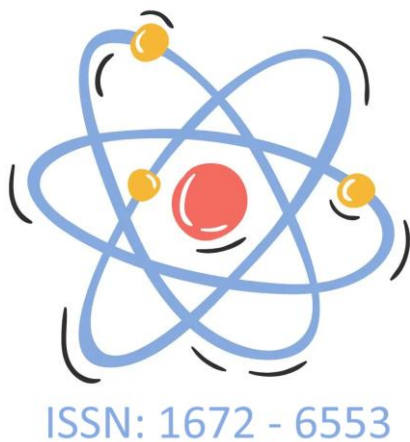




JOURNAL OF DYNAMICS AND CONTROL

VOLUME 10 ISSUE 10: P26-41

NETWORK CONSTRAINED

RELIABILITY ORIENTED V2G

SCHEDULING AND FAIR REVENUE

ALLOCATION IN A SOLAR-WIND

INTEGRATED EV CHARGING STATION

Jitendra Singh, Ramesh Kumar Pachar

Department of Electrical Engineering,
Swami Keshvanand Institute of Technology,
Management & Gramothan,
Jaipur - 302017, Rajasthan, India

NETWORK CONSTRAINED RELIABILITY ORIENTED V2G SCHEDULING AND FAIR REVENUE ALLOCATION IN A SOLAR-WIND INTEGRATED EV CHARGING STATION

Jitendra Singh^{1*}, Ramesh Kumar Pachar²

Department of Electrical Engineering,

Swami Keshvanand Institute of Technology, Management & Gramothan,

Jaipur - 302017, Rajasthan, India

¹jitendrasingh2389@gmail.com, ²rameshpachar1969@gmail.com

Abstract: Vehicle-to-grid is usually justified by energy arbitrage, but the tariff an Indian charging station faces leaves no room for it. This study asks what it is worth at a twenty-bay campus station in Jaipur with the network modelled and owners paid enough to join. The station, with 150 kWp of solar, 100 kW of modelled wind and a 200-kWh battery, is scheduled by a mixed-integer linear program carrying per-vehicle state of charge, battery wear, a linearized model of the 415 V feeder and an outage stage in which the fleet replaces diesel. The surplus is divided between the operator and six owner groups by the Shapley value, the nucleolus, a proportional rule and an equal split, enrolment responds to the payout through a logit model. Vehicle-to-grid eliminates diesel from every outage that is evaluated, reducing the anticipated daily cost of diesel from Rs 41.60 to zero. However, it contributes nothing during regular operation and maintains hosting capacity at 4.10 times current demand. All four rules settle at 9% enrollment, the excess of Rs 37.79 per day is seventy-seven times too tiny. Only the nucleolus is steady. The magnitude of the excess is the binding restriction rather than fairness.

Keywords: Vehicle-to-Grid, Transactive Energy Management, Cooperative Game Theory, Distribution Network Constraints, Photovoltaic, Electric Vehicle Charging Station

1. Introduction

Electric mobility is expanding faster in India than the distribution system that has to carry it, and campuses are one of the places where the two meet. A university that owns rooftop photovoltaic capacity and a diesel backup plant, and that now runs a public charging station, is in effect operating a small microgrid with several competing claims on one transformer. How it should be scheduled, and who should be paid for the flexibility it holds, is the subject of this paper. The question belongs to the wider problem of how developing economies sequence their energy transitions under tight capital and network constraints [1], and it is sharpened in Rajasthan, whose semi-arid climate brings exceptional solar resource alongside water and land stress [2].

Vehicle-to-grid (V2G) operation was proposed two decades ago as a way of turning parked cars into a grid resource, and the original economic case rested on selling power back at times when it is scarce [3,4]. Most of the work since has kept that framing and refined it in four largely separate directions, set out strand by strand by references in Table 1 as scheduling that trades discharge revenue against battery wear, whether by an explicit ageing term [5,6] by comparing the ways ageing can be represented [7,8] or by carrying wear and range anxiety together in a predictive controller [9], network services such as congestion relief [10], transactive coordination, in which charging follows a price signal rather than a central schedule [11,12,13], and cooperative allocation of whatever value results, usually by the

*Corresponding Author

Shapley value or a relative of it [14,15,16,17,18].

What the allocation studies share is that the surplus is taken as given, the prior question, whether it is large enough for anyone to bother joining, is rarely asked. The willingness literature asks it, and the answer is not encouraging. Contract terms matter more than the headline payment, with a guaranteed minimum range and the required plug-in time driving acceptance more strongly than the money on offer [19], and a survey of 1018 drivers found 42 % likely or very likely to enroll, financial return the most cited reason in favour and loss of flexibility the most cited against [20]. Compensation for degradation alone has been put at around EUR 132 per MWh of throughput for a 2030 fleet [21]. None of this has been joined to a network-constrained dispatch model and an allocation rule in the same study.

India makes the gap between these strands visible. A demonstration programme has installed alternating-current bidirectional chargers on retrofitted passenger cars at four sites in Delhi and Kerala, and its own recommendation is that vehicle-to-grid be developed as an alternative to diesel generator sets rather than as an arbitrage product [22]. That recommendation reflects a real price signal. Diesel-generated electricity in India costs well above Rs 15 per unit and is commonly quoted at Rs 22 to Rs 24 [23], two to three times the retail tariff, whereas the time-of-day spread available to a charging station under the Rajasthan schedule is little more than one rupee per kilowatt-hour [24]. If vehicle-to-grid pays anywhere in India, it should pay against diesel.

This paper tests that proposition on a specific system and carries it through to the question of who would take part. A campus charging station in Jaipur with twenty bidirectional bays, 150 kWp of allocated photovoltaic capacity, a proposed 100 kW wind array and a 200 kWh stationary battery is scheduled together with the campus block that shares its 250 kVA transformer. Three things usually left out are represented. The 415 V feeder enters the dispatch problem through a linearized branch-flow model, so the voltage band and the transformer rating constrain the schedule instead of being checked afterwards. Outages enter as a second stage in which the fleet, the stationary battery and the on-site generation compete with the diesel plant to serve the islanded campus. And the owners are not assumed to participate: the surplus is allocated by four rules, each payout is fed into a logit enrolment model, and the loop is iterated to a fixed point.

Table 1. Comparative Features of previous relevant Studies.

Reference	Bidirectional dispatch with per-vehicle SOC	Distribution network inside the dispatch	Outage or backup recourse	Surplus allocation among participants	Owner enrolment endogenous
[3,5,6,7]	Yes	No	No	No	No
[10]	Yes	Partial	No	No	No
[8,9,20]	Yes	No	Partial	No	No
[11,12,13]	Partial	No	No	Partial	No
[14,15,16,17,18]	No	No	No	Partial	No
[19,21]	No	No	No	No	Partial
[22]	Yes	Partial	Partial	No	No
This study	Yes	Yes	Yes	Yes	Yes

Table 1 sets the present work against those strands. The gap it shows is not that any element is missing from the literature each has been treated carefully but that they have been treated apart: a wear-aware schedule computed without asking whether the feeder can carry it, a network service delivered without asking who is paid for it, an allocation rule compared on a surplus some earlier study supplied, and willingness measured on a contract no dispatch model produced. The last row is what this paper adds: the four are solved together on one system.

The contributions are four. A scheduling formulation that combines bidirectional per-vehicle state of charge, a contractual reserve, battery wear, the distribution network and an outage recourse in one mixed-integer linear program. An exactly solved cooperative game

over the operator and six owner groups, comparing the Shapley value, the nucleolus, a proportional rule and an equal split on fairness and on stability. A coupling of allocation to enrolment that makes the participation rate an outcome of the payout rather than an assumption. And a quantitative statement of what vehicle-to-grid at this site is and is not worth: it removes diesel from every outage scenario examined, it does not extend the feeder's hosting capacity, and the surplus it creates falls short of what enrolment needs by a factor that survives an order-of-magnitude change in the assumed price sensitivity of Indian owners. The site, the tariff and the resource model are shared with a companion study of forecast accuracy under unidirectional charging, everything concerning bidirectional operation, the network, the outage recourse, the enrolment model and the allocation game is new here.

