Toward Green Residential Systems: Is Cooperation The Way Forward?

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***Abstract*—Achieving self-sustainability has been one of the key challenges in designing smart grid connected residential systems. Solar enabled and power grid connected, dual-powered residential systems is an attractive solution, but it is not carbon free and cost optimal for the end user. This paper proposes temporal energy cooperation among the dual-powered residences as a potential cost and energy efficient solution. Through this paper, we present a microgrid based, multi-residence cooperative energy transfer mechanism to offset the power grid dependency. The developed analytical framework characterizes the green energy storage as a discrete time Markov model and aims to exploit the temporal residential load variations, towards designing self-sustainable systems at a much lower capital expenditure (CAPEX). Our simulation results capture the variation of optimum residence cluster size as a function of energy sharing price and load skewness to become cost profitable. The results also demonstrate a significant reduction in CAPEX, achieved through the proposed energy cooperative framework, over a non-cooperative residential system.**

***Index Terms*—Energy cooperation, smart grid, carbon footprint, CAPEX, revenue analysis**

I. INTRODUCTION

Traditional power grid (termed as macrogrid henceforth) connected residential systems are powered mainly by carbon emitting thermal plants. The US Energy Information Administration (EIA) estimates around 21% increase in residential electricity consumption by 2040 [1]. While meeting energy efficiency is crucial to reduce the carbon footprint, cost has emerged as an important factor towards realizing the energy efficient solutions [2], [3]. Hence there has been a significant need to develop scalable, energy efficient, and cost optimal solutions for residential frameworks. In this work, we present a futuristic energy cooperative framework for realizing profitable and self-sustainable green residential systems.

A. *State-of-the-art and motivation*

Traditional strategies to reduce carbon footprint have been to optimize the power consumption of the macrogrid connected residences [4], [5]. The framework in [4] presented a peak load shifting strategy in accordance with real-time energy prices. Discrete time Markov model based approaches were proposed in [5], [6]. Both the proposed frameworks consider different Markov models for the energy harvest, load, and battery. The combined Markov model is computationally intensive and comprises of a large number of states. Recently, the authors in [7] presented a game theory based grid connected residential framework on gauging the demand response based on time varying energy prices. Along this line, the framework in [8] presented a decentralized framework for load management in smart grids.

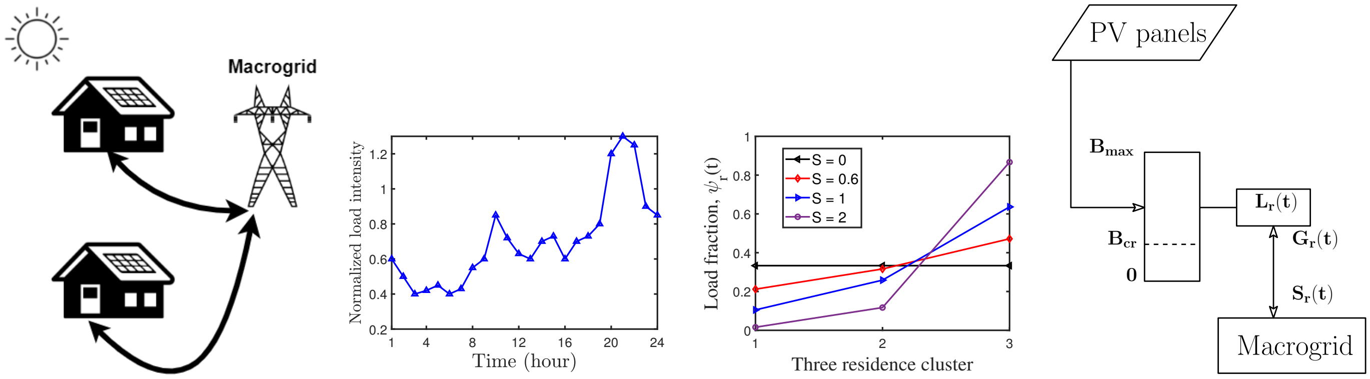
Provisioning residential systems with solar energy supplies in addition to macrogrid connectivity has been an attractive solution [4], [9]. While these dual-powered residential systems are not carbon free, achieving self-sustainability is impractical, incurring a significant capital expenditure (CAPEX) to the residence owner [10]. Additionally, in a multi-residential system, being a non-cooperative framework, the spatio-temporal load variations may often result in improper utilization of the green energy with some residences [11].

