity is the break-even point when the LCOE of the RTS becomes less than or equal to the price of purchasing electricity from the grid, i.e. it is reached when the RTS can generate power at a cost less than or equal to the grid price. When an energy source reaches grid parity, it is considered to be ready for widespread adoption even without subsidies. Germany was among the first countries to reach grid parity in 2011-12 for utility scale and residential PV installations [23]. Even in countries like Qatar with abundant fossil fuel, large scale electricity generation from solar is sold for $ 0.01567 /kWh, cheaper than any form of fossil fuel [24]. Achieving grid parity depends on many aspects like solar irradiance, orientation, local electricity price, incentives and subsidies etc. However, the grid parity value depends on location, customer type, and time of generation. Higher the grid power price, shorter the time to achieve grid parity. An increase in grid power price, can result in renewable energy sources to reach grid parity. Whereas a drop in grid power price due to unexpected decline in oil prices can result a system to lose its parity. The billing policies such as flat rate tariff, slab based tariff, time based pricing, real time pricing also influence grid parity. In the long run, widespread grid parity is expected worldwide due to increasing fuel prices and decreasing renewable prices.

LCOE and payback period from the DCF study are point forecasts. All the standard LCOE models are deterministic as they assume perfect knowledge of all model parameters [25],[17]. However, LCOE models for RTS consist of multiple technical, economic, and policy aspects with uncertain input parameters, making the model output uncertain. Literatures suggest modified traditional LCOE methods to improve the accuracy. LCOE models such as system adjusted LCOE [26], marginal system LCOE [27], levelized avoided cost of electricity(LACE) [28] and, omega LCOE [29] are proposed. System-adjusted LCOE is proposed to include the cost of variability with the standard LCOE [26]. Many studies consider uncertainty and sensitivity analysis in the context of LCOE for renewables [25],[30]. To understand uncertainty in LCOE, statistical methods such as Monte Carlo Methods are employed [29]. The input variables such as specific capital cost (Cost/kW), O&M cost (Cost/kW-yr), Lifetime and Capacity Utilization Factor, are expressed as distributions with uncertainty [30]. All such methods rely on LCOE-based uncertainty modelling and analysis at the project initiation stage. However, such approaches are static as they do not respond to the various techno-economic changes that occur in the lifetime of solar PV.

With static LCOE considered in the Power Purchase Agreements (PPA), the power tariff of solar PV becomes static during its 25 years lifetime. The static PPA tariff has resulted in the significant artificial curtailment [31] of renewables in India [32]; despite the 'must-run' regulations for renewables [33]. Artificial curtailment occurs when RE sources are curtailed for commercial reasons despite grid availability [34]. With the significant drop in RE prices, PPA's are now being renegotiated in many states. Thus, novel strategic market models need to be developed to reduce LCOE and overcome the high capital cost barrier.

Sensitivity analysis is done by changing one parameter at a time while keeping all the other parameters fixed [35], however it cannot examine the cross-influence between parameters. Sensitivity analysis at the design stage is used to determine the techno-economic feasibility of RTS [35]. If Sensitivity analysis is done post-installation, system-level improvements cannot be made; only future economics can be predicted. Uncertainty modelling is suitable in a relatively stable environment but not in the present dynamically changing energy scenario. The present uncertainties are mostly unanticipatable uncertainties with the dynamically changing global energy scenarios. With significant changes in RE capital costs and the electricity tariffs in the recent decades, there is a significant reduction in LCOE. The market value of electricity from PV decreases with an increase in PV penetration [36]. As a result, the grid parity scenario is changing dynamically. RE intermittency and its long lifetime of 25 years add to uncertainty. The accuracy of probabilistic methods relies on the accurate definition of the probability distribution functions of the input variables. As the range of variation in input variable cannot be modelled for a long term, it is not possible to realistically model its long term probability distribution of the input variables. Even Uncertainty analysis and Sensitivity analysis thus become unrealistic under such situations. This uncertainty affects all RTS stakeholders including the policy makers, prosumers and RE developers. A dynamic adaptive strategy needs to be formulated for each stakeholder to mitigate the uncertainty risk, so that the policies, business models and economics are sustainable in the long term. The main objective of the work is to develop novel prosumer strategies that can reduce capital investment, Solar PV size, payback period, and LCOE to promote RTS. The strategy should be capable to accommodate the uncertainties by adapting itself with unanticipated changes in its techno-economic factors. To address the above problems, this study proposes an adaptive staggered investment strategy.

The case studies conducted in various countries based on solar PV system types [37] and its techno-economics suggest a need for improved policy initiatives is highlighted as a significant step for improved Solar PV penetration. [38]. Policy, transparency and accountability, lack of financing, and infrastructure are the significant barriers to utility-scale solar power deployment in India [5]. Similar barriers exist for residential-scale RTS in India; thus there is a need for economic business models.

In the present work, we devise a novel *adaptive staggering strategy* for promoting solar PV installations in urban Indian residential microgrids. This dynamic strategy helps in improving performance indices such as LCOE and capital cost. It is validated to reduce the *capital investment, so*lar PV size, LCOE, and *payback period*. To this end, the major contributions of this paper are as follows:

1. Formulating a novel adaptive staggering strategy for the RTS optimal costing problem in urban Indian residential microgrids, incorporating the existing regulatory guidelines and the electricity demand of the urban consumer. The proposed investment plan ensures improved profitability unaffected by the decreasing solar price trends.
2. A comparative study of decentralized and centralized RTS, with and without community grid is conducted. A centralised RTS implemented in a community grid significantly reduces the capital and operational expenses of the prosumer compared to the typical grid-connected decentralised RTS model.
3. Both capital cost and the cost per prosumer are reduced with a centralized RTS connected to the community grid.
4. To validate the proposed approach, a retrospective analysis is adopted by emulating a *realistic scenario* considering the ongoing pricing and tariff trends.

2. Present Indian Scenario

India introduced the National Solar Mission in 2010 under the National Action Plan for Climate Change (NAPCC 2008) [5]. Initially, when solar PV was an expensive technology, the central and various state governments introduced FIT with long-term contracts of 25 years where the utility companies signed the PPAs with a premium on average power purchase cost (APPC) to make solar PV projects viable [39]. Recent bidding statistics show that the winning bid in the reverse auction process quoted a solar tariff of 2.5 to 2.7 Indian Rupees (₹) /kWh. These prices are well below the APPC of 3-4 ₹/kWh. In line with the Paris commitment of 40% energy from renewables, India has a target of 175 GW of renewable energy by 2022. This includes 100 GW of solar and 60 GW of wind energy [40]. The installed capacity target for solar power includes 60GW of utility-scale and 40GW of RTS (Fig.1) [41]. India revised the RE target to 500GW during the recent UN climate action summit in 2021 [42] this would account for 50% of the installed capacity.

India has the lowest renewable energy costs in the Asia Pacific. As per the Wood Mackenzie report on RE competitiveness in Asia Pacific, India's LCOE of solar PV has fallen to US $ 38 /MWh in 2019, thus becoming 14% cheaper than the traditional coal-fired power plants [43].

Under the MNRE Solar PV Phase II plan, the subsidy is increased for domestic consumers along with policies to incentivize DISCOMs [44]. In Phase I, MNRE initiated the Sustainable Rooftop Implementation for Solar Transfiguration of India (SHRISTI) Scheme to achieve the 40GW policy target. SHRISTI incentivizes DISCOMS based on the installed capacity of RTS in the respective areas. In March 2019, India launched the Phase II of the GCRT solar PV program. India's solar PV installed capacity is 30GW, with RTS of 4GW (June 2019). Thus, the residential RTS segment in India needs improvement. The GCRT solar photovoltaic (PV) phase–II program targets installing 38 GW of RTS by

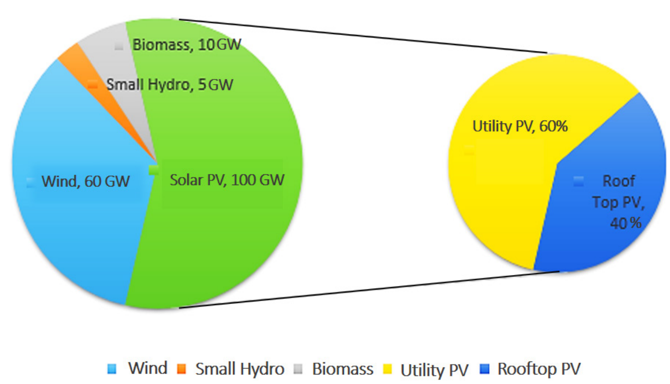


Figure 1: India's Renewable Energy Target by 2022.