The rest of the paper is organized as follows. Section 2 describes the case-study system and the tariff it faces, sets out the linearized feeder model, the bidirectional scheduling problem and the outage recourse, and then defines the enrolment model, the allocation game and the experimental design. Section 3 reports the representative day, the feeder's hosting capacity, what vehicle-to-grid contributes under outage, how the four rules divide the surplus, the enrolment each sustains, the parameter sweeps, the avoided emissions and the limitations of the study. Section 4 draws the conclusion.

2. System and method

2.1. The system description

The site is a public charging station on a campus in Jaipur, India with twenty bays and about one hundred arrivals on a working day. It shares a 250 kVA transformer with a campus block that carries its own rooftop photovoltaic capacity and a diesel backup plant, and it has an allocated photovoltaic array, a modelled wind array, a stationary battery and a small auxiliary load of its own. The wind array is not built, so its output is modelled from a Weibull speed distribution and a cubic power curve rather than measured, an approach whose limits for small machines in low-wind urban settings are well documented [25]. Figure 1 shows the arrangement and Table 2 lists every parameter with its value.

Electricity is bought under the Rajasthan schedule in force from 1 October 2025 [24]. In the EV/LT-8 category a time-of-day adjustment applies to the energy charge alone: a 5 % rebate from 12:00 to 16:00 and a 10 % surcharge from 06:00 to 08:00 and from 18:00 to 22:00. The same schedule bills demand-metered consumers at Rs 150 per kVA of billing demand per month, spread here over a thirty-day month and applied to the day's peak import. With the fixed surcharges included, the resulting price varies only between Rs 8.67 and Rs 9.87 per kWh, a spread of Rs 1.20, this is the first reason arbitrage is weak here.

Table 2. System and model parameters.

Parameter	Value	Parameter	Value
Charging bays	20	Voltage band	0.94–1.06 pu
Avg. Arrivals per working day	100 EVs	Energy charge	Rs 8.00/kWh + Rs 1.00 surcharge + Rs 0.0701 FSA
Energy requested	713.1 kWh/day	Time-of-day adjustment	–5 % 12–16 h, +10 % 06–08 h and 18–22 h
Photovoltaic capacity, station	150 kWp of 400 kW installed	Demand charge	Rs 150/kVA/month of billing demand
Photovoltaic capacity, campus block	250 kWp of 400 kW installed	EV pack capacity (e2w / e3w / car)	4.0 / 10.0 / 40.0 kWh
Wind array	5 × 20 kW Modelled	Contractual reserve	SOC 0.30
Stationary battery	200 kWh / 100 kW, 93 % RTE, SOC 0.10–0.95	Battery wear cost	Rs 1.875/kWh one-way throughput
Station auxiliary load	102 kWh/day	Diesel cost	Rs 22/kWh

Parameter	Value	Parameter	Value
Campus block peak load	180 kW	Outage exposure	24 events/year
Distribution transformer	11 kV/415 V, 250 kVA	Grid emission factor	0.736 t CO ₂ /MWh (combined margin)

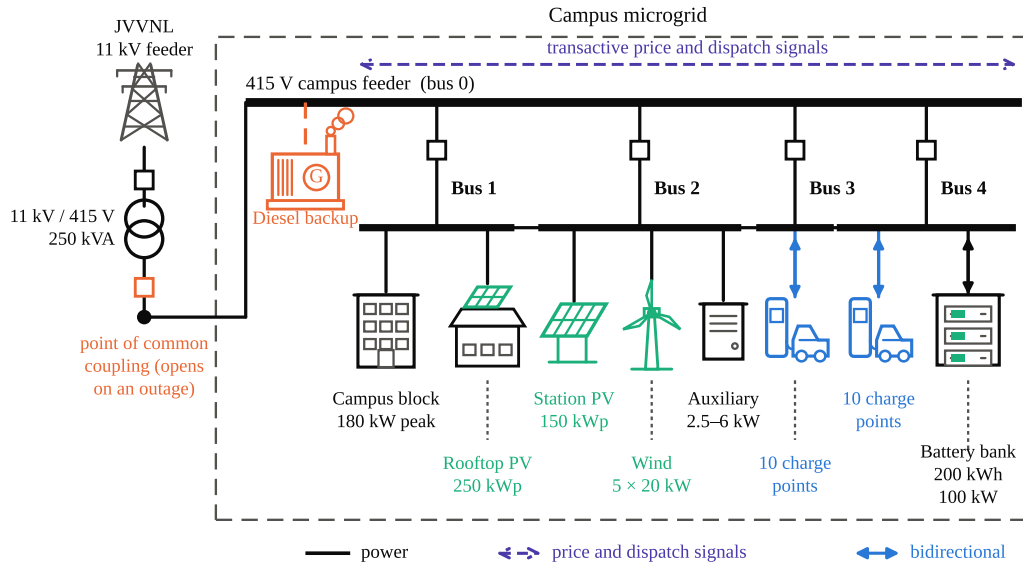


Figure 1: The campus microgrid architecture with 415 V feeder.

Each session is given a pack capacity drawn from the Indian market: 4.0 kWh for two-wheelers (e2w), 10.0 kWh for three-wheelers (e3w) and 40.0 kWh for cars (ecar), the last matching the vehicle used in the national demonstration [22]. Its arrival state of charge is implied by the energy requested and a departure target of 0.90. Dwell time is the time needed to deliver that energy plus a class-dependent parking buffer, and sessions are admitted to bays in arrival order, so no more vehicles are connected at once than the station has bays. Of the hundred arrivals, ninety-three are served, requesting 713.1 kWh across the day, the fleet carries 1452 kWh of pack capacity, of which 170.8 kWh sits above the contractual reserve. The station is bay-saturated from 09:00 to 13:00 and again from 17:00 to 22:00.

2.2. Distribution feeder model

The 415 V feeder downstream of the 11 kV/415 V transformer is radial, so the linearized branch-flow model of Baran and Wu applies [26]. Writing $u = V^2$ in per unit and neglecting losses, the voltage at bus j on a branch fed from bus i is

$$u_j = u_i - 2(R_{ij} P_{ij} + X_{ij} Q_{ij}) \quad (1)$$

where P_{ij} and Q_{ij} are the active and reactive flows on that branch, and R_{ij} and X_{ij} its resistance and reactance. Each flow is the sum of the withdrawals downstream of it, so u_j is an affine function of the bus injections [26]. The voltage band therefore enters the dispatch problem, through Eq. (1), as a pair of linear constraints

$$u_j = 1 - \sum_k A^P[j, k] p_k - \sum_k A^Q[j, k] q_k \quad (2)$$

$$(V_{\min})^2 \leq u_j \leq (V_{\max})^2$$

with the sensitivity matrices A^P and A^Q of Eq. (2) assembled from the branch resistances and reactance along the path from the transformer terminal to bus j , and with p_k and q_k the net active and reactive withdrawals at bus k . The Central Electricity Authority's decision on declared supply voltage sets the low-voltage band at $\pm 10\%$ now, narrowing to $\pm 6\%$ [27],

the tighter forward-looking band, 0.94 to 1.06 per unit, is used for the headline case. Cable data are standard manufacturer values for 3.5-core aluminium XLPE. Chargers operate at unity power factor and the campus block at 0.90 lagging, so the reactive flow through the transformer is fixed hour by hour, and the apparent-power limit, taken against the nameplate rating as the Central Electricity Authority's distribution-infrastructure guidelines specify [28],

$$|P_{DT}(t)| \leq \sqrt{(S_{DT,max})^2 - (Q_{DT}(t))^2} \quad (3)$$

in Eq. (3) is exact and linear rather than an approximation of a circle. The transformer is rated 250 kVA. Bus 1 carries the campus block and its 250 kWp array, bus 2 the station incomer with the allocated photovoltaic capacity, the wind array and the auxiliary load, and buses 3 and 4 the two groups of ten bays, with the stationary battery at bus 4.