Despite a broad range of research being carried out to reduce the carbon footprint, the state-of-art has not explored the possibility of cooperative energy management [12] in residential systems. Additionally, the lack of synchronization among the residences has not been investigated. While significant research has been performed from a circuit level perspective, relatively lesser research is present from a system design viewpoint.

As an advance, in this paper, we present a Markovian analysis approach to investigate the benefit of energy cooperative residential systems.

B. *Contributions*

The key contributions in this work are as follows. (i) A three state discrete time Markov model based analytical framework is presented to characterize the battery storage of a dual-powered, solar enabled and MAcrogrid connected RESidential (MA-RES) system. (ii) The MA-RES system is optimized to compute the optimal solar CAPEX at which the system becomes cost profitable and further self-sustainable. (iii) Next, an energy cooperative dual-powered MIcrogrid based RESidential setting (MI-RES) is considered, and a two state Markov model based analytical framework is proposed to capture the optimal system design towards achieving green residential system. (iv) The MI-RES system is optimized to compute the optimal quantum of energies to be purchased, sold, or shared among the residences. (v) Our results show the variation of optimum residence cluster size as a function of load skewness and energy sharing price. It also demonstrates a significant reduction in per residence CAPEX achieved through the MI-RES framework as compared to the MA-RES framework, towards achieving sustainability.



(a) (b) (c) (d)

Figure 1: (a) Pictorial representation of a dual-powered non-cooperative MA-RES framework, (b) Normalized hourly load profile, (c) Illustration of skewed load generation for a three residence cluster, (d) Energy flow in a MA-RES framework.

C. Organization

The paper layout is as follows. Section II briefs the system model under consideration. Section III and IV present the proposed MA-RES and MI-RES frameworks, respectively. Section V discusses the results and inferences observed. Section VI concludes the paper.

II. SYSTEM MODEL

We consider a residential society having $\mathcal{R}$ dual-powered, solar-enabled and macrogrid connected, non-cooperative residences represented as $\mathbf{R} = \{1, \cdots, r, \cdots, \mathcal{R}\}$. Each residence r generates $L_r(t)$ demand hourly and depends on the solar harvest and/or the macrogrid to meet the demand as shown in Fig. 1(a). We discuss the load and energy harvest profile in the upcoming subsections.

A. Load profile

The average hourly load, $L(t)$, generated by a residence is illustrated in Fig. 1(b) [13]. We generate temporal load variations of varying skewness between the residences as explained below.

$$\psi_r(t) = \frac{e^{Sr}}{\sum_{r=1}^{\mathcal{R}} e^{Sr}}, \text{s.t.}, \sum_{r=1}^{\mathcal{R}} \psi_r(t) = \sum_{r=1}^{\mathcal{R}} \frac{e^{Sr}}{\sum_{r=1}^{\mathcal{R}} e^{Sr}} = 1. \tag{1}$$

Here, $\psi_r(t)$ represents the skewed fraction of average load that a residence will generate and S represents the *skewness parameter* influencing the temporal variations among the residence loads. Fig. 1(c) illustrates the temporal load variations depending on S, for a three residence cluster. For a multi-residence system, depending on S, $L_r(t) = L(t) \times \psi_r(t) \times \mathcal{R}$.

B. Energy harvest profile

Each residence r is assumed to be enabled with N_{PV} panels of rating R_{PV} and N_B batteries of capacity B_{cap}, harnessing $H_r(t) = I_r(t)\eta N_{PV}$ Watts of energy hourly. Here, $I_r(t)$ represents the hourly solar irradiance obtained from National Renewable Energy Laboratory (NREL) [14] and η represents the PV panel efficiency. The upper limit of the energy storage is given as $B_{max} = N_B B_{cap}$ and the critical threshold level below which energy cannot be disbursed to the residence is given as $B_{cr} = \delta B_{max}$. Here, δ represents the depth of discharge fixed in the battery management system. The hourly battery level of a residence r is computed as

$$\begin{aligned} B'_r(t) &= B_r(t-1) + H_r(t) - L_r(t) \\ B_r(t) &= \min\{\max\{B'_r(t), B_{cr}\}, B_{max}\}. \end{aligned} \tag{2}$$

In the upcoming section, we discuss the optimal design framework for a MA-RES system.

