PRIED
Policy Research Institute
for Equitable Development

Harnessing Pakistan's Solar Revolution:

A Techno-Economic Assessment of Swarm Electrification

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Foreword

Pakistan's energy transition has entered a new phase. Today, drive through almost any city in the country, or walk through a village, you will see majority rooftops carry panels. People have started generating their own power, on their own terms. So, the country has pulled one of the fastest solar revolutions in the world and has emerged as the second largest PV importers globally.

The irony? This rapid shift. Although the solar story is extraordinary, nevertheless this transformation is creating new challenges. Many of today's grids were designed for the 20th-century, when the share of Distributed Energy Resources (DERs) was small. Now that a growing portion of electricity is produced by DERs, new challenges are emerging such as reverse power flows and deepening duck curves in high solar penetration areas, challenging traditional grid operations.

This report began with a simple observation: How can this locally generated surplus be better utilized within communities? So, we have dived deeper into the concept of swarm grids which is an emerging model of localized electricity distribution—one that enables peer-to-peer energy exchange within a community. To find out whether this idea could actually work in Pakistan, data was collected from the field in our chosen diverse case study areas— two small villages in Tharparkar, as well as one of the sunniest and least electrified parts of the country, and to a busy, solar-heavy neighbourhood in Islamabad.

Transition ahead is redesigning our energy use into a more resilient, efficient, secure and inclusive system. This will require regulatory reforms, more coordination, and developing market participation models that can better assimilate these emerging DERs. The decisions taken during this decade will shape the energy systems of the future and determine whether the world can still deliver on the promise of a sustainable, equitable and prosperous energy future for all.

My hope is that whether you read this cover to cover, or simply skim the parts that catch your eye, you come away with the same sense of possibility that our team felt walking away from those rooftops and courtyards. Pakistan doesn't need to wait for a perfect, distant future to start solving its energy challenges. Sometimes, the answer is already sitting on the roof next door — it just needs an introduction.

Warmly Badar Alam

Executive Summary

Pakistan is undergoing a massive rooftop solar PV revolution, as people move away from the high costs and unreliability of grid electricity. Cumulative solar panel imports crossed 50 GW, placing Pakistan among the world's largest importers of Chinese solar PV in 2025. What is unfolding is the evolution of an increasingly decentralised market — one that is displacing the centralising grid at a rapid pace. Yet as decentralised solar continues to grow, the question is no longer whether solar can power homes and businesses, but how these individual systems can be interconnected, coordinated, and integrated into a network that was never designed for consumers who also produce electricity.

This growth is also generating an equity problem. As solar-owning households buy fewer units from the grid, they shift a larger share of the system's fixed costs onto non-solarised households and businesses that remain dependent on the grid while receiving few of the financial benefits of the solar transition — with some spending as much as half their disposable income on electricity bills in peak summer months. Individual supply solutions carry the same flaw: because they require upfront capital, they generate inequitable benefits, available only to those who can afford to buy in.

The report examines swarm electrification — an organic, decentralised energy system that interconnects individual household power sources like solar panels and batteries into a local sharing network — as a bottom-up alternative capable of addressing both problems together. Rather than being centrally planned like a mini-grid, a swarm grid grows organically as neighbouring households with solar home systems begin sharing what they generate, diverting surplus electricity to poorer households that cannot afford a system of their own. The study assesses whether this model is technically, economically, and institutionally feasible in Pakistan, across two settings that together capture the majority of the country's electrification reality:

- **Rural Tharparkar, Sindh** (Thario and Khario villages)
- **Urban Islamabad** (Sector G-13)

Drawing on household surveys, network load-flow snapshots, and household-level economic analysis (comparing diesel-backed and BESS-backed Peer 2 Peer sharing against net metering and net billing), the study finds that swarm grids are technically feasible in both the rural and urban cases examined. However, **commercial viability differs**: urban swarm grids look more immediately attractive, while rural deployment needs targeted financial support to be economically viable — not necessarily permanent subsidies, but transitional incentives.