2022, of which 4GW will be in the residential sector. A Central Financial Assistance (CFA) for 4 GW of GCRT solar projects is set up in the residential sector, with the respective DISCOMs as the nodal points for implementation of the program [45].

3. State of the Art Techniques in Rooftop Solar PV Market Model-India

Broadly the RTS deployment market model can be classified (Fig.2) as self-owned (CAPEX) (Fig.3) and developer-owned (OPEX) models (Fig.4) installed on-site or off-site [46]. Consumers with high electricity consumption with a higher average tariff [47] will have higher savings when compared to consumers with lower electricity consumption [48].

3.1. CAPEX Model

In the CAPEX Model, the following classifications are described:

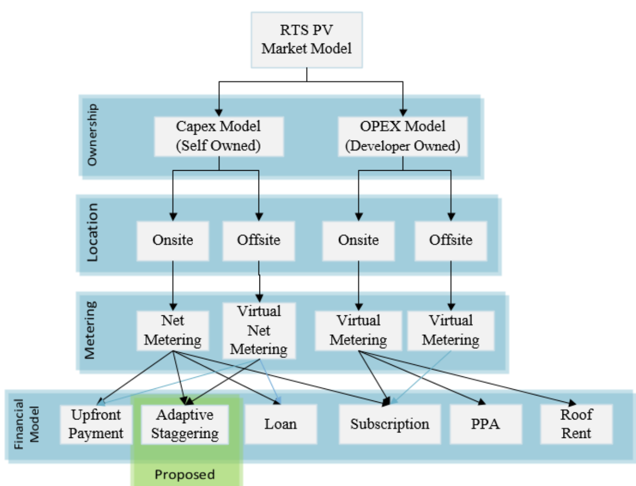


Figure 2: Classification of Implementation Models for C-RTS[49].

3.1.1. Onsite Upfront Payment

Communities with upfront capital and adequate roof space can directly opt to own the RTS by paying the upfront cost (Eq.(1)).The subsidies are computed based on SECI guidelines.

$$OCC = C(1 - D)P \tag{1}$$

where OCC is the overall CAPEX considering upfront payment excluding capitalisation of interest cost(₹); C is the MNRE Benchmark cost (₹/kWh); P is the power rating of the RTS (kW); D is the MNRE RTS Phase II discount (%) for the specified power rating.

3.1.2. Onsite Solar Financing

In market surveys, initial investment cost is cited as the primary factor for reduced willingness to pay (WTP) towards RTS implementation in India [50]. Even with faster payback and a longer lifespan of 25 years, many residential consumers are not opting for RTS because of its high initial investment cost. Thus, to promote solar financing, banks are encouraged to offer solar energy loans up to ₹10 lakh under a priority-lending scheme, thus enabling prosumers to repay the loan from their electricity bill savings. [46, 47].

3.1.3. Offsite Upfront Payment

Communities having upfront capital but do not have shadow-free roof space can opt for an off-site RTS. Identifying an off-site rooftop with no cost or low cost will help to reduce the capital land cost. The panels can be installed in remotely located areas where land costs are low. In India, the provision for virtual net metering (VNM) in off-site RTS installations is gaining popularity, wherein the exported energy of off-site RTS can be used locally, which is then adjusted in the electricity bill of the prosumer based on his ownership stake in the off-site RTS. The DISCOMs are compensated for the distribution

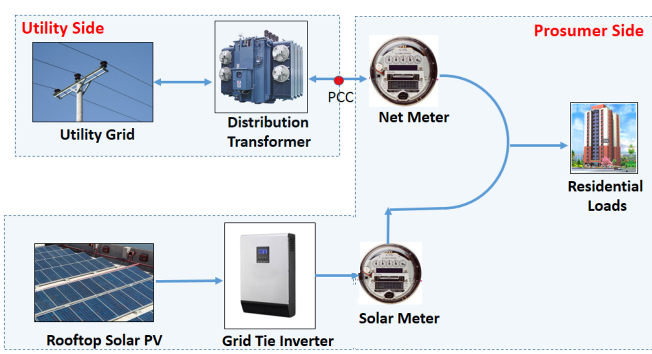


Figure 3: CAPEX Model.

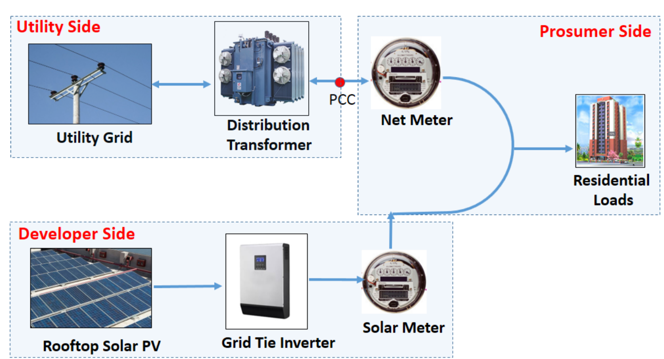


Figure 4: OPEX Model.

infrastructure. Thus, the same electricity generated by remote RTS is not necessarily consumed by the prosumer. This eliminates the need for HV lines and transmitting over large distances.

3.2. OPEX Model

OPEX Model (Fig.4) has the following methods:

3.2.1. Onsite PPA

The developer installs the system at the consumer's premises and then charges the consumer every month. Large consumers of electricity, such as housing societies and townships, can significantly benefit from solar PPA contracts. The term of the PPA contract will be equal to the lifetime of the solar PV. The tariff is decided for the entire term at 20-30% below the grid power tariff, thus ensuring savings for the consumer from day one. Energy prices are locked in for this term.

3.2.2. Onsite Subscription

When the initial investment cost is high, the community can opt for an onsite subscription model, wherein the developer owns the system, and the community can subscribe to the electricity by paying the monthly subscription charges.

3.2.3. Off-Site PPA

The solar aggregator or developer owns and operates an onsite/offsite facility, to which the consumer subscribes for a certain amount of monthly generation. A PPA is signed between the consumer and the developer. The consumer buys electricity from the developer at a price lower than the grid tariff and higher than the LCOE.

3.2.4. Roof Top Renting Model

In this model, the rooftop owner hosts the RTS system, the developer owns the system, and DISCOM agrees to buy power from the developer. The roof owners are compensated with roof rent.

3.4. Economic Analysis

This paper conducts a techno-commercial optimal model for minimizing the overall capital cost and the levelised cost of RTS in residential homes in the Indian context with decision variables as number of participating homes and RTS capacity per home based on the Central Electricity Regulatory Commission tariff guidelines 2020 and MNRE benchmark price 2020-21 and MNRE subsidy. Lifetime cost of RTS is given by Eq.(2):

$$Cost_{lt} = \sum_{t=0}^{T} \mathrm{O\&M}(t) + D(t) + I(t) + R(t) \quad (2)$$

Where D (t) is the Depreciation Cost; I (t) is the Interest on the Term Loan; R (t) is Return on Equity. LCOE is defined as (Eq(3a)):

$$LCOE = \frac{Lifetime\ Cost}{Lifetime\ Energy\ Production} \quad (3a)$$

LCOE is the mean electricity price at which the energy is sold, such that Net Present Value (NPV) is zero.