2.3. Bidirectional scheduling problem

The microgrid is dispatched over a 24 h horizon at hourly resolution. Relative to the unidirectional charging formulation adds a discharge variable for every session, an explicit state of charge for every pack, a contractual reserve, and a wear charge on throughput in both directions. The state-of-charge recursion is the one used throughout the bidirectional-scheduling literature [5,7,9], with separate charge and discharge efficiencies so that the round trip is not taken as lossless, for session i in hour t it reads

$$\text{soc}_i(t+1) = \text{soc}_i(t) + [\eta^c p_i^c(t) - \frac{p_i^d(t)}{\eta^d}] \frac{\Delta t}{C_i} \quad (4)$$

with soc_i in Eq. (4) bounded below by the contractual reserve σ and above by 0.95, and $\text{soc}_i(d_i) \geq 0.90$ at departure. A session is eligible only if it arrives at or above σ , since the contract undertakes never to take the pack below that level, at $\sigma = 0.30$, seventy-two of the ninety-three sessions qualify. Charging wear on throughput in both directions rather than on a cycle count follows the treatment recommended for non-residential vehicle-to-grid studies [6], [8], the objective is

$$\begin{aligned} \min \quad & \sum_t [\pi(t) g(t) - \pi^x x(t)] + \delta D + c^b \sum_{i,t} [p_i^c(t) + p_i^d(t)] + \\ & c^s \sum_t [b^c(t) + b^d(t)] + \sum_w \rho_w c^{df} \sum_t z_w(t) \end{aligned} \quad (5)$$

It charges energy at the retail price, the billing demand D bounded below by every hour's import at the daily equivalent δ of the demand charge, and the wear of the vehicle and stationary batteries, and it adds the expected cost of diesel across the outage scenarios described below. Battery wear is taken at the pack level: at Rs 9000 per kWh, 3000 equivalent full cycles to 80 % state of health and a reference depth of discharge of 0.80, the marginal cost is Rs 1.875 per kWh of one-way throughput, or about Rs 4.07 per kWh delivered once the recharge is counted. The upper bound of Rs 12.5 per kWh implied by the European break-even estimate is carried in the sensitivity study [21].

Binary variables forbid simultaneous charging and discharging. Because wear is charged on throughput in both directions, simultaneous operation is strictly dominated, and the continuous relaxation proved integral in every case reported, agreeing with the integer objective to a relative difference of 1.4×10^{-16} . The relaxation was therefore used for the 64 coalition evaluations and verified against the mixed-integer solution.

2.4. Outage recourse

Grid outages are represented as a second stage evaluated against the day-ahead schedule. Four representative scenarios are used, listed in Table 2 and weighted towards the evening because that is when Rajasthan's unserved-energy episodes cluster. In each scenario the microgrid islands, charging is suspended, and the campus load and station auxiliary must be met from on-site generation, the stationary battery, the fleet, or the diesel plant. The contractual reserve σ below which a pack is never drawn is the guaranteed-minimum-range term that drives acceptance in stated-preference work [19], the availability constraint that follows from it is introduced here. For vehicle i the energy available at the outage start is

$$a_{w,i} \leq [\text{soc}_i(s_w) - \sigma] C_i, \quad a_{w,i} \geq 0 \quad (6)$$

The lower bound of zero in Eq. (6) is what makes a vehicle sitting below its reserve contribute nothing rather than subtract from what the rest of the fleet can deliver, and the cumulative discharge over the outage is bounded by $\sum_i a_{w,i}$. Exposure is taken as 24 events per year in the base case and swept, because Indian utilities publish reliability indices only sporadically: about half the country's distribution companies report outage data at all, and what is reported is irregular [29].

2.5. Owner enrolment model

Enrolment is modelled as a binary logit choice over the payout on offer, the expected wear, the flexibility the contract ties up and an environmental-attitude score. No stated-preference survey of Indian owners with vehicle-to-grid contract attributes exists, so the coefficients are calibrated to the evidence that does. The reported salience of the reasons for and against enrolment (financial return 49 % against environmental motivation 25 %, loss of flexibility 55 % against battery degradation 27 %) fixes the ratios between the four coefficients, and the intercept is set so that a reference contract reproduces the 42 % enrolment found in that sample [20]. The reference contract is taken at Rs 40 per vehicle per day, roughly Rs 1200 per month. Because the sample is Dutch, the calibration is carried through the results as a parameter and swept rather than presented as an Indian estimate.

2.6. Allocation game and solution concepts

The operator and the owners form a cooperative game with transferable utility [30], whose characteristic function is defined, as in comparable energy-system studies, by the cost a coalition avoids [15,16]. A coalition without the operator can deliver nothing, so its worth is zero, a coalition containing the operator is worth the reduction in expected daily microgrid cost J that its member groups make possible,

$$\begin{aligned} v(S) &= J_0 - J(S) && \text{if the operator belongs to } S, \\ v(S) &= 0 && \text{otherwise} \end{aligned} \quad (7)$$

The worth defined by Eq. (7) is evaluated by re-solving the scheduling problem for each coalition. Owners are aggregated into groups by the two attributes that determine how much backup service a vehicle can supply: its class, which fixes pack size and discharge rating, and whether it is plugged in during the evening window in which most outages fall. Six groups result, so the game has seven players and 64 coalitions containing the operator. This keeps the game exactly solvable: the Shapley value [30] is computed by enumeration rather than by permutation sampling, and the nucleolus [31] by lexicographic minimization of the excess vector over the full coalition set. Two non-cooperative rules are compared: a proportional split weighted by the energy each group holds above its reserve, and an equal split. Each allocation ϕ is tested for individual rationality, for membership of the core, and for evenness using Jain's fairness index [32]. The game is monotone by construction and this was verified numerically, it is not convex, which matters for the results.

2.7. Experimental design and computational environment

Nine experiments were run and are reported in the order of Section 3. All were implemented in Python 3.11 with NumPy 2.4, SciPy 1.17 (HiGHS for both the linear and the mixed-integer programs), pandas 3.0 and Matplotlib 3.10, on a single core. Random seeds are fixed at 42 for the fleet, 202 for enrolment and 909 for the game, no model is trained on data generated here, so no held-out validation split arises. A single dispatch solve takes about 0.02 s and the complete coalition game about 0.9 s. The code, the input data and the computed output accompany this paper.

3. Results and discussion

3.1. Operation on the representative day

Figure 2 shows the microgrid on the representative day. The two rooftop arrays and the wind machines supply 2109 kWh against a total demand of 3162 kWh, so about a third of the day's energy is imported. The campus load peaks in the teaching hours, which is also when the arrays produce most, and the two largely cancel, grid imports are therefore flat

rather than peaked, and the demand charge in the objective keeps it that way. Billing demand settles at 95.1 kW in every case examined. The time-of-day bands are visible in the lower panel, spanning only Rs 1.20 per kWh.