Key recommendations include: developing entirely new regulations for P2P trading, covering participation, transactions, and settlement; enforcing NEPRA-approved standards for solar equipment installed on the distribution network; opening the retail electricity market to greater prosumer participation; strengthening demand-side management by shifting flexible loads toward periods of higher solar generation; and making swarm-grid operations more gender-inclusive by training.

Chapter 1: From isolated rooftops to a managed network

Pakistan is undergoing a massive rooftop solar PV revolution. People in large numbers are shifting to solar energy as they seek relief from high costs of grid-provided electricity and unreliable power supply. Cumulative solar panel imports in the country have now crossed 50 GW, as per figures by Bloomberg.[1] This growth placed the country as the world's largest Chinese solar importer in 2025[2] and one of the largest global importers of Chinese solar PV. The full extent of the solar drive continues to be largely unknown since current data doesn't capture local production or informal imports. The actual state of this decentralised solar PV drive therefore could be far greater than what the current uneven data empirics suggest.

But overall, what we are witnessing in Pakistan is the evolution of a market that is increasingly decentralised—a shift displacing the centralizing grid at a rapid pace. Pakistan also has ideal solar resource potential. This, combined with falling solar panel prices made it more affordable for people to meet their energy needs and manage their energy costs. Solar integrated with battery storage is beginning to deliver what state-led infrastructure failed to offer all these years, i.e., a reliable, affordable, and clean source of power. But as decentralized solar PV systems continue to grow, the question is no longer whether solar can power homes and businesses but how these individual systems can be interconnected, coordinated, and integrated into an electricity network that was never designed for a future in which consumers also produce their own electricity and feed it into the grid.

These realities are therefore opening up a different pathway to electrification that underscores the need for an approach different from what has traditionally served the electricity needs of the country . This is the pivot which our report addresses: Pakistan's challenge today is the absence of any mechanism to connect, coordinate, and make full use of the clean electricity that already exists, scattered across millions of individual rooftops that were never designed to work together.

In this context, the concept of swarm grids or swarm electrification - an organic, decentralized energy system that interconnects individual household power sources—like solar panels and batteries—into a local sharing network – is worth exploring. This report examines whether such a model is technically, economically, and institutionally feasible in Pakistan, evaluating its potential in two distinct settings that together capture majority of the country's electrification reality: urban areas, where rooftop solar adoption is already high and reverse power flow has become a growing operational challenge for the grid; and rural areas, where an electricity connection may exist on paper, but reliable, uninterrupted power remains largely unavailable in practice.

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[1] https://www.transitionzero.org/shedding-light-on-pakistans-distributed-solar-revolution

[2] https://janrosenow.substack.com/p/pakistan-the-solar-revolution-nobody

1.1- Introducing swarm electrification: A bottom-up networked economy

A swarm grid essentially is an organic, decentralized energy system that interconnects individual household power sources — solar panels and batteries — into a local sharing network. Essentially the setup is somewhat similar to a microgrid, but instead of being built top down, it grows organically as households with solar home systems (SHSs) begin sharing electricity.

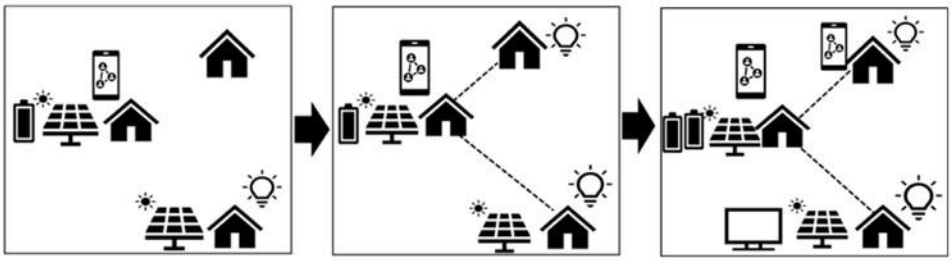


Figure 1: The evolution of swarm grids from standalone solar home systems

So, the starting point of a swarm grid is fundamentally different from mini-grids: rather than being centrally planned and built top-down, it emerges bottom-up where neighbouring households with solar home systems begin sharing what they generate. Over time, these individually owned systems knit themselves into a decentralized network capable of exchanging electricity directly, house to house, without first routing through the national grid or any centralized operator.