4. Case Study

This case study considers a typical south Indian state with average solar irradiation of 1266.52 W/m^2 with 5.5 hours of sunshine. The study is conducted for a typical residential high-rise apartment complex in India comprising 15 storied buildings with 4 homes per floor and thus 60 homes per building (Table 1). At high power levels, residential demand in electricity supply contract in India is typically expressed by regulators in kVA [53]. For 60 homes, a combined MD of 180kVA is considered.

The residential system is connected to the utility grid by an 11kV/415V, 250 kVA distribution transformer. C-RTS generation can reduce the size and cost of the system once we consider the diversity factor of the residential facility when operated as a community grid [54]. The typical values of diversity factor of an apartment complex are discussed in standards such as NFC14-100 (French), which are applicable for domestic consumers supplied at 230/400V. A diversity factor of 1.2 is considered, including safety factors and future expansion. Considering the MD of individual homes to be 2 kVA, for 60 homes, ∑MD is 120 kVA. For the diversity factor of 1.2, the MD of the system is computed to be 100kVA. Thus, C-RTS installation reduces the capacity requirement of RTS from the sum of individual MD to MD of the community.

Table 1: Input Parameters

Parameter	Value
No of Homes	60
No of Floors	15
No of Houses/floor	4
Average Solar Irradiation	1266.52 W/m^2
Hours of sunshine	5.5 h

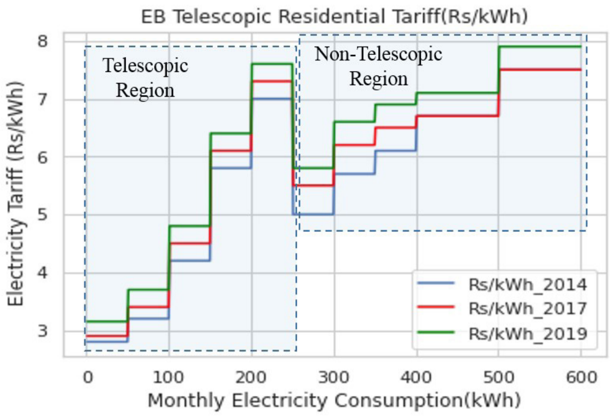


Figure 5: Tiered Residential Energy Tariff.

State DISCOMS have a tiered tariff rate for the residential consumer that increases with the increase in net energy consumption (Fig. 5).

From Fig. 5, it is observed that

1. The electricity tariff increases after every revision, thus helping to achieve grid parity. After every revision, the tariff increases and becomes closer to the LCOE. With RTS capital cost reduction, the LCOE decreases and becomes closer to the tariff. With time, this gap decreases further until LCOE becomes equal to the tariff, achieving grid parity. As the gap between LCOE and consumer tariff decreases, the payback period decreases.
2. The shift of energy consumption by 1 kWh, i.e., from 250 kWh to 251 kWh, raises the billing amount from ₹1282.5 to ₹. 1455.8, an increase of ₹173.3 (13.5%). Thus, having a low LCOE helps to offset higher and lower electricity tiers.
3. For households with lower tariff rates below the LCOE, it is advisable to continue with the grid power. Whereas for the households with tariff rates above LCOE, it is advisable to go for RTS power.
4. Thus arises the opportunity for staggered installation of solar PV which would help to overcome the high initial investment barrier.

A feasibility study considering the electricity expenses has to be conducted and profitability has to be established during the C-RTS project inception stage.

4.1. Problem Formulation of adaptive staggering investment for RTS Installation

Prosumers are categorised based on their willingness to pay and profit expectations. Type-1 prosumer has willingness to make larger capital investment and expects an optimality with high capital cost, at high profits. Type-2 prosumer has lower willingness in making large capital investment and expects an optimality with lower capital cost, at a moderate profit expectation. The objective function is thus formulated as a *weighted single-objective optimization problem* to meet the expectations of both the prosumer types.

4.1.1 Objective Function

The optimisation problem is defined with objective to minimise the LCOE (Eq. (3a)) and the intial investment cost (Eq. (1)) and thus the payback period of the system.

Minimise

$$w1 * LCOE(i,j) + w2 * OCC(i,j) \tag{4}$$

where LCOE is expressed as (Eqn.3b):

$$LCOE(i,j) = \frac{\sum_{t=1}^{T} P_{solar}(i,j) * SAC(i,j,t)}{P_{solar}(i,j) N_h \text{ CUF } (1 - P_{aux}(i,j)) \times T} \tag{3b}$$

From Eq. (1(a)), OCC can be expressed as (Eqn.1 (b)).:

$$OCC(i,j) = C(i,j)(1 - D(i,j))P(i,j) \tag{1b}$$

where T is optimisation time horizon, i.e. the lifetime of the solar PV; i is the CAPEX market model index; j is the pricing scheme index; P_{solar} is the *decision variable* representing the power rating of RTS; N_h is the decision variable representing the number of participating homes; P_{aux} is the maximum auxiliary consumption of RTS project; T is the total no of hours.

Here SAC or specific annual cost is the annual cost per kW RTS capacity (Rs/kW), given by

$$SAC(i,j,t) = O\&M(t) + D(t) + I(t) + R(t) \tag{3c}$$

The optimisation problem is subject to the following constraints. (Eq.(5)-(10)).

The microgrid needs to meet the Energy Balance Constraint (Eqn.5).

$$\sum_{t=1}^{T} (P_{dem}(t) - (P_{grid}(t) + P_{solar}(t))) = 0 \tag{5}$$

where $P_{dem}(t)$ is the residential power demand, and $P_{grid}(t)$ is the power supplied by the grid at instant, t. For the Grid Connected RTS Phase II subsidy, the maximum capacity for individual home (Eq. (6)) and the maximum capacity of GHS/RWA (Eq.(7)) is specified by MNRE.

$$0 \le P_{rated}(n) \le P_{H,max} \quad (6)$$

$$0 \le \sum_{n=1}^{N_h} P_{rated}(n) \le P_{GHS,max} \quad (7)$$

where $P_{rated}(n)$ is the rated PV capacity of the n^{th} home; $P_{h,max}$ is the maximum allowable PV capacity of individual home, $P_{GHS,max}$ and is the maximum capacity of GHS/RWA. The maximum capacity for individual home is specified as 10kWp and the GHS/RWA maximum capacity is specified as 500kWp inclusive of the RTS in individual homes [9]. The cumulative power rating of homes shall not exceed 75% of the rated capacity of the distribution transformer (S_{rated}) as shown in Eq.(8) [23]:

$$\sum_{n=1}^{N_H} P_{rated}(n) \le 0.75 S_{rated} \quad (8)$$

Considering the high-rise building of 15 floors with 4 homes/floor, number of homes participating for RTS installation is given by Eq.(9):

$$0 \le N_h \le N_{h,max} \quad (9)$$

where $N_{h,max}$ is 60 homes i.e. the maximum no of homes participating in solar PV installation. The proposed RTS system must be able to meet the roof area constraint in Eq. (10).

$$A_{rooftop} \ge A_{RTS} \quad (10)$$

Where $A_{rooftop}$ is the available shadow free roof area and A_{RTS} is the roof area required for RTS.

4.2. Discounted Cash Flow (DCF) method

DCF Method estimates the present value of RTS investment based on the expected future cash flows and discount factors. Cash inflow includes the income from electricity generation from RTS, and cash outflows include fixed costs such as O&M expenses, depreciation, interests on loan and working capital, and return on equity. From the discounted values of Cash inflows and outflows, DCFs are computed. A project-specific tariff shall be determined for solar PV projects. [6, 24]. The capital costing is conducted based on MNRE benchmark prices and discount rates [55]. The Net Present Value (NPV), payback period, and LCOE are computed using the DCF method for a lifetime of 25 years. The net electricity generation (MWh/annum) is estimated in Eq.(11):

$$E_{gen} = \frac{P_{solar,ghs}\, N_h\, CUF\,(1 - P_{aux}) \times T}{100} \quad (11)$$

where $P_{solar,ghs}$ is the RTS power rating of the housing society ; CUF is specified as 21% [56]; The maximum auxiliary consumption is specified as 0.75% for solar PV projects [57]; T is the total number of hours specified as 8766 Hours. Based on the baseline weighted average CO_2 emission factor, the net reduction in GHG emission is computed using Eq. (12):

$$GHG_{Reduction} = \sum_{t=1}^{T} \left(\frac{tCO_2}{MWh}\right) E_{gen}(t) \quad (12)$$

where the baseline weighted average CO_2 emission factor is the average CO_2 emission per MWh electricity generation from the grid. It is specified as 0.82 tCO_2/MWh by Central Electricity Authority (CEA). The input parameters for power generation and the financial assumptions are summarised in Appendix-1.