Table 3 compares the four combinations of bidirectional operation and network constraints. Two results stand out. The energy cost and the demand charge are identical in all four: neither the network constraints nor bidirectional capability changes what the station pays for energy at present demand, and no vehicle discharges during normal operation in any case. This is not a failure of the solver but a consequence of the prices. Round-trip wear costs about Rs 4.07 per kWh delivered, against a time-of-day spread of Rs 1.20, peak shaving would have to buy down a broad plateau rather than a narrow spike, so the demand charge cannot pay for it either. Under the tariff in force, arbitrage and peak shaving are both out of reach.

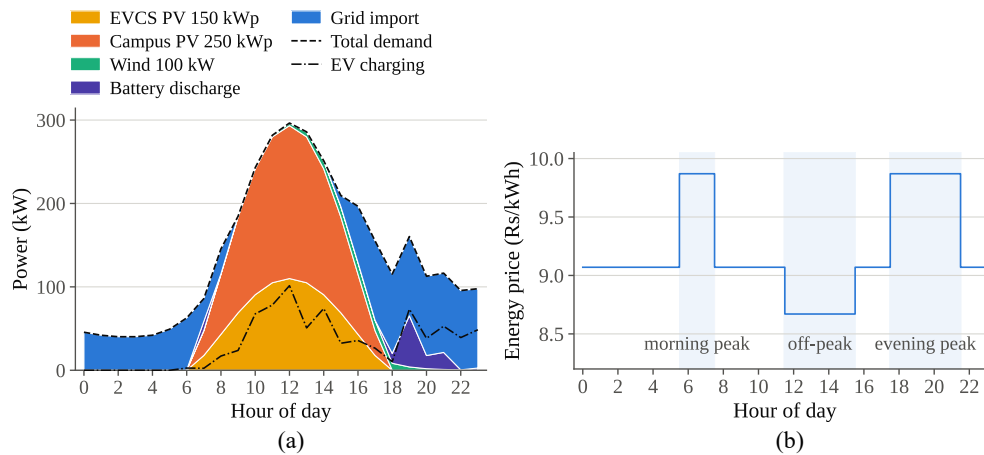


Figure 2: (a) Supply and demand on the representative day, and (b) the RERC EV/LT-8 time-of-day energy charge.

Table 3. Outcome of the representative day under the four modelling cases.

Parameter	No V2G, no network limits	No V2G, network-constrained	V2G, no network limits	V2G, network-constrained
Total daily cost (Rs)	12842.10	12842.10	12804.31	12804.31
Energy cost (Rs)	10561.13	10561.13	10561.13	10561.13
Demand charge (Rs)	475.27	475.27	475.27	475.27
Billing demand (kW)	95.1	95.1	95.1	95.1
Expected diesel cost (Rs)	41.60	41.60	0.00	0.00
V2G energy, normal operation (kWh)	0.0	0.0	0.0	0.0
Lowest bus voltage (pu)	0.9808	0.9804	0.9808	0.9789
Peak transformer loading (kVA)	113.0	113.0	113.0	113.0

3.2. Network limits and hosting capacity

The feeder is not comfortable even today. Figure 3(a) shows that the lowest bus voltage already sits near 0.98 per unit at present demand and reaches the 0.94 per unit limit at the hosting boundary. (b) separates the two constraints: voltage is at 96 % of its limit at present demand and rises slowly, because the campus block dominates the drop, whereas transformer loading starts at 45 % and rises steeply with EV uptake. Both reach their limits together at about four times present demand, where the voltage limit binds for nine hours of the day and the transformer rating for six.

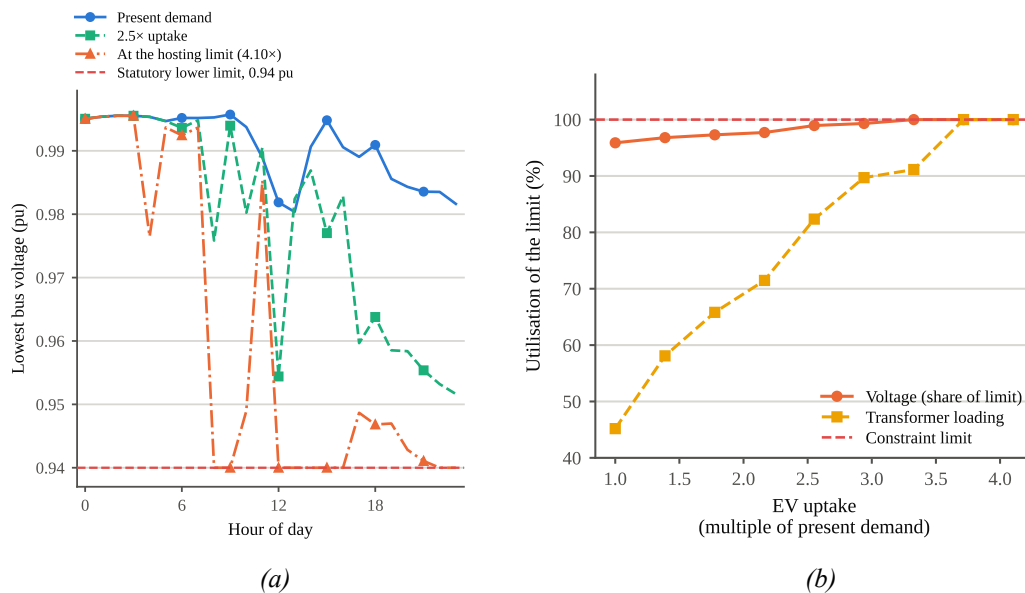


Figure 3: (a) Lowest bus voltage through the day at three levels of EV uptake, and (b) how the voltage and transformer limits approach as uptake rises.

Bisection puts the feeder's hosting capacity at 4.103 times present uptake, about 410 arrivals per day, without vehicle-to-grid. With the whole fleet enrolled it is 4.113 times an increase of 0.2 %, which is to say none. Figure 4 makes the comparison. This contradicts a common expectation that bidirectional capability should extend hosting capacity, and the reason is visible in Figure 3(a): the constrained hours are not isolated spikes but two long blocks, 09:00-13:00 and 17:00-22:00, which between them cover most of the time vehicles are plugged in. Discharging inside a constrained hour obliges the schedule to recharge in another, and at the hosting boundary there is no unconstrained hour left to recharge into.

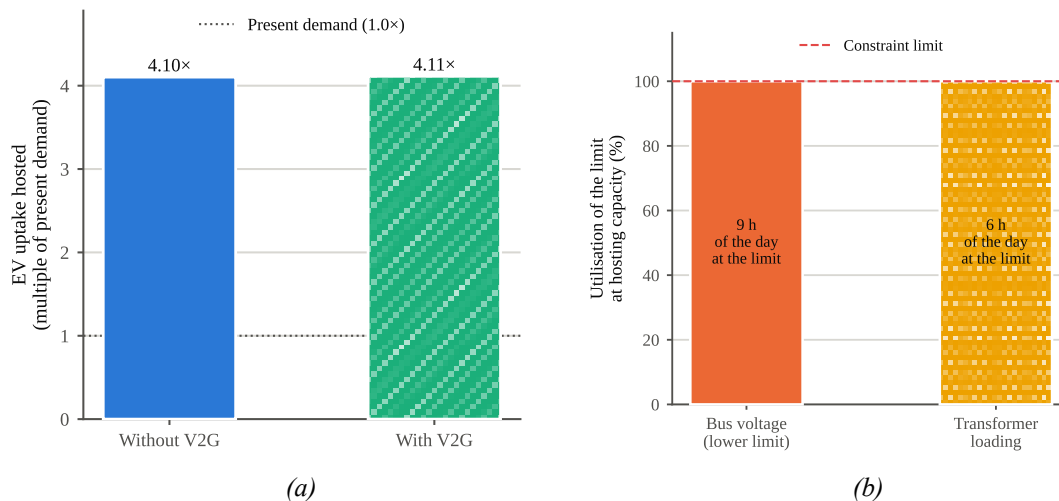


Fig. 4: (a) The EV uptake the feeder can host with and without vehicle-to-grid, and (b) the utilization of each constraint at that limit.