So, this bottom-up energy network mainly interconnects existing SHSs and distributed storage, enabling a network economy based on prosumerism and local value creation. It creates an electricity distribution mechanism—a bottom-up small grid through which surplus renewable electricity from SHS is diverted to poorer households that cannot afford a SHS of their own, as well as to those who need additional capacity flexibly, thus creating a peer-topeer renewable electricity trading platform.

1.2- Why Swarm grids could essentially be an optimal model for Pakistan

The solar revolution in Pakistan represents a transformative opportunity. This bottom-up solar surge could be leveraged to increase energy security and reduce energy import dependency. Replacing fossil fuels with local renewables will not only deliver economic benefits and energy security but also help to achieve the country's climate targets.

The rapid growth of rooftop solar is also creating new challenges for Pakistan's electricity grid. During sunny hours, especially in the spring and autumn when electricity demand is relatively low, many solar systems generate more electricity than the household can immediately use. For homes with net-metering arrangements, this excess electricity is exported back to the national grid. Multiply this across tens of thousands of connections, and this can cause severe reverse power flow issues.

The reverse power dilemma

The IESCO region exported 247,482,034 kWh to the grid and imported 280,474,900 kWh, resulting in only 32,992,866 kWh of extra electricity from the grid in FY 2024.[3]

These rooftop solar systems generated more than their owners needed during the day and pushed the surplus onto a grid that already had enough supply. That means the grid wasn't receiving power; it was short of it — it was receiving power it had to absorb, manage, and reroute whether it needed it or not. The result is that distribution infrastructure designed to deliver power in one direction is now handling significant flows in both directions — and the sheer volume of that two-way traffic (247 million kWh exported, 280 million kWh imported, for a net consumption of only 33 million kWh) reveals that the gross churn is seven and a half times larger than the actual need.

The grid is essentially being used as a free, unlimited battery — absorbing solar surplus during the day and returning it at night — at no storage cost to the prosumer, but at real operational cost to the utility: voltage fluctuations, reverse flow protection issues, transformer stress, and planning complexity.

The 33 million kWh figure looks modest. The 247 million kWh of uninvited injection is the actual problem.

A second, related strain compounds the first: the deepening "duck curve," which illustrates the growing difference between daytime and nighttime electricity demand on the grid. The "duck curve" describes the net load curve — total demand minus renewable generation — over a 24-hour period, whose distinctive shape creates three operational challenges for grid operators: a high-capacity head, an idle-capacity belly, and a steep-ramp neck. The head is the early morning and evening demand peak, before solar ramps up and after it drops off. Grid operators must keep dispatchable capacity — usually gas peakers — on standby to meet this peak, even though it runs only a few hours a day, making it costly and poorly utilized. The belly is the midday trough, when abundant solar pushes net load very low. This forces curtailment of renewable output, idles conventional plants, and can depress wholesale prices toward zero, hurting the economics of generation assets on both ends of the curve. The neck is the steep late-afternoon transition, when solar output falls just as evening demand rises. Grid operators need thousands of megawatts of fast-ramping capacity — batteries, hydro, or gas peakers — online within a couple of hours, since slowramping baseload plants can't respond quickly enough. Households with hybrid or off-grid solar systems rely mostly on solar energy during the day, greatly reducing their electricity demand from the grid. After sunset, when solar

[3] https://nepra.org.pk/publications/State%20of%20Industry%20Reports/State%20of%20Industry%20Report%202024.pdf

generation stops, these same households return to the grid for their electricity needs. This sharp drop in daytime demand, followed by a rapid increase in evening demand, makes it more difficult and expensive for grid operators to balance electricity supply and demand. Distributed solar deepens the belly further as more households remove daytime demand from the grid; it steepens the neck, since household systems tend to stop producing around the same time, synchronizing the evening ramp; and it raises uncertainty around the head, since behind-the-meter generation is harder for operators to forecast and monitor than utility-scale solar, forcing larger reserve margins to compensate.