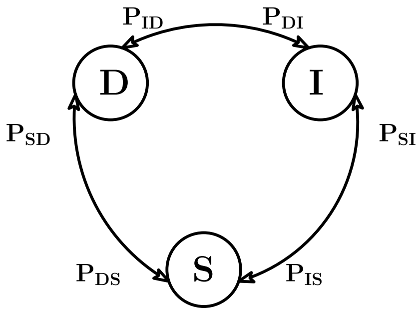


Figure 2: Proposed Markov model for a MA-RES system.

III. OPTIMAL MACROGRID CONNECTED SYSTEM DESIGN

In this section, we discuss the optimal design of a MA-RES framework, through a three state discrete time Markov approach to characterize the battery storage of a residence.

A. Markovian modeling of energy storage

Depending on the hourly residential load and energy harnessed by the PV panels, the residential battery level can transit among three states, namely, deficit (D), intermediate (I), and surplus (S). The hourly deficit $D_r(t)$ and surplus $S_r(t)$ energies in a residence r are computed as

$$\begin{aligned} D_r(t) &= \left|\min\left\{0, B'_r(t) - B_{cr}\right\}\right| \\ S_r(t) &= \max\left\{0, B'_r(t) - B_{max}\right\}. \end{aligned} \tag{3}$$

The energy flow in a MA-RES system is shown in Fig. 1(d). The deficit and the surplus states refer to the condition when the battery level goes below the critical level $(B'_r(t) < B_{cr})$ and above the battery upper limit $(B'_r > B_{max})$, respectively. The intermediate state refers to the condition when the battery level is between B_{max} and B_{cr}. This transition is modeled via a three state Markov model as shown in Fig. 2. The transition matrix $(\underline{\mathrm{T}}_1)$ corresponding to the Markov model is represented below, with the transition probabilities from state $i \longrightarrow j$ being $P_{ij}\ \forall\ i, j \in \{D, I, S\}$.

$$\underline{\mathrm{T}}_1 = \begin{bmatrix} P_{DD} & P_{DI} & P_{DS} \\ P_{ID} & P_{II} & P_{IS} \\ P_{SD} & P_{SI} & P_{SS} \end{bmatrix}. \tag{4}$$

The steady state probabilities of the three states are given as $\underline{\pi}_1 = \{\pi_D, \pi_I, \pi_S\}$, respectively. The matrices, $\underline{\pi}_1$ and $\underline{\mathrm{T}}_1$, are solved using the system of equations given below to obtain the steady state probabilities in terms of the transition probabilities.

$$\begin{aligned} \underline{\pi}_1 &= \underline{\pi}_1^T \underline{\mathrm{T}}_1 \\ \sum_i \pi_i &= 1\ \forall i \in \{D, I, S\}. \end{aligned} \tag{5}$$

It may be noted that the steady state probabilities, π_D and π_S, represent the probabilities of energy outage and energy overflow, respectively.

B. Achieving cost effectiveness and sustainability

In this subsection, we formulate an optimization problem towards computing the optimal CAPEX such that the MA-RES system becomes profitable and further self-sustainable. The grid energy procurement occurring in the event of transition to a deficit state is given as

$$G_r(t) = \begin{cases} 0, & B'_r(t) \geq B_{cr} \\ |B'_r(t) - B_{cr}|, & B'_r(t) < B_{cr}. \end{cases} \tag{6}$$

Thus, $G_r(t) = \sum_t D_r(t)$. The hourly operational revenue, $\mathrm{OP}_{rev1}(t)$, earned by a residence r is given as

$$\mathrm{OP}_{rev1} = \begin{cases} C_{Sell} S_r(t), & \text{if } B'_r(t) > B_{max} \\ C_{buy} G_r(t), & \text{if } B'_r(t) < B_{cr}. \end{cases} \tag{7}$$

Here, C_{Sell} and C_{buy} correspond to the price of selling/buying unit energy to/from the macrogrid. Hence, it can be noted that the energy selling or energy procurement by a residence r from the macrogrid are disjoint with each other. Let t_1 and t_2 denote the time indices when energy selling/buying occurs. Then the net operational revenue for a residence r is given as

$$\begin{aligned} \mathrm{OP}_{rev1} &= \sum_{t_1} C_{Sell} S_r(t_1) - \sum_{t_2} C_{buy} G_r(t_2) \\ &= \sum_{t_1} C_{Sell} \left(B'_r(t_1) - N_B B_{cap}\right) - \sum_{t_2} C_{buy} \left(\delta N_B B_{cap} - B'_r(t_2)\right) \\ &= f\left(N_{PV}, N_B\right). \end{aligned} \tag{8}$$