The daily import at that point, 3729 kWh, is well below the 6000 kWh the transformer could pass in a day, so the limit is not one of energy, it is that the hours of scarcity are contiguous. Where the literature reports hosting-capacity gains from vehicle-to-grid, the constrained periods are typically short, and that distinction deserves to be stated explicitly.

3.3. Contribution of Vehicle-to-Grid

The service that does pay is reliability. Figure 5 shows each outage scenario with and

without the fleet. Renewable generation covers the mid-morning outage on its own and the stationary battery covers the afternoon and late-night scenarios. The three-hour evening outage is the demanding one: the islanded campus needs 218.1 kWh, of which the battery supplies 146.2 kWh, so without the fleet the remaining 71.9 kWh comes from diesel. With the fleet enrolled, vehicles supply 125.9 kWh and diesel runs in no scenario at all. Expected diesel cost falls from Rs 41.60 per day to zero, leaving a surplus of Rs 37.79 per day. That is the whole of what vehicle-to-grid is worth here: it is a reliability product, and nothing else.

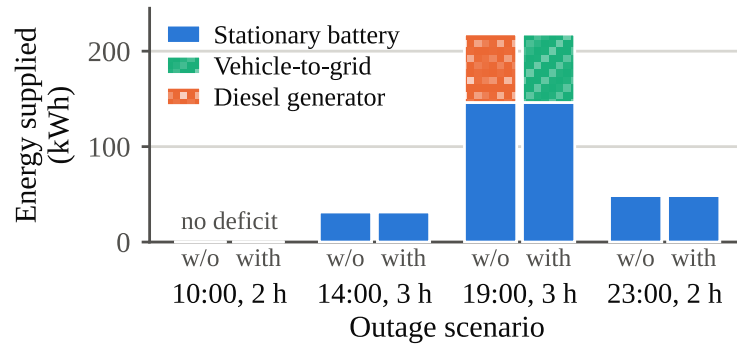


Figure 5: Energy supplied during each outage scenario, without and with vehicle-to-grid

3.4. Allocating the surplus

The coalition game has seven players and 64 coalitions containing the operator, all evaluated exactly in 0.9 s. Its structure is unusual and drives everything that follows. Table 3 gives the stand-alone worth of each player: the ten cars parked during the evening window can deliver the whole surplus of Rs 37.79 by themselves, evening three-wheelers about a third of it, and the three off-window groups fifty-nine of the ninety-three sessions nothing at all, because they are not plugged in when the outage falls. The game is monotone, which was verified over all 64 coalitions, but it is not convex.

Table 4. Stand-alone worth of each player with the operator, and the payout each allocation rule awards (Rs/day).

Player	Stand-alone worth	Shapley	Nucleolus	Proportional	Egalitarian
EVCS operator	0.00	21.12	13.34	18.85	5.40
e2w/off-window	0.00	0.00	0.00	1.10	5.40
ecar/off-window	0.00	0.00	0.00	8.87	5.40
e3w/off-window	0.00	0.00	0.00	2.29	5.40
ecar/evening	37.79	14.45	24.45	4.10	5.40
e3w/evening	12.49	2.08	0.00	2.12	5.40
e2w/evening	0.85	0.14	0.00	0.47	5.40
Total	37.79	37.79	37.79	37.79	37.79

Table 5. Fairness, stability and enrolment each rule sustains.

Rule	Jain index (owners)	Worst excess (Rs)	In core	Payout to the highest-paid group (Rs/vehicle/day)	Enrolment at the fixed point
Shapley	0.217	2.22	no	2.33	8 of 93
Nucleolus	0.167	0.00	yes	4.66	8 of 93
Proportional	0.561	14.84	no	0.31	8 of 93
Egalitarian	1.000	26.99	no	0.93	8 of 93

Figure 6 and Table 4 show what the four rules do with this. Only the nucleolus lies in the core: it concentrates the surplus on the evening cars and the operator, and its worst excess is zero. The Shapley value spreads it a little further, reaching the evening three-wheelers, but leaves the operator and the evening cars with less than they could secure by contracting alone, so it falls outside the core at a worst excess of Rs 2.22. The proportional rule, which weights by stored energy above the reserve rather than by delivered service, misallocates badly it awards Rs 8.87 to off-window cars that can deliver nothing. The equal split scores a perfect 1.000 on Jain's index and has a worst excess of Rs 26.99, which is to say it is the fairest and the least stable of the four. Table 5 collects the fairness and stability diagnostics alongside the enrolment each rule sustains.

The trade-off is therefore sharp and is worth stating plainly for practitioners: in a game where a small, identifiable subset creates all the value, evenness and stability cannot both be had. Cooperative-game studies of energy systems have tended to adopt the Shapley value by default [14,15,16]. It fails the stability test that the nucleolus passes, and a proportional rule based on a plausible but wrong proxy for contribution performs worse than either.

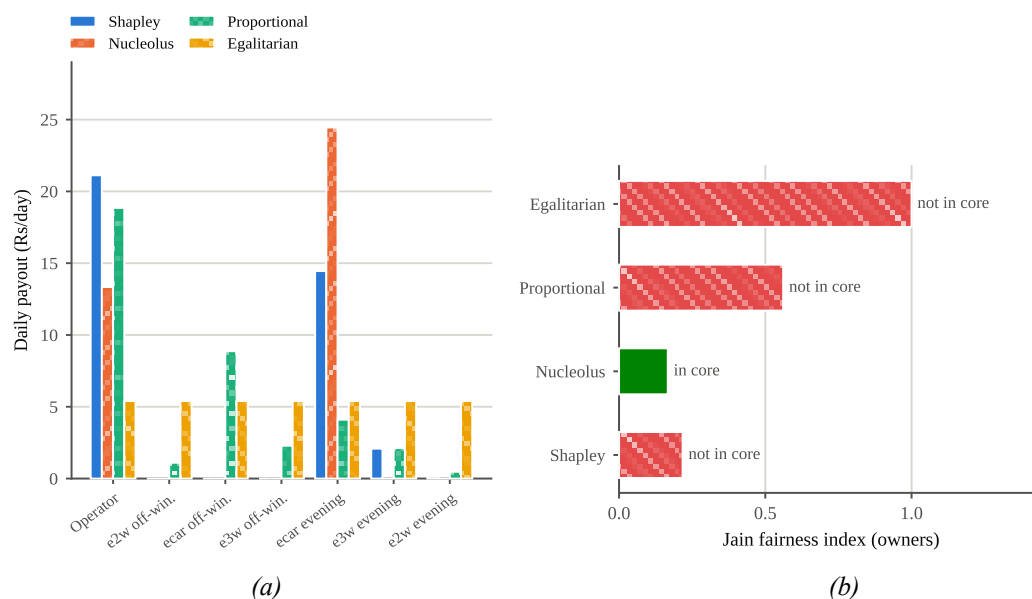


Figure 6: (a) The surplus each allocation rule awards, and (b) the fairness and stability of each rule

3.5. Enrolment under each rule

None of these matters as much as the size of the surplus. Iterating the loop between payout and enrolment to a fixed point gives the same answer under all four rules: about 9 % of owners enrol, or eight of ninety-three vehicles, which is the altruistic floor of the logit model the rate at which people would take part for no money at all. The payouts responsible are Rs 2.33 per vehicle per day under the Shapley value, Rs 4.66 under the nucleolus, Rs 0.31 under the proportional rule and Rs 0.93 under the equal split, all an order of magnitude or more below the Rs 40.53 per vehicle per day at which the model predicts 42 % enrolment. The loop converges monotonically from full enrolment, it has no second, high-participation equilibrium. Fairness, in other words, is not the binding constraint at this site. No rule, however well designed, can distribute a surplus that is not there.