IESCO

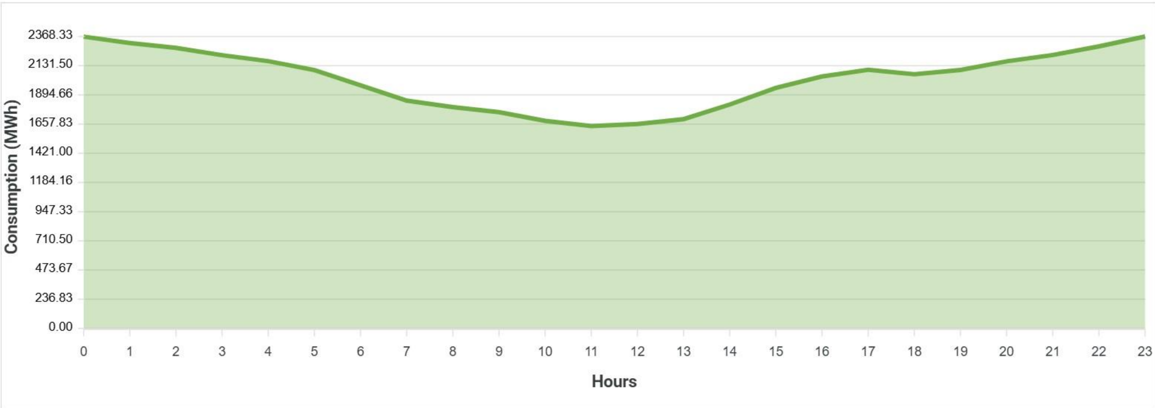


Figure 2: IESCO's load curve on a typical day in July 2026

These challenges are not only confined to these operational and technical areas — it also shows up directly on household electricity bills, and it does so unevenly. As wealthier households generate more of their own power, they buy fewer units from the grid and often shift into lower tariff categories, reducing their contribution to the fixed costs of running the power system. Hence, as these households generate a larger share of their own electricity, they purchase fewer units from the grid. This reduces the contribution of high-consuming customers who traditionally help cover a significant share of the fixed costs of operating the power system. Consequently, many move into lower overall units consumed, thus shifting cost onto non-solarised households. According to forecasts by the Private Power and Infrastructure Board (PPIB), the impact of this cost shifting was expected to increase by an estimated 4.64 rupees per kWh by 2034 under the previous net metering regime.[4] The shift from net metering to net billing has since reduced the financial benefit they receive for their excess generation. This has resulted in a feeling of betrayal by the consumers who installed solar based on the Net-Metering policy promised by the government.

As more consumers adopt solar, a greater share of system costs is shifted onto households and businesses that cannot afford solar and remain dependent on the grid. These consumers continue paying for the grid while receiving fewer of the financial benefits of the solar

[4] https://pide.org.pk/research/an-enigma-of-net-metering/

transition. In peak summer months, some non-solarised Pakistani households spend as much as half of their disposable income on electricity bills.

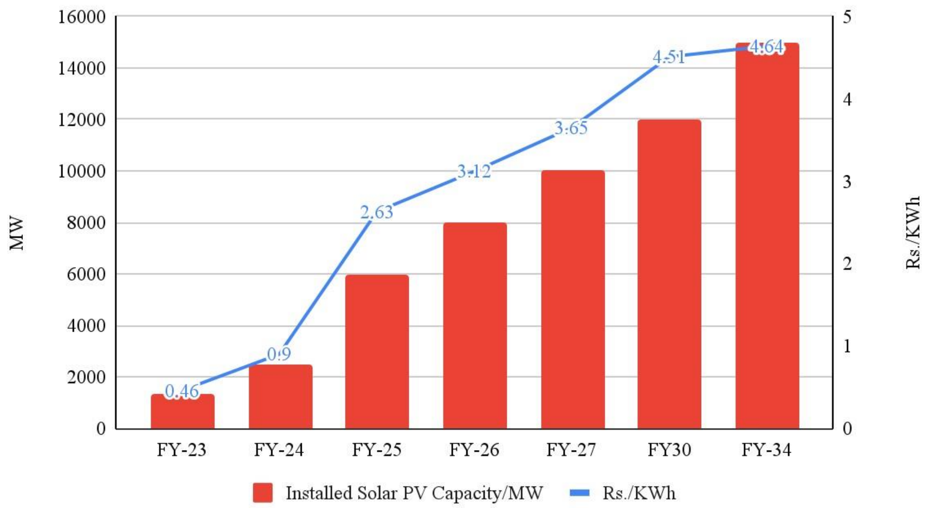


Figure 3: **Impact of previous Net metering regime- cost shifting on non-net-metered consumers**