5. Cost Optimal Strategy

This paper recommends an adaptive staggering approach for RTS installation for domestic households. An algorithm is developed for computing the optimal RTS installation strategy based on the Annual MNRE benchmark price [55], MNRE subsidy for RTS, and Grid price revisions for the state by conducting a DCF study. The algorithm based on techno-economic calculation formulates the strategy for RTS implementation (Fig. 6).

1. Estimate Maximum Demand(MD) of the Housing Society
   - Estimate MD at individual home
   - Compute sum of individual MD of the Housing Society
   - Select suitable diversity factor, estimate MD of the Housing Society
2. Select a Suitable Market Model
3 Initialise Energy from DISCOM based on historic Electricity Bill
4. RTS Capacity Estimation
5. Optimise RTS Capital Cost
   - Find Capital Cost solar using Eq.(1)
   - Find optimal no of participating homes
   - Find power allocation for each participating homes

6. Conduct Discounted Cash Flow Study(DCF)
7. Compute Levelised Cost of Energy (LCOE) using Eq.(3b) subject to constraints Eq.(5)-(10).
8. Check for Grid Parity
   - Compare with Local DISCOM Electricity tariff and check for grid parity
   - If grid parity is reached, then go for 100% renewable, where the net annual generation from RTS balances the net annual electricity demand. Here 100% from renewables corresponds to an annual renewable generation (kWh/Yr) matching the annual load demand (kWh/Yr). During sun shining hours, the generation from RTS will be greater than load demand, so as to supply the instantaneous load demand and compensate for the load demand at night. That is, solar power generation would be meeting the load demand during day and night.
   - If partial grid parity is reached, find the energy (Ep) up to which grid parity occurs.
9. Implement Cost Optimal Strategy.
   - Consume from Grid an energy equivalent to Ep units.
   - The remaining energy can be consumed from RTS. (Eq.(5))
   - Find Payback period (Eq.(13)), Objective Function (Eq.(4)), and GHG emissions reduction (Eq.(12))
10. Repeat steps (2)-(9) for different Market models with and without subsidy and conduct comparative study.

Table 2: Pricing Scheme

Type	Pricing Scheme
1	MNRE Price without subsidy
2	MNRE Price with subsidy
3	Tender Price without subsidy
4	Tender Price with subsidy

The grid connected solar PV system is designed for operational economy. During times of MD at say night 8pm, the apartment can easily get power from grid in grid to Home (G2H) mode. Meeting MD using PV is not at all a concern in grid-connected mode, as the power drawn from the grid can be compensated during the day in solar to Grid (S2G) Mode.

The optimization algorithm gives the optimal values of cost, the number of PV panels, the sizing of panels, and the no of participating homes. The algorithm is repeated for different pricing schemes (Table 2) and Market models (Table 3) with and without subsidy, and a comparative study is conducted.

6. Results & Discussion

6.1 Capital Cost Analysis- I-RTS & C-RTS

The investment cost is calculated for I-RTS and C-RTS installation based on the MNRE the benchmark cost FY 2020-21 [25] (Eq.1), and the GCRT Solar

Table 3: Grid Connected Rooftop (GCRT) Solar PV – Market Models

Model	Market Model	Grid Connection	RTS Capacity (kWp)	MNRE Price (before subsidy)[4] (₹/kW)	MNRE Price (after subsidy) (₹/kW)	Capacity (per home) (kW)	Participating homes (No’s)
1	Decentralised RTS (I-RTS)[1] (Individual)	Utility Grid	180	42	25.2	3	60
2	Centralised RTS (C-RTS)[2] (Community)	Utility Grid	180	37.79	35.82	3	All 60
3	C-RTS[3] with Diversity Factor	Community Grid	150	42	25.2	3	50
4	Cost Optimal C-RTS[3] Adaptive Staggering (Upfront payment)	Community Grid	≤ 150	42	25.2	2 to 3	49 to 34
5	Cost Optimal C-RTS[3] Adaptive Staggering (Solar financing)	Community Grid	≤ 150	42	25.2	2 to 3	49 to 34

[1]Purchase, install and use individually
[2]Purchase, install and use as a community
[3]Install and use as a community, purchase individually
[4]Based on MNRE Benchmark price for GCRT for FY2020–21

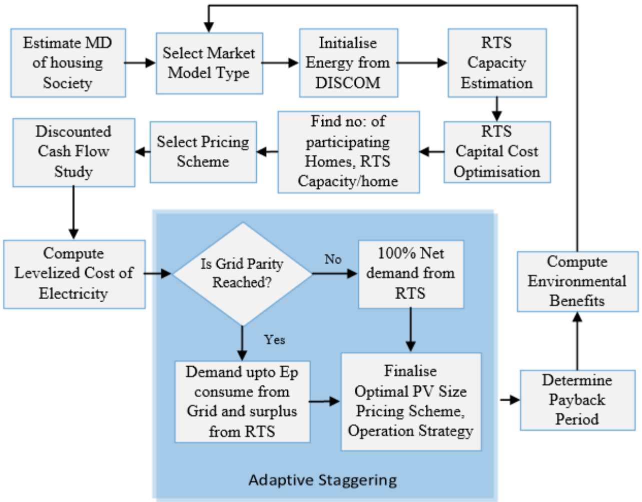


Figure 6: Cost-optimal RTS implementation flowchart.

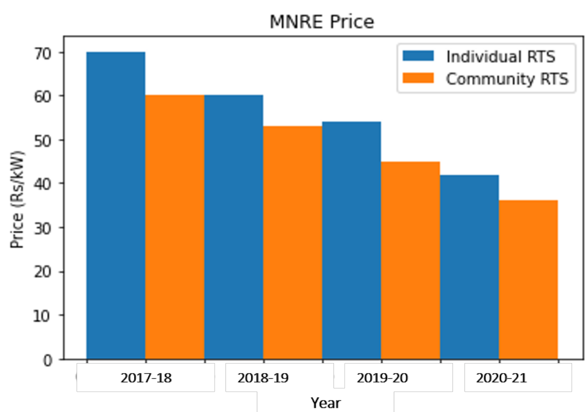


Figure 7(a): MNRE Benchmark price (₹/kW) for individual and community RTS installation (FY 2016-17 to FY 2020-21).

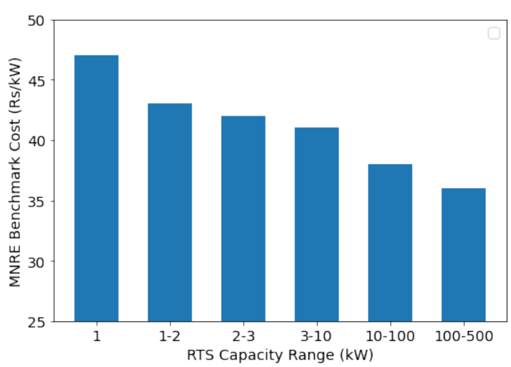


Fig. 7(b) MNRE Benchmark Price reduction with capacity.