3.6. Key factors enabling service viability

Figure 7(a) puts the two quantities on the same axes. The most an operator can offer an enrolled owner is the value the fleet creates divided among those who provide it, which at the base exposure of 24 events per year is Rs 0.525 per vehicle per day across the seventy-two eligible sessions. What owners require, from the enrolment model, is Rs 40.53 per vehicle per day for the 42 % enrolment the survey found a shortfall of seventy-seven times.

The affordable payment rises in proportion to outage exposure, so the two curves do cross, but only at about 1340 events per year for the lowest target and 2210 for the middle one, 2210 events of the durations modelled amount to roughly 5900 hours, two-thirds of the year without grid supply. Read the other way, vehicle-to-grid of this kind pays only where the grid is effectively absent, which is an argument for it as an off-grid or weak-grid product rather than as a service on a functioning urban distribution system.

The obvious objection is that the enrolment model is calibrated to a Dutch sample and that Indian owners would accept far less. Figure 7(b) and Table 6 test exactly that by scaling the payment coefficient. Even at twenty times the surveyed sensitivity that is, if Rs 2 per day secured 42 % enrolment the shortfall is still fourfold. The conclusion does not depend on the calibration.

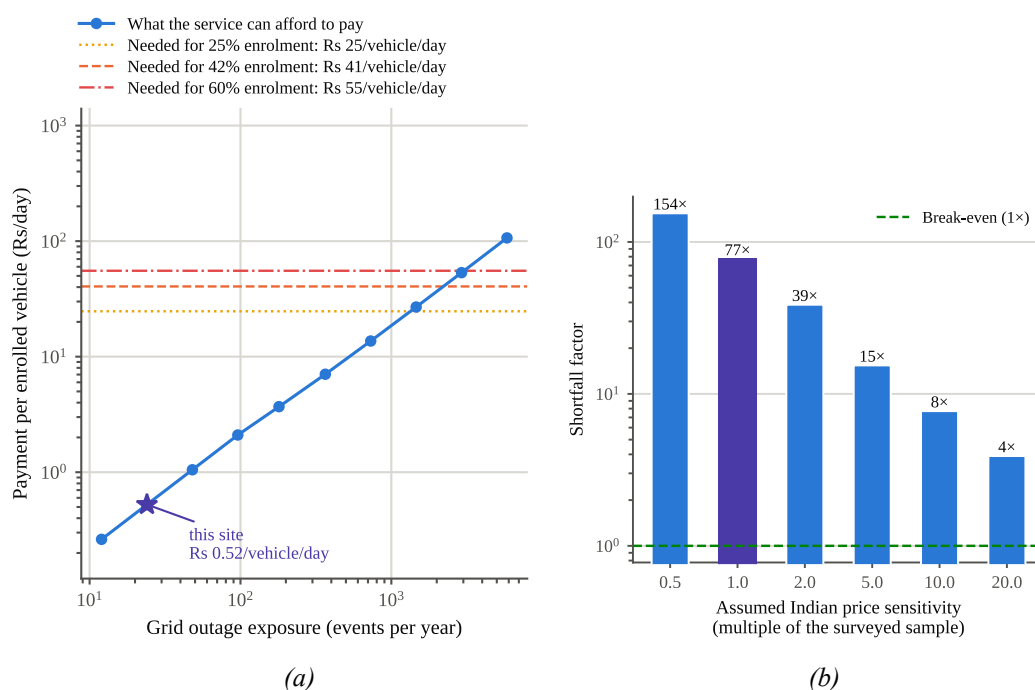


Figure 7: (a) What the reliability service can afford to pay against what enrolment requires, as outage exposure rises, and (b) how the shortfall responds to the assumed price sensitivity of Indian owners

3.7. Sensitivity

Table 7 collects the parameter sweeps, each run to its own fixed point. Surplus scales almost linearly with outage exposure and with diesel price across the plausible ranges. Battery wear matters less than might be expected: moving from the base Rs 1.875 per kWh to the Rs 12.5 per kWh implied by the European break-even estimate [21] reduces the surplus only from Rs 6.48 to Rs 2.77, because diesel at Rs 22 per kWh remains far more expensive than even a pessimistic wear cost. The contractual reserve is the most sensitive single lever the operator controls: tightening it from 0.30 to 0.50 cuts the surplus to Rs 1.20, because it both reduces the energy each vehicle can offer and disqualifies sessions that arrive below it. Relaxing it to 0.20 raises the surplus to Rs 9.12 helpful, but nowhere near enough, and bought at the cost of exactly the guarantee that owners say they care about most [19].

Table 6. What the service can afford to pay against what enrolment requires, and the robustness of the comparison to the enrolment calibration

Price sensitivity (multiple of the surveyed sample)	Payment required for 42 % enrolment (Rs/vehicle/day)	Payment the service can afford (Rs/vehicle/day)	Shortfall
0.5	81.06	0.525	154×
1.0	40.53	0.525	77×
2.0	20.27	0.525	39×
5.0	8.11	0.525	15×
10.0	4.05	0.525	8×
20.0	2.03	0.525	4×

Table 7. Sensitivity of the surplus at the enrolment fixed point. Base-case values are shown in the first column of each block.

Parameter	Values	Surplus (Rs/day)
Outage exposure (events/year)	0, 6, 12, 24, 48, 72, 120	0.00, 1.62, 3.24, 6.48, 12.96, 19.43, 32.39
Diesel cost (Rs/kWh)	0, 10, 15, 22, 30, 40, 60	0.00, 2.59, 4.21, 6.48, 9.07, 12.31, 18.79
Battery wear (Rs/kWh)	0.5, 0.9, 1.875, 3.0, 6.0, 12.5	11.13, 6.87, 6.48, 6.09, 5.04, 2.77
Contractual reserve (SOC)	0.20, 0.30, 0.40, 0.50	9.12, 6.48, 3.84, 1.20

3.8. Avoided Emissions

Displacing 690 kWh of diesel generation a year avoids 558 kg of carbon dioxide, using the 2006 IPCC default of 74.1 kg CO₂ per GJ for gas/diesel oil at a genset efficiency of 0.33, or 0.808 kg CO₂ per kWh delivered [33]. Grid import is unchanged, so nothing further is avoided there, although at the combined-margin factor for the Indian unified grid [34] the grid term would have been the larger of the two had any energy been displaced. Half a tonne a year is a small number and should be read as such: the carbon case at this site is as thin as the economic one, and for the same reason. Where campus decarbonization is the objective, adding photovoltaic capacity or improving its yield [35] or reducing building energy intensity will do considerably more per rupee than paying for bidirectional chargers.

3.9. Limitations

Four limitations qualify these results. The charging demand is synthetic, and the irradiance, temperature and wind-speed series are representative profiles built from published regional values rather than site measurements, the wind array is proposed, not built. The campus block load and its 250 kWp share are assumptions, since no metered campus series was available, and the feeder topology is a plausible reconstruction rather than an as-built drawing. Outage exposure is a swept parameter because Indian distribution utilities do not publish reliability indices consistently [29]. Finally, the enrolment model is transferred from a European sample, Section 3.6 shows the conclusion survives that transfer, but an Indian stated-preference study with explicit contract attributes would be the single most useful addition to this line of work. The analysis is also confined to one representative day per scenario and to a deterministic resource profile, seasonal and stochastic extensions are treated in the companion study of the same testbed under unidirectional charging.