Premised on that, swarm grids can help address these challenges by reducing reverse power flows in distribution grids. Surplus solar can be directed to neighbouring homes instead of being fed into the grid, easing pressure on the network especially in times of high solar generation as well as during crises like the recent oil shortages or when supply is curtailed for hours in certain regions, swarm grids create an arbitrage opportunity for a community to share electricity enabling them to fund battery storage at their own expense and sized appropriately for the need in each neighborhood. With battery storage, surplus solar generated during the day can be stored and discharged in the evening, helping to reduce the duck-curve effect described above to some extent.

A swarm grid can effectively help address most of these problems. One of the key advantages is reduced volume of reverse power flow in the distribution grids. Surplus solar is fed to neighbouring houses instead of being fed to the grid. Especially when battery storage is also layered into the network, it can hold surplus solar generated during the day and discharge it in the evening, directly softening the duck-curve swing described above. By keeping surplus electricity inside the community instead of exporting it back onto an already-strained network, swarm grids improve the utilization of solar energy precisely where it is generated, while directly reducing the operational load.

Further, swarm grids also enable utilisation of surplus electricity that would otherwise be wasted. It allows prosumers to recover value for their surplus solar generation, as well as enabling non-solar households to gain a cheaper source of electricity; this local exchange of energy creates real economic value inside the community itself. This is also where the case for swarm electrification becomes explicitly economic rather than purely technical.

Since the national grid also suffers from low reliability and limited resilience, swarm electrification can make better use of existing solar generation and expand access to affordable electricity for households without solar systems, especially in remote regions. Pakistan had an installed generation capacity of approximately 43,000 MW in 2024, while peak electricity demand was only about 30,150 MW[5], indicating that the country had more than enough generation capacity to meet demand. Yet brownouts and blackouts remain common because much of the transmission and distribution infrastructure is old, overloaded, and poorly maintained. Although official figures indicate that more than 98 percent of Pakistan's population has access to electricity, reliable supply remains a major challenge in many parts of the country. Frequent load-shedding continues, particularly in areas with high Aggregate Technical and Commercial (AT&C) losses. These losses occur because of technical inefficiencies in the network as well as commercial issues such as electricity theft and poor bill recovery. As a result, distribution companies often limit electricity supply to these areas despite the availability of generation capacity. By enabling households to share locally generated electricity, swarm grids can expand access to affordable energy, improve the use of distributed solar power, and reduce pressure on the national grid. While utilities struggle to make recoveries, the bilateral contracts between consumers and prosumers allow for higher recovery volume. For underserved and energy-poor communities, they offer a promising pathway toward a more inclusive, resilient, and decentralized electricity system. Surplus generation from solar home systems stops being treated as waste or excess and becomes instead a measurable, tradable resource — one that can be used immediately by a nearby household that needs it, rather than pushed through a centralized utility that was never designed to receive it efficiently.

So coordination of these distributed assets can create strong community-level economic benefits, while in parallel addressing system-level operational challenges. The result is a genuine local energy market, built on the same solar assets that already exist.

1.3- What this report sets out to determine

The report sets out to examine the technical, economic, and institutional feasibility of swarm electrification in Pakistan. The objectives of this study are:

1. Techno-economic feasibility – Compare the economic cost and technical performance of three electrification models—swarm grids with grid electricity as a backup, swarm grids with a diesel generator as a backup, and lastly, we propose a more technically feasible swarm grid with enhanced solar system sizes using realworld demand and cost profiles from G-13 sector Islamabad capital territory and Khario Ghulam Shah and Thario in Tharparkar Desert Pakistan. The former demand profiles are used to assess a highly populated urban area with dense installation of high-quality and larger-sized rooftop solar.