Here, T_1 and T_2 represent the cardinality of sets indexed by t_1 and t_2. The net profit $\mathcal{P}$ earned by a residence is then computed as

$$\mathcal{P} = \mathrm{OP}_{rev1} - CAPEX, \tag{9}$$

where $CAPEX = (N_{PV} C_{PV}/L_{PV} + N_B C_B/L_B)$, with C_{PV}, C_B being the costs of unit PV panel and battery and L_{PV}, L_B being the corresponding lifetime. An optimal CAPEX computation problem such that a residence incurs net profit over a time duration is formulated as

$$\begin{aligned} \min_{N_{PV}, N_B}\ & CAPEX = (N_{PV} C_{PV}/L_{PV} + N_B C_B/L_B) \\ \text{s.t.,}\ & \mathrm{OP}_{rev1} \geq 0, N_{PV} > 0, N_B > 0. \end{aligned} \tag{10}$$

Further, we also formulate a problem to design a self-sustainable system as given below

$$\begin{aligned} \min_{N_{PV}, N_B}\ & (N_{PV} C_{PV}/L_{PV} + N_B C_B/L_B) \\ \text{s.t.,}\ & \pi_D = 0, N_{PV} > 0, N_B > 0. \end{aligned} \tag{11}$$

In the upcoming section, we propose a multi-residence cooperative energy transfer framework to improve upon the CAPEX incurred per residence for achieving self-sustainability.

IV. COOPERATIVE MULTI-RESIDENCE SYSTEM DESIGN

In this section, we propose a microgrid based cooperative energy transfer mechanism among multiple dual-powered residential systems, called MI-RES, as shown in Fig. 3(a). The microgrid is visualized to be a local co-located energy reserve at the community/society level (if the residences are flats in an apartment) or is a virtual entity controlling energy flow among the individual solar-enabled residences.

A. Markovian characterization of energy storage

The battery level of a MI-RES system is proposed to be in two states namely, deficit (D) and non-deficit ($\bar{D}$), as illustrated in Fig. 3(b). The corresponding transition probabilities are shown in the transition matrix $\underline{\mathrm{T}}_2$ as, $P_{ij}\ \forall\ i, j \in \{D, \bar{D}\}$.

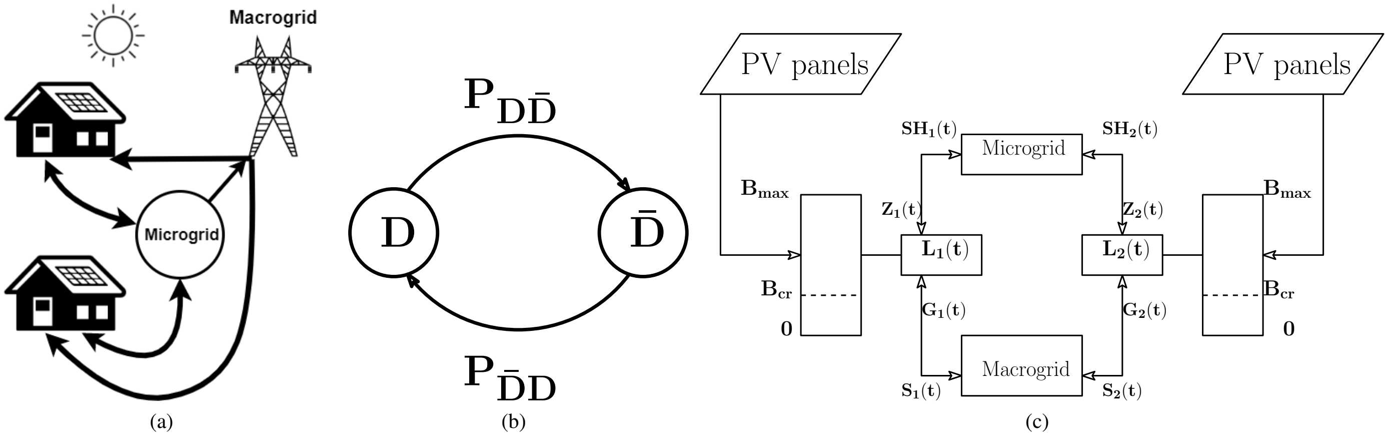
$$\underline{\mathrm{T}}_2 = \begin{bmatrix} P_{DD} & P_{D\bar{D}} \\ P_{\bar{D}D} & P_{\bar{D}\bar{D}} \end{bmatrix}. \tag{12}$$