Subsidy(Fig. 8) under the Phase II Scheme. A comparative study on the capital cost of C-RTS and I-RTS installation with and without subsidy is conducted. It can be inferred that:

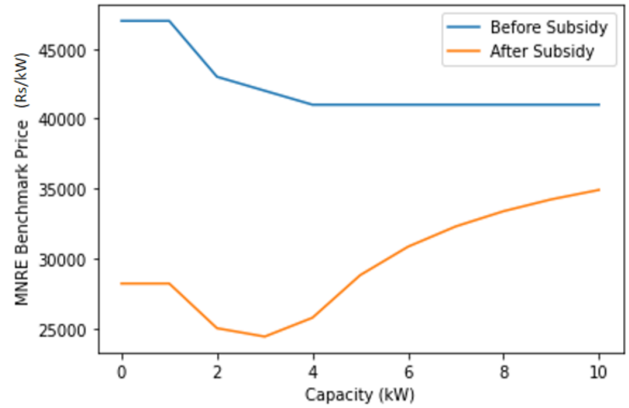


Figure 8: MNRE Benchmark Price – before and after subsidy for residential RTS (FY2020-21) [25].

1) C- RTS has a lower benchmark cost when compared to I-RTS.

2) The MNRE benchmark price is decreasing every year (Fig. 7(a)). With decreasing prices, the subsidies can be phased out once grid parity is reached.

3) As RTS size increases from 1kWp to 180 kWp the benchmark price (2020-21) decreases from 47000 ₹/kW_p to 36000 ₹/kW_p, i.e. a decrease of 11000 ₹/kW_p(Fig, 7(b)) [55]. The RTS system cost (₹/kW) decreases as capacity increases. Considering capital cost before subsidies, C-RTS is better than I-RTS, with a nearly 25% reduction in capital cost.

4) The net cost considering the MNRE benchmark price inclusive of subsidy is computed (Fig. 8).It can be inferred that the maximum subsidy (%) can be availed for an installed capacity of 3kW.

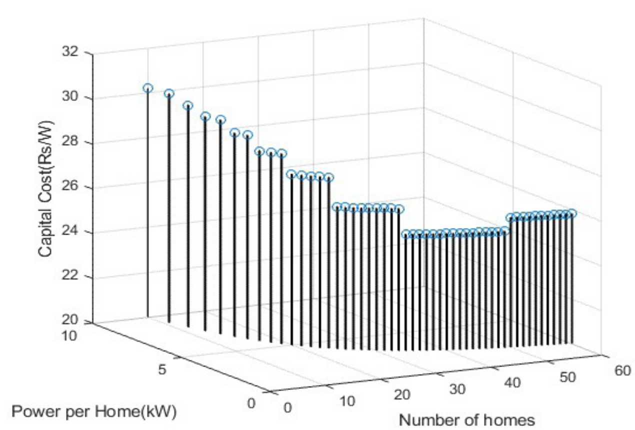


Figure 9: Capital Cost Optimisation for different RTS Market Models.

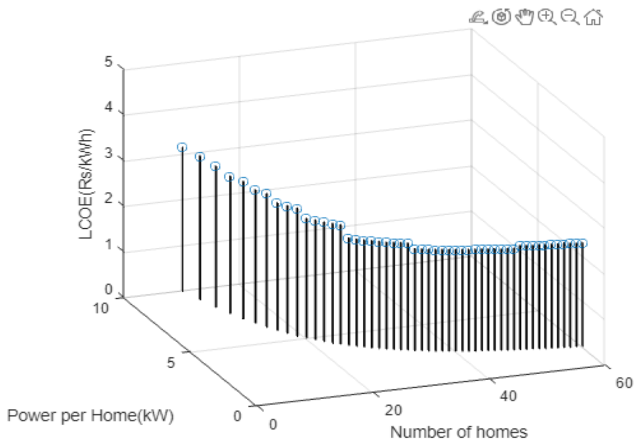


Figure 10: LCOE optimisation for different RTS Market Models.

6.2 Maximum Demand Estimation

A sanctioned load of 2 kW/home is considered for each home, with an average monthly consumption of 200kWh/home. For C-RTS installation, for a diversity factor of 1.2, the RTS capacity reduces from 180kWp to 150kWp (20% reduction).

6.3 RTS Optimization

The single objective weighted optimization algorithm obtains the best combination of PV panel sizing per home and the number of participating homes (Section 5). Based on the objective function and all the constraints of the decision variable, the search space is defined. All market models (Table 3) are evaluated by employing a brute force search method. The simulation results demonstrate that RTS panels of capacity 2 to 3kW/home for 49 to 34 participating homes respectively minimise the capital cost to 24.4 ₹/W. Thus, the optimal RTS capacity/ home and the number of participating homes for the lowest capital cost are computed. The objectives OCC and LCOE are plotted with respect to the decision variables, for comparative analysis. From the plot, we thus validate that the problem can be treated as a weighted single objective problem (Fig 9,10). The objective values of both functions are optimised (minimised) in the same region in the search space. The weight factors are tuned (w_1=1, w_2=20) to normalise the priority of the two terms of the main objective function in Eq (2).

6.4 Market Model Comparison

An optimal methodology for selecting the suitable RTS model in the Indian context is developed (Fig.11).

This paper focuses on the self-owned onsite CAPEX models and various techno-economic interventions to improve its economics (Table 3). I-RTS is considered first (Model-1). C-RTS with the same capacity (Model-2) is considered next. When we purchase RTS as a community, according to MNRE Benchmark pricing, for capacity from 10 to 100kW, the rate is 38 ₹/W, and above 100 kW, the price is 36 ₹/W. The effective subsidies for these cases are calculated as 3% compared to 40% for 3kW capacity (Model-1). Thus, for a 180kW capacity, the price after subsidy is calculated as 35.82 ₹/W (Model-2) when compared to 25.2 ₹/W (Model-1) for a 3kW capacity individual installation. Thus, community purchase of RTS becomes uneconomical. For C- RTS, it is thus cost-optimal to purchase RTS individually and use it as a community after installation. I-RTS capacity is allocated based on connected load at each home, whereas C-RTS capacity is based on the MD of the apartment complex. In C-RTS, when considering the diversity factor of the

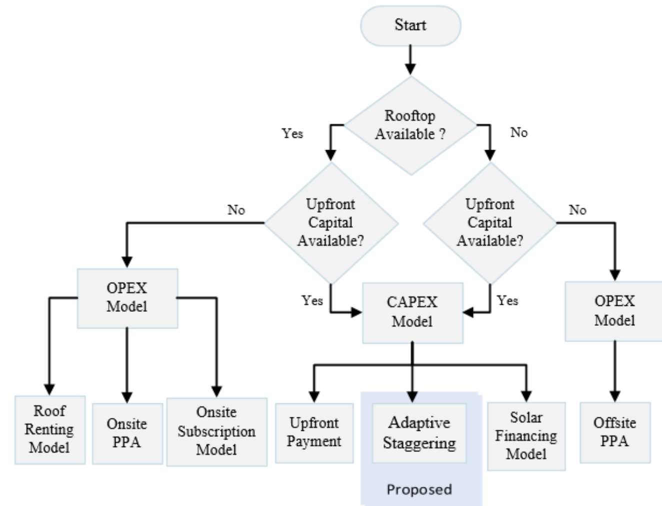


Fig. 11: Market Model Selection Methodology.

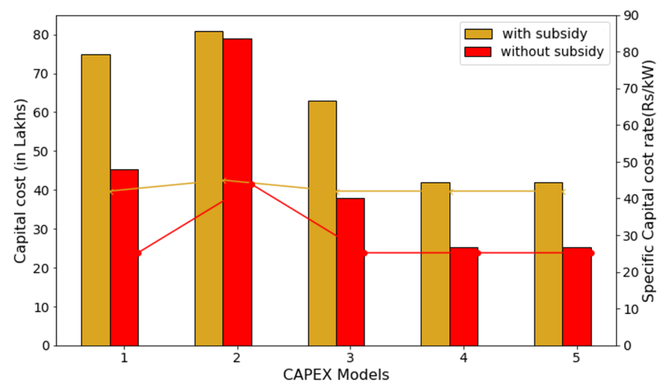


Figure 12: Capital Cost and Specific Capital cost (₹/W) comparison with and without subsidy for different Market Models.