[5] https://peci.renewablesfirst.org/power-sector

The latter case is used to assess the rural side with a scattered population and small solar systems. The urban case is generally studied in the light of reliability and affordability, whereas for the rural case the system is designed more for increasing electricity access for the communities. Assessment of technical and financial viability is based on three key metrics: levelized cost of electricity (LCOE), payback period, and efficiency gains.

Surplus energy utilization is assessed based on quantifying the amount of surplus renewable electricity shared within a swarm network.

2. Case application – Applying the analysis to a rural electrification case study in Thar and an urban centre in Islamabad to demonstrate practical implementation and impacts.
3. Scalability assessment – Identifying the policy levers, regulatory frameworks, and enabling conditions required for large-scale adoption of swarm grids.

Chapter 2: Existing Decentralised Energy Models

Chapter 1 of this report introduced swarm grids— and explained their socio-technical benefits. This chapter examines a few other key decentralised energy solutions—individual SHS's, minigrids, micro-grids. It explains how each of these models works and offers their own unique benefits— and why swarm electrification makes more sense for Pakistan. The chapter also illustrates a few real-world examples of swarm electrification in countries like Bangladesh and India.

2.1: Individual Supply Solutions: Let every end-user solve it on their own

The most conceptually straightforward solution to any electrification gap has been individual options. Households can simply buy their own equipment — a diesel generator, or increasingly, a solar panel and battery. These solutions are quick to implement: no waiting on anyone else, no coordination required, and a household can scale it to whatever they can afford. Diesel generators were, for years, the default choice for households and businesses seeking backup power; solar home systems have since overtaken them as panel and storage prices have fallen, offering a cleaner and increasingly cheaper alternative.

However, these individual solutions also carry a few issues: not everyone can participate in them since they require upfront costs, and so these solutions generate inequitable benefits. Further, these systems are also frequently sized incorrectly for what a household actually needs, as each household makes that sizing decision alone. A system sized too small leaves a household under-served precisely when it needs power most; a system sized too large represents capital tied up in capacity that mostly sits idle. Multiplied across millions of individually-purchased systems, this mismatch represents a meaningful loss of efficiency and value at the national level — the exact inefficiency that swarm electrification, by pooling and coordinating demand across neighbouring households, is designed to correct.

2.2: Micro and Mini-Grids: The Right Idea, Built on Conditions Pakistan Doesn't Yet Have

In many Global South countries where electricity rates are either low or grid extension is costly, Micro and mini grids are built to meet electricity demand and improve the accessibility and reliability of electricity. A micro-grid is a localized, small-scale electricity network that can operate either connected to a larger grid or in islanded mode (independently). So it can either operate in tandem with the main grid or disconnect and run independently when the main grid fails, ensuring a reliable power supply during outages. Whereas mini-grids have a similar setup like micro grid, but it provides electricity to a specific community, village, or region. Both micro and mini grids often rely on renewable energy sources like solar and wind, sometimes combined with energy storage systems to ensure standalone power supply.

These grids have become an increasingly attractive alternative to conventional electricity networks. By combining distributed energy resources such as renewable energy, Battery

Energy Storage Systems (BESS), backup generators, and intelligent controllers, microgrids can deliver dependable power while reducing reliance on centralized utility infrastructure. Done well, this avoids both extremes: it's cheaper than a full grid extension, and better sized than an individual solar system.

Globally, microgrid installations are growing rapidly; the microgrid market is projected to grow from USD 41.69 billion in 2024 to USD 163.17 billion by 2033, at a CAGR of 16.37percent (2025–2033).[6] Growth is driven by rising energy demand, especially in rural areas, and the need for reliable, localized power systems that reduce dependence on centralized grids and enhance energy security. For the case of Pakistan, though, currently, 13 micro-grid-based installations are in the construction or operational phase, that too based on hydropower and solar energy only.[7]

Also, the number of solar-powered mini-grids has grown very fast because component costs went down. Solar panel prices specifically dropped 90 percent over the last ten years, making projects more viable. However, progress is uneven. China leads with about 60,000 mini-grids, while Nepal, India, Vietnam, and Sri Lanka each have between 100 and 1,000. These are often powered by diesel or hydro and run by the government [4]. Pakistan, despite strong renewable energy potential, has faced regulatory, institutional, and business-model barriers to mini-grid development, limiting their development.