The steady state probabilities for the two state Markov chain are given by $\underline{\pi}_2 = \{\pi_D, \pi_{\bar{D}}\}$. The steady state values are obtained by solving the system of equations given below.

$$\begin{aligned} \underline{\pi}_2 &= \underline{\pi}_2^T \underline{\mathrm{T}}_2 \\ \sum_i \pi_i &= 1\ \forall\ i \in \{D, \bar{D}\}. \end{aligned} \tag{13}$$

It may be noted that π_D here corresponds to the probability of energy outage . Let, at an hour t, R residences out of $\mathcal{R}$ be in state D (indexed by r), while the remaining R' residences be in state $\bar{D}$ (indexed by r'), such that $R + R' = \mathcal{R}$.

The energy flow occurring in a MI-RES framework is illustrated in Fig. 3(c). When the battery level is in state D, the residence can supplement the deficit energy $(D_r(t) = |\min\{0, B'_r(t) - B_{cr}\}| = Z_r(t) + G_r(t))$ either from the microgrid or the macrogrid. Here, $Z_r(t)$ refers to the green energy transferred, to a residence r in state D, cooperatively



(a) (b) (c)

Figure 3: (a) Pictorial representation of the proposed MI-RES framework, (b) Corresponding Markov model for battery storage, (c) Energy flow in the MI-RES framework.

by the residences in state $\bar{D}$ and $G_r(t)$ refers to the energy purchased by a residence r from the macrogrid. When the battery level is in state $\bar{D}$, the residence after meeting its demand can share $SH_{r'}(t) = \max\{0, B'_r(t) - B_{cr}\}$ energy to the microgrid. Thus, depending on the hourly energy harvest and the load of each residence, a society will have $\sum_{r'} SH_{r'}(t)$ sharable energy and $\sum_r D_r(t)$ deficit energy. The following cases may arise in a multi-residence MI-RES framework.

$$\text{If } \sum_{r'} SH_{r'}(t) \geq \sum_r D_r(t), \text{then:} \begin{cases} \sum_r G_r(t) \overset{(a)}{=} 0 \\ \sum_r Z_r(t) \overset{(b)}{=} \sum_r D_r(t) \\ \sum_{r'} S_{r'}(t) \overset{(c)}{=} \\ \sum_{r'} SH_{r'}(t) - \sum_r D_r(t). \end{cases} \tag{14}$$

$$\text{If } \sum_{r'} SH_{r'}(t) < \sum_r D_r(t), \text{then:} \begin{cases} \sum_r G_r(t) \overset{(a)}{=} \\ \sum_r D_r(t) - \sum_{r'} SH_{r'}(t) \\ \sum_r Z_r(t) \overset{(b)}{=} \sum_{r'} SH_{r'}(t) \\ \sum_{r'} S_{r'}(t) \overset{(c)}{=} 0. \end{cases} \tag{15}$$

From (14b) and (15b), we can rewrite (14c) and (15a) as $\sum_{r'} S_{r'}(t) = \sum_{r'} SH_{r'}(t) - \sum_r Z_r(t)$ and $\sum_r G_r(t) = \sum_r D_r(t) - \sum_r Z_r(t)$, respectively. In the next subsection we will discuss about computing the optimal CAPEX in a MI-RES framework, to achieve self-sustainability.

B. Optimal CAPEX towards achieving self-sustainability

In this subsection, we formulate an optimization problem towards computing the optimal CAPEX in a multi-residence cooperative cluster towards achieving self-sustainability. The net operational revenue ($\text{OP}_{rev2}(t)$) earned by the society at an hour is given by

$$\text{OP}_{rev2}(t) = \underbrace{C_{Sell} \sum_{r'} S_{r'}(t)}_{\text{Selling}} - \underbrace{C_{buy} \sum_r G_r(t)}_{\text{Buying}} - \underbrace{C_{sh} \sum_r Z_r(t)}_{\text{Transfer}}. \tag{16}$$

The above equation can be further expanded and simplified as

$$\begin{aligned} \text{OP}_{rev2} &= C_{Sell}\left(\sum_{r'} SH_{r'}(t) - \sum_r Z_r(t)\right) - C_{sh}\sum_r Z_r(t) \\ &\qquad - C_{buy}\left(\sum_r D_r(t) - \sum_r Z_r(t)\right) \\ &= (C_{buy} - C_{Sell} - C_{sh})\sum_r Z_r(t) + C_{Sell}\sum_{r'} SH_{r'}(t) \\ &\qquad - C_{buy}\sum_r D_r(t). \end{aligned} \tag{17}$$