Table 4: RTS Performance Indices

	Model	1	2	3	4	5
Electricity Generation	kWh p.a.	328870	328870	274058	182705	182705
Emissions Reduction	tCO_2 p.a.	270	270	225	150	150
Equivalent no of teak trees	Nos p.a.	421	421	351	234	234
Solar to Grid (S2G)	kWh p.a.	184870	220870	130058	38705	38705
Capital Cost with subsidy	₹ Lakh	45.36	79	37.8	25.2	25.2
Capital Cost Rate with subsidy	₹/kWp	25.2	43.94	25.2	25.2	25.2
Simple Payback without Subsidy	Years	6.34	6.23	6.10	5.50	5.50
Simple Payback with Subsidy	Years	3.80	6.09	3.66	3.30	3.30
LCOE Without Subsidy	₹/kWh	3.79	4.05	3.8	3.8	3.39
LCOE With Subsidy	₹/kWh	2.3	3.96	2.3	2.3	2.06
Objective Function	p.u.	0.57	0.99	0.53	0.45	0.42

community load demand, the required capacity of centralized installation decreases to 150kW (Model-3). It is economical to purchase electricity from the grid for the lower tier of telescopic billing. The RTS capacity requirement can reduce further (Model 4). For a low initial investment, consumers can avail themselves solar financing model (Model 5).

The capital cost with and without subsidy is computed for all 5 models (Fig 12).

6.5 Energy Management

For 300 sunny days per year, the annual electricity generation is computed using (11).The electricity demand of 200 kWh/month per home is used to compute the annual electricity demand. The excess energy is supplied to the Grid (S2G).An Internet of Things (IoT) based intelligent Energy Management System (EMS) in smart grid environment can be utilized to automatically operate the system and switch between the operating modes optimally [58–60].

A cloud-based data analytics tool can be implemented that is common for all RTS stakeholders [61]. For large communities with large no of consumers and RTS installations, the data becomes large and the EMS becomes complex. In such scenarios, a deep learning-based EMS can be implemented [62].

For an installed RTS capacity of 100kW, considering 100 sq.ft./kW_p, the total roof area requirement for the panel is 10000 sq. ft. LCOE with and without subsidy is calculated (Table 4).

Subsidy significantly reduces the LCOE and helps to achieve grid parity for consumers and market penetration for policymakers (Fig.13).

The PV panel price by tender is typically much lower than the MNRE benchmark prices. LCOE reduces from

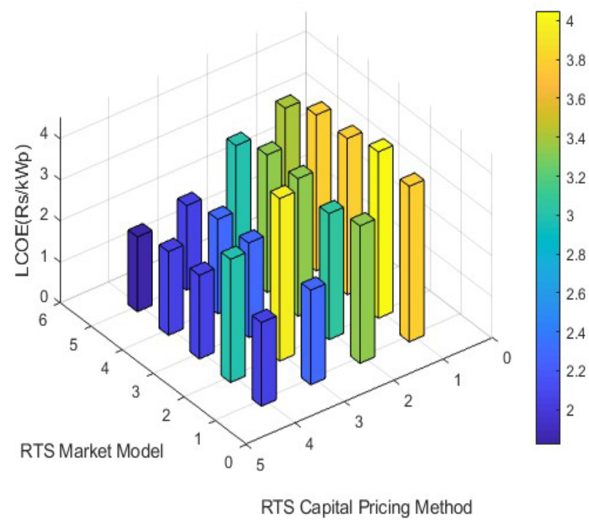


Figure 13: LCOE for different Market Models and Capital Pricing Methods.

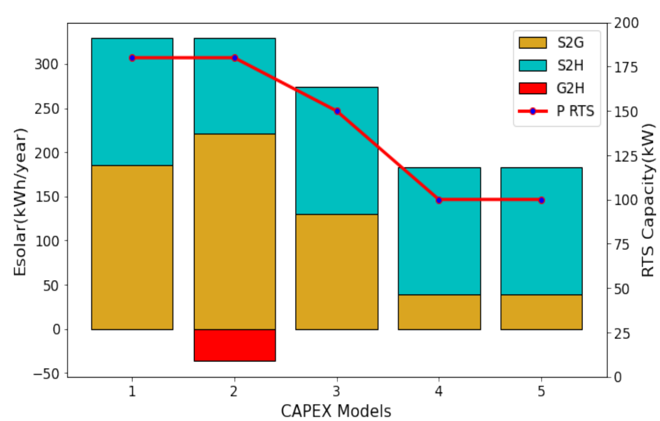


Figure 14: Annual Generation from RTS, Energy Exchanges – Solar to Grid (S2G), Grid to Home (G2H) and Solar to Home (S2H) for various Market Models.

the existing 3.8 ₹/kWh to 3.5 ₹/kWh. In the grid price plot, we include the LCOE to find the electricity to be drawn from the grid. We find the optimal electricity generation.

1) When LCOE < Grid tariff tier, we can install more panels.

2) When LCOE > Grid tariff tier, it is better to get power from the grid and reduce the RTS capacity.

3) When the LCOE = Grid tariff tier, we have reached the optimal LCOE and corresponding optimal energy from the grid.

Thus, the optimal operating energy from the grid corresponds to the point where the LCOE curve meets the grid price curve. The electricity exchange from RTS to the grid (S2G) for models 1-5 are computed (Fig.14). The asynchronicity in generation and consumption is not discounted, it is managed using grid support. With net metering, during daytime the RTS supplies surplus energy to the grid such that during night time in absence of RTS energy, an equivalent energy is supplied by the grid back to the home.

When grid price is below LCOE, it is beneficial to absorb power from the grid, especially in subscription mode.

In Model 5, electricity is supplied by the grid at prices below the LCOE; thus grid to home (G2H) becomes a better financial option for the customer. It can be observed that the overall life cycle system cost is the lowest for Model5. Thus, we need not install the 150kWp panel.

Since LCOE is always less than the grid price for all tier rates, the entire residential electricity demand can be met by RTS. The energy absorbed from the grid (G2H mode) during the night and cloudy days can be compensated during peak sun hours (S2G mode), with a net metering facility. The LCOE is 2.3 ₹/kWh, and the rate that the grid gives in S2G mode is 2.94 ₹/kWh.

As electricity tariff>FIT>LCOE, it is economical to share power within the community (S2H) and then feed surplus power to the grid (S2G) facilitated by a central net metering system. The payback period is computed as shown in Fig.15.

Thus, the 100kWp RTS system gives the lowest upfront cost and payback period.

The RTS installation has the potential to reduce GHG emissions equivalent to carbon sequestration by planting trees having high carbon dioxide removal (CDR) potential (Fig.16).

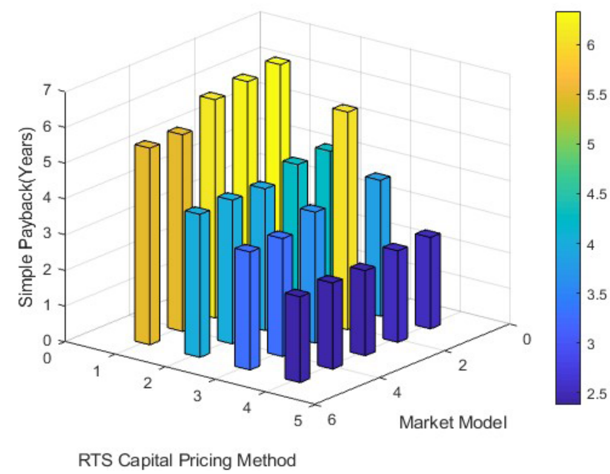


Figure 15: Simple Payback Period for different Market Models and Capital Pricing Methods.