4. Conclusion

This study modelled a twenty-bay campus charging station in Jaipur as a network-constrained microgrid in which electric vehicles can discharge, grid outages are served by the fleet instead of by diesel, and the resulting surplus must be divided among the station operator and six groups of owners. Bidirectional operation removed diesel from every outage scenario examined, cutting expected diesel cost from Rs 41.60 per day to zero, but

produced no benefit in normal operation, because round-trip battery wear of about Rs 4.07 per kWh exceeds the Rs 1.20 per kWh time-of-day spread the tariff allows. It left hosting capacity essentially unchanged, because the hours in which the voltage band and the transformer rating bind form two long contiguous blocks with no unconstrained hours to recharge into. The surplus it does create is concentrated almost entirely in the ten cars parked during the evening window, which makes the allocation problem genuinely difficult, yet the choice of rule changes nothing that matters, because all four converge to the same 9 % enrolment, the rate at which owners would participate for nothing. The payment enrolment requires exceeds what the service can afford by a factor of seventy-seven, and that factor remains fourfold even if Indian owners are assumed twenty times more price-sensitive than the surveyed sample. Vehicle-to-grid at an Indian campus charging station is therefore a reliability product rather than an energy product, and at present outage exposure not a viable one: the lever that matters is not the fairness of the payout rule but the price at which reliability is valued, and until reliability is remunerated explicitly, bidirectional capability at sites like this will remain a technical possibility rather than an economic proposition.

An Indian stated-preference study with explicit contract attributes would settle the enrolment estimate, which rests here on a European calibration. A tariff instrument that pays for reliability directly an availability payment for islanding capability, or a credit against avoided diesel needs designing and evaluating, since this study locates the crossing point only in terms of outage exposure. The framework should then be tested where exposure genuinely is high: rural feeders, industrial estates that run gensets daily, and sites with no grid at all. Aggregation deserves attention, since one station's surplus is too small to interest anyone, and whether a portfolio under a single aggregator change that is beyond a single-site model. Pricing the distribution network rather than merely constraining it, so that the transactive layer internalizes the feeder instead of being clipped by it, is the authors' next step.

Acknowledgements

The authors thank the Department of Electrical Engineering, Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, for providing the research platform and support.

Nomenclature

A^P, A^Q	voltage sensitivity matrices to active and reactive bus withdrawals, pu/pu	P_{DT}, Q_{DT}	active and reactive flow through the distribution transformer, kW, kvar
$a_{w,i}$	energy vehicle i holds above its contractual reserve when outage scenario w begins, kWh	p^c_i, p^d_i	charge and discharge power of session i , kW
b^c, b^d	stationary battery charge and discharge power, kW	p_k, q_k	net active and reactive withdrawal at bus k , kW, kvar
C_i	usable pack capacity of vehicle i , kWh	R_{ij}, X_{ij}	branch resistance and reactance, pu
c^b, c^s	wear cost of vehicle and stationary battery throughput, Rs/kWh	S	a coalition of players
c^{df}	cost of diesel-generated electricity, Rs/kWh	$S_{DT,max}$	apparent-power rating of the distribution transformer, kVA
D	billing demand, kVA	s_w	hour at which outage scenario w begins, h
d_i	departure hour of session i , h	$so c_i$	state of charge of vehicle i
g, x	grid import and export at the point of common coupling, kW	t, w	indices of the hour and of the outage scenario
φ_i	payout allocated to player i , Rs/day	$u = V^2$	squared bus voltage magnitude, pu
i, j, k	indices of sessions and of feeder buses	V_{min}, V_{max}	lower and upper limits of the permissible voltage band, pu
$J(S), J_0$	expected daily microgrid cost with coalition S , and with no vehicle-to-grid, Rs/day	$v(S)$	worth of coalition S , Rs/day
N	set of all players: the operator and the owner groups	z_w	diesel generation in outage scenario w , kW
P_{ij}, Q_{ij}	active and reactive flow on the branch		

from bus i to bus j , kW, kvar

Greek Symbols

δ	daily equivalent of the demand charge, Rs/kVA/day	π, π^x	retail price and export compensation, Rs/kWh
Δt	dispatch time step, h	ρ_w	daily probability of outage scenario w
η^c, η^d	charge and discharge efficiency of the vehicle pack	σ	contractual reserve state of charge

Superscripts and Subscripts

b	vehicle battery (wear cost)	$\max, \min$	upper and lower limit
c	charging direction	s	stationary battery (wear cost)
d	discharging direction	t	hour of the dispatch horizon
df	diesel fuel	w	outage scenario
DT	distribution transformer	x	export direction
i	electric vehicle charging session	0	reference case, with no vehicle-to-grid
j, k	feeder bus		

Abbreviations

CEA	Central Electricity Authority, Government of India	LinDist Flow	linearized branch-flow model of a radial distribution feeder
e_{2w}, e_{3w}	electric two-wheeler and three-wheeler	MILP	mixed-integer linear program
$ecar$	electric passenger car	PV	photovoltaic
EV	electric vehicle	RERC	Rajasthan Electricity Regulatory Commission
EVCS	electric vehicle charging station	RTE	round-trip efficiency
EV/LT-8	Rajasthan low-tension tariff category for charging stations	SOC	state of charge
FSA	fuel surcharge adjustment	ToD	time of day
IPCC	Intergovernmental Panel on Climate Change	V2G	vehicle-to-grid
ISGF	India Smart Grid Forum	XLPE	cross-linked polyethylene

References

[1] Filda Citra Yusciantoro, Purnomo Yusciantoro, Muhammad Indra Al Irsyad, Bono Pranoto, and Joni Jupesta, “Emerging Energy Research Driving Sustainable Development Goals in Developing Countries with an Indonesian Perspective,” *Evergreen*, vol. 13, no. 2, pp. 466–498, Jun. 2026, doi: 10.5109/7420064.

[2] Saurabh Singh, Niharika Panwar, Deepak Kumar Prajapat, Ankush Jain, Ajay Singh Thakur, and Ram Avtar, “Hydrological Dynamics and Ecological Consequences of Sambhar Lake through Multi-Satellite Approach to Wetland Monitoring,” *Evergreen*, vol. 12, no. 4, pp. 1888–1900, Dec. 2025, doi: 10.5109/7402623.

[3] W. Kempton and J. Tomić, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” *J. Power Sources*, vol. 144, no. 1, pp. 268–279, Jun. 2005, doi: 10.1016/j.jpowsour.2004.12.025.

[4] S. Sharma and P. Jain, “Integrated TOU price-based demand response and dynamic grid-to-vehicle charge scheduling of electric vehicle aggregator to support grid stability,” *International Transactions on Electrical Energy Systems*, vol. 30, no. 1, 2019, doi: 10.1002/2050-7038.12160.

[5] Q. Zhang, M. Ikram, and K. Xu, “Online Optimization of Vehicle-to-Grid Scheduling to Mitigate Battery Aging,” *Energies (Basel)*, vol. 17, no. 7, p. 1681, Apr. 2024, doi: 10.3390/en17071681.

[6] M. Aqib and A. Ukil, “Battery degradation model of electric vehicle with grid integration,” *J. Energy Storage*, vol. 97, p. 112709, Sep. 2024, doi: 10.1016/j.est.2024.112709.