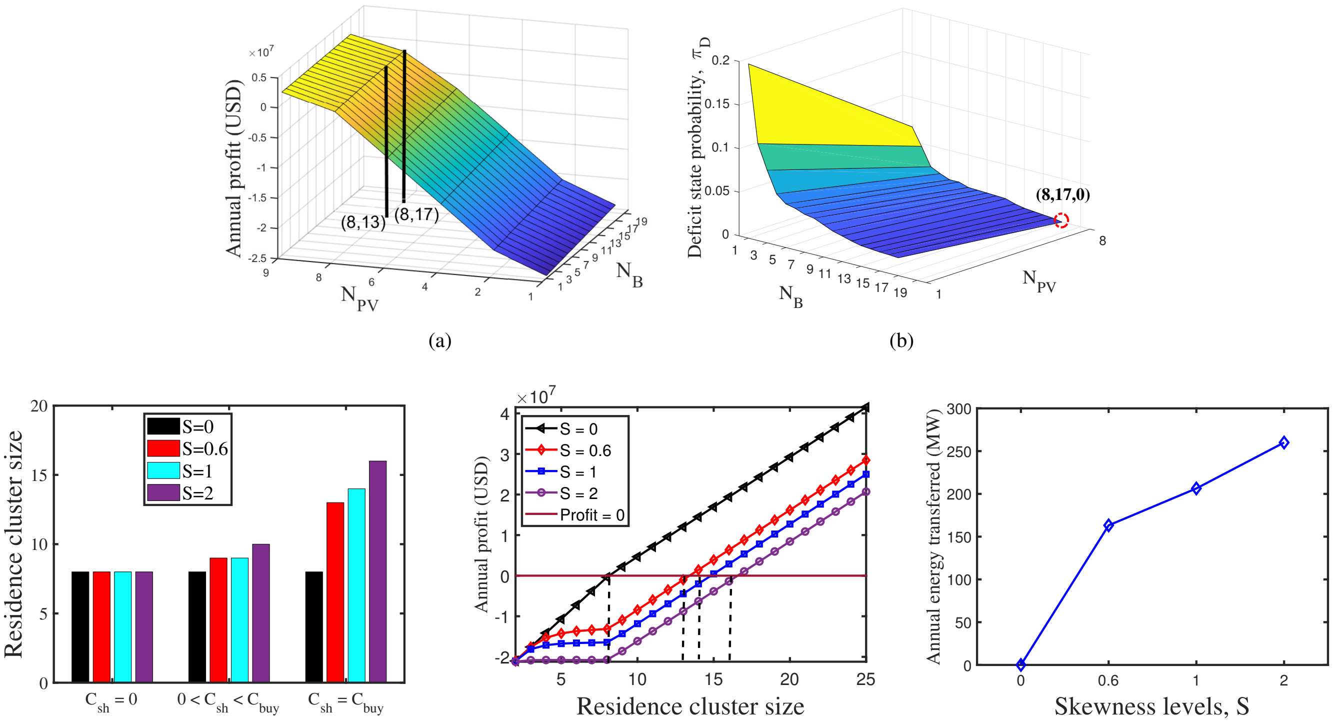
From (14b) and (15b), we observe that

$$\sum_r Z_r(t) = \min\left\{\sum_r D_r(t), \sum_{r'} SH_{r'}(t)\right\}. \tag{18}$$

Therefore, $\text{OP}_{rev2}(t)$ can be expressed as

$$\text{OP}_{rev2}(t) = \begin{cases} (-C_{Sell} - C_{sh})\sum_r D_r(t) + C_{Sell}\sum_{r'} SH_{r'}(t), \\ \qquad \text{if } \sum_r D_r(t) \leq \sum_{r'} SH_{r'}(t). \\ (C_{buy} - C_{sh})\sum_{r'} SH_{r'}(t) - C_{buy}\sum_r D_r(t), \\ \qquad \text{if } \sum_r D_r(t) > \sum_{r'} SH_{r'}(t). \end{cases} \tag{19}$$