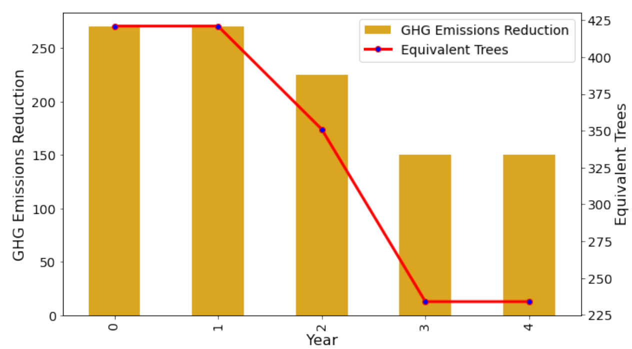
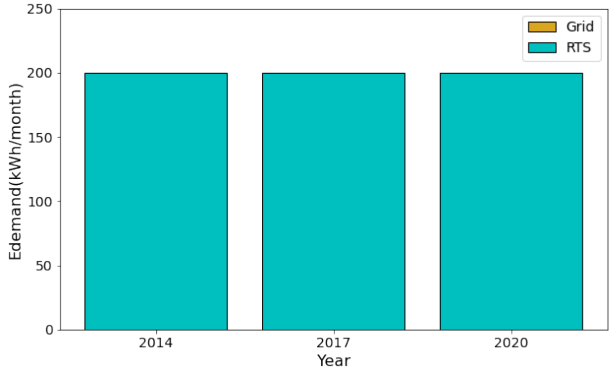


Figure 16: Environmental Benefits of RTS Models CO_2 Emissions Reduction p.a. and Equivalent No of teak trees p.a.

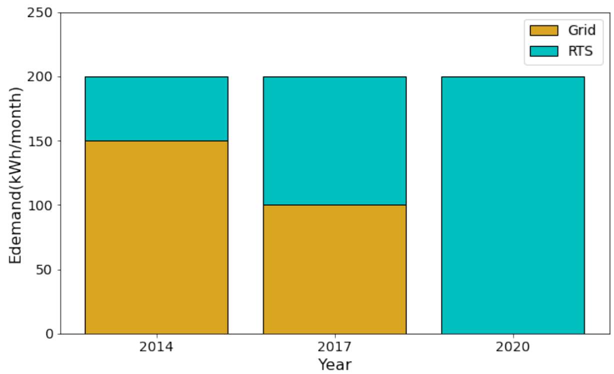
6.6 Dynamic Adaptive LCOE with Staggering Strategy-Retrospective Validation

Without staggering, the monthly demand is met by RTS. From the grid parity study, with adaptive staggering the electricity at lower tariff is met by the grid, and RTS supplies the electricity at higher tariff. The monthly demand is considered to be constant. In 2020, the entire demand is met by RTS.(Fig.17)

With reducing RTS prices and increasing residential electricity tariff, the relative grid parity point changes dynamically(Fig 18). With telescopic billing, a relative-grid parity scenario is considered. A grid parity index is proposed for quantifying the extent of achieving grid parity. A *Grid parity index* is thus defined as the ratio of electricity supplied from RTS to the Total Electricity demand. The grid parity breakeven point shifted from



(a) Without adaptive staggering



(b) With adaptive staggering

Fig.17 Energy Balance–Monthly average.

150kWh (in 2014) to 100kWh (in 2017) to 0kWh (in 2020) (Fig17).

The grid parity index improved from 25% (in 2014) to 50% (in 2017) to 100%(in 2020) (Fig 18). With the tired tariff, the grid parity changes with the change in electricity consumption. The grid parity and thus RE penetration can be improved from 25% (2014) to 100% (2020). For higher income Type-1 prosumers with high energy consumption, it makes economic sense to shift to 25% RTS in 2014, 50% RTS in 2017, and 100% RTS in 2020. A low-income Type-2 prosumer with low energy consumption can achieve grid parity and shift to renewables in 2020 with federal subsidies. In 2014, we were able to encourage only higher-income consumers; however, in 2020, we have a better social scenario where we can also encourage lower-income consumers.

The RTS capacity addition and thus RTS investment is staggered with adaptive staggering strategy. (Fig19 (a), (b)).

This is beneficial for Indian prosumers having high upfront cost barrier for RTS installation. Without

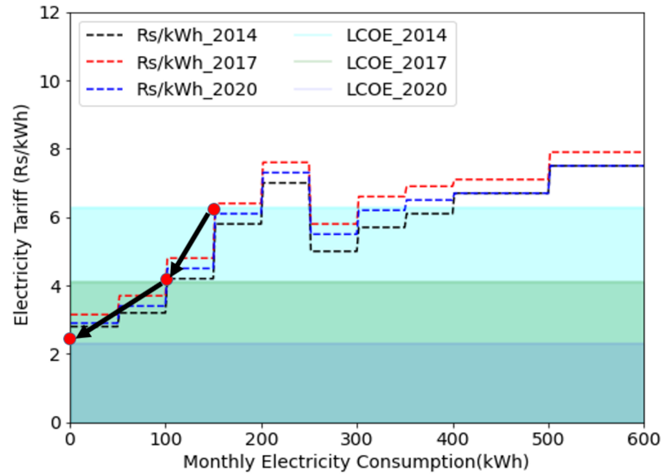


Figure 18: Telescopic Residential Tariff and LCOE.

adaptive staggering, the LCOE during solar PV lifetime remains static at the LCOE during initial investment. Without adaptive staggering, for an RTS installation in 2014, the LCOE remains static at 6.71 Rs/kWh throughout the Solar PV lifetime. With an increase in grid prices and decrease in solar PV capital cost during 2014-20, with adaptive staggering approach, the LCOE decreases after every installation.(Fig 20 (a)).

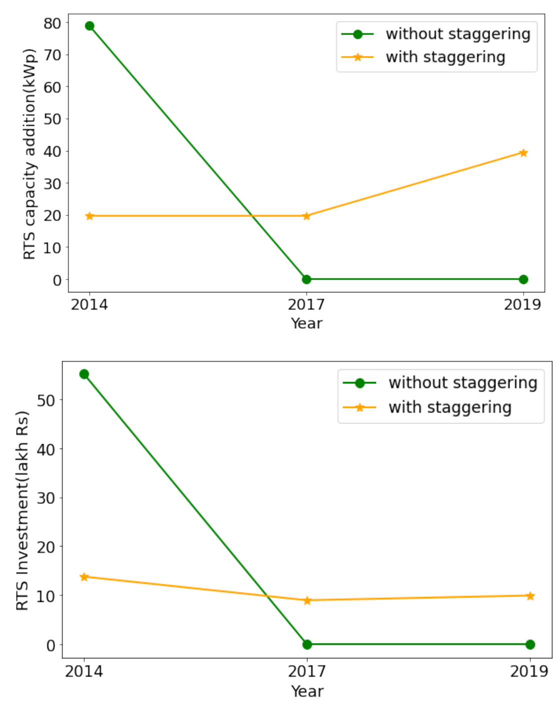


Figure 19: (a) RTS Capacity addition; (b) RTS investment with and without adaptive staggering.

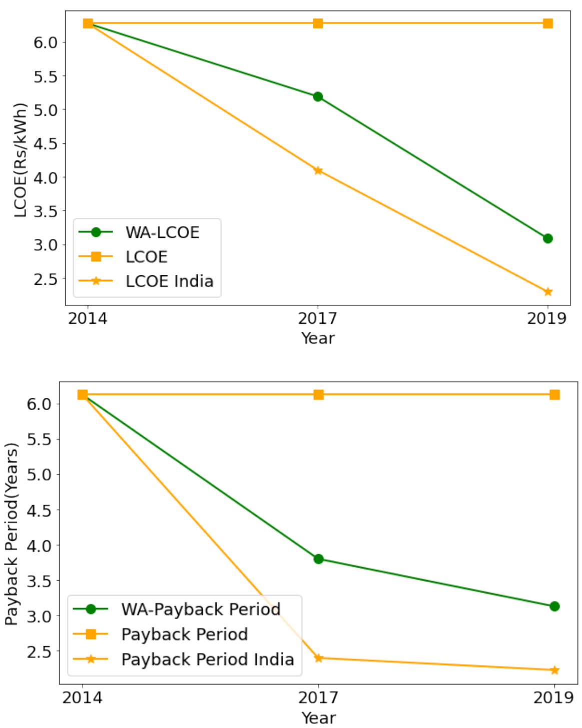


Figure 20: Dynamic adaptive (a) LCOE and (b) Payback period with and without adaptive staggering.