- [7] V. Preis and F. Biedenbach, "Assessing the incorporation of battery degradation in vehicle-to-grid optimization models," *Energy Informatics*, vol. 6, no. S1, p. 33, Oct. 2023, doi: 10.1186/s42162-023-00288-x.
- [8] A. Leippi, M. Fleschutz, and M. D. Murphy, "A Review of EV Battery Utilization in Demand Response Considering Battery Degradation in Non-Residential Vehicle-to-Grid Scenarios," *Energies (Basel)*, vol. 15, no. 9, p. 3227, Apr. 2022, doi: 10.3390/en15093227.
- [9] C.-F. Lu, G.-P. Liu, Y. Yu, and J. Cui, "A Coordinated Model Predictive Control-Based Approach for Vehicle-to-Grid Scheduling Considering Range Anxiety and Battery Degradation," *IEEE Transactions on Transportation Electrification*, vol. 11, no. 2, pp. 5688–5699, Apr. 2025, doi: 10.1109/TTE.2024.3488075.
- [10] S. Narayana Gowda, H. Nazariyouya, and R. Gadh, "Congestion Relief Services by Vehicle-to-Grid Enabled Electric Vehicles Considering Battery Degradation," *Sustainability*, vol. 15, no. 24, p. 16733, Dec. 2023, doi: 10.3390/su152416733.
- [11] Z. Wu and B. Chen, "Distributed Electric Vehicle Charging Scheduling with Transactive Energy Management," *Energies (Basel)*, vol. 15, no. 1, p. 163, Dec. 2021, doi: 10.3390/en15010163.
- [12] H. M. Mohan and S. K. Dash, "Renewable Energy-Based DC Microgrid with Hybrid Energy Management System Supporting Electric Vehicle Charging System," *Systems*, vol. 11, no. 6, p. 273, May 2023, doi: 10.3390/systems11060273.
- [13] D. B. S. Hampannavar, and S. Mansani, "Smart Monitoring of Microgrid-Integrated Renewable-Energy-Powered Electric Vehicle Charging Stations Using Synchrophasor Technology," *World Electric Vehicle Journal*, vol. 15, no. 10, p. 432, Sep. 2024, doi: 10.3390/wevj15100432.
- [14] V. P. Singh, A. Ahmad, and K. M. Jagtap, "Weighted shapley value: A cooperative game theory for loss allocation in distribution systems," *Front. Energy Res.*, vol. 11, Mar. 2023, doi: 10.3389/fenrg.2023.1129846.
- [15] X. Yang, Z. Liu, H. Chen, and L. Yang, "Research on Gain Allocation Strategy of Multi-park Integrated Energy System Based on Cooperative Game and Improved Shapley Value Method," *Journal of Electrical Engineering & Technology*, vol. 21, no. 1, pp. 189–202, Jan. 2026, doi: 10.1007/s42835-025-02445-6.
- [16] L. Li and Y. Zhang, "Equitable economic energy scheduling with fair cost distribution using shapley value in cooperative multi-hub systems coupled with CHP," *Sustainable Energy, Grids and Networks*, vol. 47, p. 102374, Sep. 2026, doi: 10.1016/j.segan.2026.102374.
- [17] Z. Ting, L. Jianpan, L. Yifan, M. Wang, R. Tian, and M. Xiaoqian, "Shared energy storage capacity optimization and cost sharing in community coalitions based on master-slave game theory and improved shapley value model," *Appl. Soft Comput.*, vol. 202, p. 115804, Oct. 2026, doi: 10.1016/j.asoc.2026.115804.
- [18] P. Li, J. Chen, H. Yang, and Z. Lin, "Peer-to-peer power trading and pricing for rental energy storage shared community microgrid: A coordinated Stackelberg and cooperative game," *Renew. Energy*, vol. 256, p. 123963, Jan. 2026, doi: 10.1016/j.renene.2025.123963.
- [19] G. R. Parsons, M. K. Hidrue, W. Kempton, and M. P. Gardner, "Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms," *Energy Econ.*, vol. 42, pp. 313–324, Mar. 2014, doi: 10.1016/j.eneco.2013.12.018.
- [20] J. Bakhuis, N. Barbour, and É. J. L. Chappin, "Exploring user willingness to adopt vehicle-to-grid (V2G): A statistical analysis of stated intentions," *Energy Policy*, vol. 203, p. 114619, Aug. 2025, doi: 10.1016/j.enpol.2025.114619.
- [21] S. Sagaria, M. van der Kam, and T. Boström, "Vehicle-to-grid impact on battery degradation and estimation of V2G economic compensation," *Appl. Energy*, vol. 377, p. 124546, Jan. 2025, doi: 10.1016/j.apenergy.2024.124546.
- [22] India Smart Grid Forum, "Report on Demonstration of Vehicle to Grid (V2G) Technology in India and Charging of EVs with Green Electricity," New Delhi, 2025. Accessed: Sep. 25, 2026. [Online]. Available: <https://www.indiasmartgrid.org/reports-detail/149>

- [23] Power Line, “Cost economics: assessing the market for diesel gensets,” *Power Line Magazine*, 2022. Accessed: Sep. 25, 2026. [Online]. Available: <https://powerline.net.in/2022/01/08/cost-economics-4/>
- [24] Rajasthan Electricity Regulatory Commission, “TARIFF FOR SUPPLY OF ELECTRICITY-2025,” 2025. Accessed: Sep. 25, 2026. [Online]. Available: <https://cescrajasthan.co.in/kedl/pages/event/uploads/Tariff-2025%202.pdf>
- [25] Taurista Perdana Syawitri *et al.*, “CFD Investigation of 3D Vertical Axis Wind Turbine Models: Insights from Blade Tip Effects,” *Evergreen*, vol. 12, no. 4, pp. 2146–2164, Dec. 2025. doi: 10.5109/7402644.
- [26] M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989. doi: 10.1109/61.25627.
- [27] Central Electricity Authority, “Minutes of the meeting to finalize declared supply voltage,” 2022. Accessed: Sep. 25, 2026. [Online]. Available: https://cea.nic.in/wp-content/uploads/dp_r/2022/06/Approved_MoM_of_the_Meeting_to_finalize_Declared_Supply_Voltage.pdf
- [28] Central Electricity Authority, “Guidelines for distribution utilities for development of distribution infrastructure (Ver-1),” 2018. Accessed: Sep. 25, 2026. [Online]. Available: https://cea.nic.in/wp-content/uploads/2020/04/guidelines_dtt.pdf
- [29] Upasa Borah and Renuka Sane, “A review of outage reporting by Indian DISCOMs,” 2025, *The Leap Blog*, September 2025. Accessed: Sep. 25, 2026. [Online]. Available: <https://blog.theleapjournal.org/p/the-leap-blog.html#gsc.tab=0>
- [30] L. S. Shapley, “A Value for n-Person Games,” in *Contributions to the Theory of Games (AM-28), Volume II*, Princeton University Press, 1953, pp. 307–318. doi: 10.1515/9781400881970-018.
- [31] D. Schmeidler, “The Nucleolus of a Characteristic Function Game,” *SIAM J. Appl. Math.*, vol. 17, no. 6, pp. 1163–1170, Nov. 1969, doi: 10.1137/0117107.
- [32] R. Jain, D. Chiu, and W. Hawe, “A Quantitative Measure Of Fairness And Discrimination For Resource Allocation In Shared Computer Systems,” Sep. 1998.
- [33] Amit Garg and Tinus Pulles, *2006 IPCC guidelines for national greenhouse gas inventories, volume 2: energy*, vol. 2. IGES, Japan, 2006.
- [34] Central Electricity Authority, “CO2 baseline database for the Indian power sector, user guide version 21.0,” 2025, *Government of India, New Delhi, November 2025*. Accessed: Sep. 25, 2026. [Online]. Available: https://cea.nic.in/wp-content/uploads/baseline/2025/12/User_Guide_V_21.0.pdf
- [35] Henrik Zsiborács, Nóra Hegedűsné Baranyai, and András Vincze, “Performance Analysis of Bifacial Photovoltaic Modules and Its Practical Implications,” *Evergreen*, vol. 13, no. 2, pp. 801–812, Jun. 2026, doi: 10.5109/7432656.