Hence we observe that, if $\sum_r D_r(t) \leq \sum_{r'} SH_{r'}(t)$, then the operational revenue at that hour does not depend on C_{buy} (i.e., intuitively no macrogrid energy procurement). Also, if $\sum_r D_r(t) > \sum_{r'} SH_{r'}(t)$, then the hourly operational revenue does not involve C_{Sell} (i.e., no energy selling involved to earn additional revenue). From (19) we observe that $0 \leq C_{sh} << C_{Sell} << C_{buy}$, such that $\text{OP}_{rev2}(t) \geq 0$ if $\sum_r D_r(t) \leq \sum_{r'} SH_{r'}(t)$ and $\text{OP}_{rev2}(t) \leq 0$ if $\sum_r D_r(t) > \sum_{r'} SH_{r'}(t)$. If $C_{sh} = 0$, we term the MI-RES framework as *social cooperation*, and if $0 < C_{sh} \leq C_{buy}$ then it is termed as *business cooperation*. It may be noted that if $C_{sh} > C_{buy}$



(a) (b)

(c) (d) (e)

Figure 4: (a) Annual optimal profit in a single residence MA-RES framework, (b) Steady state probability variation of deficit state, π_D, in a MA-RES framework, (c) Variation of cluster size with C_{sh} to achieve profitability in a MI-RES system, with $(N_{PV} = 1, N_B = 1)$, (d) Variation of annual profit with residence cluster size at $C_{sh} = C_{buy}$, (e) Maximum annual energy transferred to a residence in the MI-RES system, achieving self-sustainability when $(N_{PV} = 1, N_B = 1)$ (corresponding cluster size = 10).

then there is no point of cooperation. The net profit earned in the MI-RES framework can be represented as

$$\mathcal{P} = \sum_t \mathrm{OP}_{rev2}(t) - N_{PV}C_{PV}/L_{PV} - N_B C_B/L_B. \quad (20)$$

Thus, the problem to design a cooperative, macrogrid energy independent system, is formulated as

$$\min_{N_{PV},N_B} CAPEX = \sum_r^{\mathcal{R}} (N_{PV}C_{PV}/L_{PV} + C_B N_B/L_B)$$
$$\text{s.t., } N_{PV} \geq 0, N_B \geq 0, \mathcal{R} \geq 2, \pi_D = 0. \quad (21)$$

Thus, the formulated problem in a MI-RES framework depends on the solar provisioning (N_{PV}, N_B) and the number of cooperative residences $(\mathcal{R})$, or the residence cluster size. $\mathcal{R} \geq 2$ since atleast two residences are required for cooperation. The formulated problems in (10), (11), and (21) are observed to be mixed-integer linear optimization problems. These problems have been solved using standard linear optimization solvers in MATLAB. We will discuss the simulated results obtained and our inferences and observations in the upcoming section.

V. RESULTS AND DISCUSSION

The simulations have been performed in MATLAB R2020a software, with annual hourly solar irradiance data of Jaipur city in India. The parameter values used in simulations are, $\delta = 0.3$, $\eta = 0.5$, $B_{cap} = 2460$ Wh, $R_{PV} = 1$ KW, $C_{buy} = 0.08$ USD, $C_{Sell} = 0.057$ USD, $C_{sh} = 0.02$ USD, $C_{PV} = 1500$ USD, $C_B = 400$ USD, $L_B = 0.25$, $L_{PV} = 1$. Through our results, we first illustrate the optimal CAPEX required to design a profitable and further self-sustainable MA-RES framework. Then we illustrate the working of the proposed MI-RES framework demonstrating the reduction in CAPEX per residence with the proposed framework.

Table I: Cluster size versus CAPEX in MI-RES system, for self-sustainability

$(\mathbf{N_{PV}, N_B})$	$(\mathbf{1,1})$	$(\mathbf{2,1})$	$(\mathbf{3,1})$	$(\mathbf{4,1})$	$(\mathbf{5,1})$
Cluster size	10	5	4	3	2
$(\mathbf{N_{PV}, N_B})$	$(\mathbf{1,2})$	$(\mathbf{1,5})$	$(\mathbf{1,10})$	$(\mathbf{1,15})$	$(\mathbf{1,20})$
Cluster size	10	10	9	9	9

Through Figs. 4(a) and 4(b) we illustrate the design of a profitable and self-sustainable MA-RES framework. Fig. 4(a) shows the variation of annual profit with change in solar provisioning, i.e., N_{PV} and N_B. It is observed that the MA-RES framework becomes profitable, i.e., the solar provisioning at which annual profit is greater than 0, at $(N_{PV}, N_B) = (8, 13)$. The corresponding CAPEX is computed to be $32,800$ USD.