Also, it is worth noting that the total investment cost is not only staggered but also reduced with adaptive staggering strategy, for the same installed RTS capacity of 78.82kWp.(Fig.21).

Dynamic Adaptive LCOE (DA-LCOE) based on the Weighted Average Levelised Cost (WA-LCOE) has reduced by adaptive staggering. Thus, with adaptive staggering strategy, the dynamic LCOE of the project significantly bridges the gap between historical LCOE

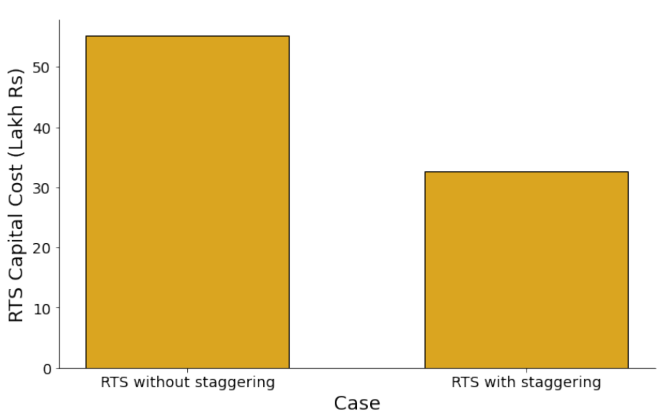


Figure 21: RTS overall capital cost- with and without adaptive staggering.

and the present-day LCOE. With adaptive staggering strategy, the LCOE and payback period are expected to decrease dynamically with grid price increase and RTS benchmark price decrease. Dynamic Adaptive payback period (DA-PBP) or the Weighted Average payback period (WA-PBP) has reduced by adaptive staggering. The payback period adapts and decreases dynamically with improvement in the market scenario, and the benefit is transferred to the prosumer (Fig 20(b)).

Different states in India follow different tired tariff schemes. Thus, the RTS payback period and grid parity will be different. A normalization needs to be done from a policy perspective. A decentralized adaptive approach can be employed. Instead of the existing fixed centralized federal subsidy for the nation, a normalized decentralized subsidy can be provided based on the respective state electricity tariff and the electricity demand of the prosumer. The level of subsidy can be computed such that grid parity is achieved for all electricity demand tiers of that state, sufficient to transit the prosumer to 100% net electricity from RTS. With an adaptive staggering algorithm, the subsidy can be revised from time to time by making it adaptive to future economic changes.

The recent draft Electricity Amendment Bill 2022 [63], considered in India, allows for multiple DISCOMs in the same area, with provision for power distribution lines to be used by multiple DISCOMs. This opens the door for PPA's in the RTS. At present, PPAs are applicable in India in the utility sector only. In future, PPA is expected in the residential sector [64]. The PPA, which adopts a centralised community grid with adaptive strategy, will be able to maintain lower LCOE and thus offer a lower PPA tariff throughout the RTS lifetime compared to a PPA strategy that installs consumer demand-based RTS capacity all at once.

7. Conclusion

This paper presents an optimal strategy for RTS selection for communities living in high-rise apartments in India. A case study is conducted to identify and evaluate the various market models of RTS implementation. RTS panels of capacity 2 to 3 kW/home for 49 to 34 participating homes respectively minimize the capital cost to 24.4 ₹/W. The optimized RTS capacity, payback period, and LCOE are computed with identified market models and pricing schemes. (Table 4). It is inferred that:

1. The LCOE and payback are the lowest for the centralised RTS based community grid, when implemented with adaptive staggering strategy using solar financing model (2.06 ₹/kWh). (Model-5)
2. With the prevailing subsidy, Grid parity is achieved for all tariff tier rates (Models-1, 3, 4 and 5). The entire electricity demand of the home is thus economically supplied by solar (S2H mode) and surplus electricity is supplied to the grid (S2G mode).
3. For C-RTS connected to the utility grid (Model 2), high investment cost results in a high payback period of above 6 years, both with and without subsidy. For C-RTS, it is thus cost-optimal to purchase and install RTS individually and then use it as a community.
4. Without community grid (Model-1,2), RTS installed capacity is 180kW. Although annual revenues from S2G power exchanges are high, large roof area and upfront cost requirements are limiting factors, in the urban Indian residential context.
5. C-RTS when implemented with community grid (Model-3), the required capacity of centralised RTS installation is reduced from 180kW to 150kW (16.6% reduction).
6. For the community grid based models with adaptive staggering based capacity optimised models (Models 4 and 5) RTS installed capacity is 44.4% lower than models without community grid (Model-1,2), Thus for non-community based models, although annual revenues from S2G power exchanges are high, roof area and upfront cost requirements are 44.4% higher and thus becomes limiting factors, in the urban Indian residential context.

A centralised RTS based community grid, when implemented with adaptive staggering strategy, the total capital cost is staggered over 5 years as well as significantly reduced by 40%, thereby lowering annual operating cost as well. The levelised cost and the payback period are also significantly reduced. Levelised cost gets reduced by 51% and payback period gets reduced by 49%.

Strengths and limitations: The adaptive staggering strategy is applicable to all types of prosumers, including domestic, commercial, and industrial and also to all types of tariff schemes, such as tiered monthly tariffs, time of day (TOD) tariffs, and Real Time Pricing (RTP) tariff. In the long term, with technological advancements, solar PV technology will continue to become established and cost effective, a decrease in solar PV capital cost is expected. This scenario is well suitable for implementing adaptive staggering algorithm. Thus, this methodology requires a decentralised implementation for optimality and during policy changes and significant input parameter changes the new optimal investment strategy needs be re-computed. With this algorithm, policymakers can ensure that grid parity is achieved with the subsidy for all the states, irrespective of their tariffs, thus promoting rooftop solar PV penetration. The proposed methodology is replicable across the country in cities for consumers with high electricity tariff tiers. With strong policy support, favourable market models, and falling technology costs, India is expected to be on track to meet the residential RTS targets.

The future scope includes the extension of implementation of adaptive strategies in PPAs for all the renewables with long lifetimes on the verge of grid parity. With decreasing RTS MNRE benchmark prices and improved RTS penetration, in few years the subsidies are expected to be phased out for RTS in India. The adaptive staggering algorithm will identify the new optimal investment strategy. Considering the future electricity amendments, with adaptive strategy, a developer with lower LCOE can offer PPA to an offsite consumer at a lower tariff. The PPA tariff can be of short-term and revised with the market scenario changes based on a pre-specified revision criterion.

Acknowledgement

The authors would like to thank Kerala State Electricity Board Limited (KSEBL) Engineers for their invaluable suggestions and guidance.

Appendix 1

Table A1: DCF-Technical and Economic Parameter Inputs [57]

Parameter	Unit	Value
Technical Parameters		
CUF	%	21
Auxiliary Consumption	%	0.75
Useful Life	Years	25
Financial Assumptions		
Tariff Period	Years	25

Debt	%	70/80
Equity	%	100
Moratorium Period	Years	0
Repayment Period	Years	15
Interest Rate	%	9.67
Return on Equity for 1st 20 years	%	16.96
Return on Equity after 20 years	%	21.52
Discount Rate	%	8.61
Depreciation Rate for 1st 15 years	%	4.67
Depreciation Rate 16th year onwards	%	2.00
O&M Expenses		
O&M expense p.a. (% of capital cost) [65]	%	2
Normative O&M expense (/MW p.a.)	₹ lakh	7.2
Escalation factor	%	3.84
Working Capital Estimation		
O&M expense p.a.	Month	1
Installed Power Generation Capacity	kWp	100
Maintenance Spares (% of O&M expense)	%	15
Receivables	Days	45
Interest on Working Capital	% per annum	11.17

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