Fig. 4(b) represents the variation in steady state probability of the deficit state (π_D) with a change in solar provisioning.

A general trend inferred from Fig. 4(b) is that, π_D decreases with an increase in N_B. It is also inferred that with an increase in N_{PV}, the rate of decrease of π_D with increasing N_B, decreases. It is observed from Fig. 4(b) that the steady state probability of the deficit state (π_D) becomes zero at $(N_{PV}, N_B) = (8, 17)$, corresponding to a CAPEX of $39,200$ USD. Since π_D represents the long-term energy outage probability, hence $\pi_D = 0$ corresponds to a scenario where there is no transition into state D in the Markov model proposed in Section III-A and hence we can say that the MA-RES system becomes self-sustainable at that (N_{PV}, N_B).

Next, we demonstrate the working of a cooperative MI-RES system, through Figs. 4(c)-4(e). Each residence of the cooperative framework is solar provisioned as $(N_{PV} = 1, N_B = 1)$. Through Figs. 4(c) and 4(d) we demonstrate the variation of cluster size with changing values of C_{sh}, to achieve a cost profitable MI-RES system. It can be observed from Fig. 4(c) that $C_{sh} = 0$ (i.e., social cooperation) results in all the skewness levels attaining profitability at the same cluster size. Upon increasing C_{sh} such that, $0 < C_{sh} \leq C_{buy}$, it is observed that *higher skewness levels require much higher collaborative residences in order to become profitable.* For instance, when $C_{sh} = C_{buy}$, at $S = 2$ (extreme skewness level), a MI-RES residential setting requires a cooperative residence cluster of 16 residences in order to become cost profitable. On the contrary, at $S = 0$ (balanced load scenario), a cooperative cluster of only 8 residences (each provisioned with $(N_{PV} = 1, N_B = 1)$) is required. This variation of annual profit with cluster size when $C_{sh} = C_{buy}$ is shown in Fig. 4(d). It may be noted that while variation in C_{sh} results in a change in optimal cluster size to become cost profitable, the optimal cluster size to achieve self-sustainability does not change (given in Table I). This is due to the fact that, while higher values of C_{sh} result in lower profits, the energy being shared is still green energy.

Finally through Fig. 4(e) we illustrate the maximum annual energy transferred at a certain skewness level to a residence, attaining self-sustainability. We observe that the quantum of energy transferred increases with increasing skewness and is maximum at $S = 2$ (extreme skewness level). It is also observed that $S = 0$ (balanced load scenario) does not involve energy transfer. This is due to the assumption that the hourly energy harvest at all the residences is assumed equal. The optimum residence cluster size at which a MI-RES system achieves self-sustainability for a given (N_{PV}, N_B) is shown in Table I. From Table I *we observe that an increase in N_{PV} leads to a faster reduction in residence cluster size, as compared to an increase of N_B*. At $(N_{PV}, N_B) = (1, 1)$, we observe the optimal cluster size to be 10. This implies that an optimal MI-RES cluster of ten residences having a joint collocated CAPEX of $35,800$ USD $(N_{PV} = 10, N_B = 10)$, corresponds to a per residence CAPEX of $3,100$ USD $(N_{PV} = 1, N_B = 1)$. This amount is about 13 times lower when compared to a non-energy-cooperative MA-RES system, requiring much higher CAPEX $(39,200$ USD$)$ to achieve sustainability. Thus achieving a significant reduction in CAPEX per residence, in addition to greenness.

VI. CONCLUSION

The paper has presented a multi-residence dual-powered, microgrid-based cooperative energy transfer, MI-RES framework, to design self-sustainable next-generation residential frameworks. The designed cooperative mechanism captures and exploits the temporal load inhomogeneities occurring in a dual-powered multi-residential system, thus improving the temporal green energy utilization. The proposed cooperative analytical model has been designed with the green energy storage characterized as a two-state discrete time Markov model. The designed analytical framework has been optimized to compute the optimal quantum of energies to be purchased, sold, or transferred from/to a residence. The proposed cooperative multi-residential MI-RES framework has been compared to a non-cooperative dual-powered, MA-RES framework. The frameworks have been compared in terms of CAPEX incurred per residence towards achieving self-sustainability. The presented cooperative MI-RES framework is expected to pave the way towards self-sustainable green residential societies and motivate existing architectures towards energy cooperation.

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