2.3- Putting all these solutions side by side

Laid out together, the pattern is clear: each option solves part of the problem, but each one also depends on something Pakistan is currently short of — money, time, or institutional readiness.

Table 1: A comparison of decentralized models

Option	What It's Good At	Where It Hits a Wall	What It Needs That Pakistan Lacks
Grid extension	Unlimited electricity, backed by national infrastructure standards	Slow and expensive to build in remote or hard-terrain areas; connected communities still suffer the grid's own outages	Fast rollout capacity in remote regions, and a grid reliable enough that connection actually solves the reliability problem

[6] https://www.globenewswire.com/news-release/2025/03/25/3048500/28124/en/microgrid-markets-forecastto-exceed-us-163-billion-in-total-revenues-by-2033-industry-competition-intelligence-featuring-abb-siemensge-eaton-exelon-honeywell-schneider-electric-a.html

[7] https://www.ips.org.pk/wp-content/uploads/2023/07/21-Sustainable-Mini-grid-Solutions-for-Off-gridElectrification-in-Pakistan.pdf

Individual energy systems (generators, Solar Home Systems)	Fast to start, cheap, scales to what a household can afford	No coordination between households; systems are often mis-sized (wasted capacity or insufficient power); inequitable distribution	Shared data or planning across households to size systems correctly
Micro-grid	Purpose-sized, localized power for a defined group; can run independently or connected to the main grid	Needs professional planning, dedicated lines/generators, and costly high-quality batteries; investors fear stranded assets if the national grid later arrives	Institutional readiness — Pakistan only formalized micro-grid rules in 2022 (NEPRA regulations), after decades (1994– 2019) with no community power framework at all; just 13 micro-grid installations exist nationally
Mini-grid	Serves larger clusters of homes cost-effectively vs. full grid extension; globally driven by falling solar costs (panel prices down ~90% in a decade)	Depends on pooled community investment and steady, collective bill payment — hard where demand is seasonal (peak demand swings from ~28,000 MW to 8,000 MW in winter) and national grid AT&C losses already run up to 80% in some areas	A dedicated regulatory framework (Pakistan currently has none for mini-grids), stable financing, and reliable community payment collection — worsened by ~39% inflation, rupee depreciation of ~74% since 2021, and falling real household purchasing power (down 17% urban, 5% rural)

2.4- So why swarm grids could be a superior decentralised energy model

As explained in Chapter 1, a swarm grid is a peer-to-peer (P2P) setup—a bottom-up type of micro-grid where individual solar home systems (SHS) are connected, letting neighbouring homes share extra power or store it in batteries through a P2P network. Each household acts as a producer, a consumer, or both, and trades electricity. This removes dependence on the main grid and grows naturally in stages:

- Homes with solar home systems connect, forming a basic swarm grid.
- Neighbouring swarm grids link up to form a larger regional grid.
- The regional grid could eventually connect to the national grid.

Swarm electrification's value proposition is that it needs no years-long construction project, no individual household guesswork, and — critically — no large upfront capital, because it works with solar panels and batteries households have already bought. It simply asks a different question: instead of building something new, how to coordinate what already exists

This model is especially relevant for Pakistan, given the grid issues discussed in Chapter 1. Especially when citizens have installed 33 GW[8] of solar capacity across various sectors. According to the Household Income Economic Survey of 2025, about 18 percent of households have installed solar panels, leaving around 80 percent still relying on the grid. As of August 2025, the total residential solar installation was approximately 16.6 GW. This contrasts with the domestic sector's peak demand during the last fiscal year (FY 2024-25), which reached 24,699 MW on June 20, 2025.[9]

A key challenge is the uneven distribution of solar installations. While the HIES 2025 percentage shows that two out of every ten households may have solar panels, this capacity is concentrated in specific areas. You might see a neighborhood where every home has solar right next to one where very few or none do.[10]

A Swarm Grid, when integrated with battery storage, connected to an aggregator and consequently to the main distribution grid, and managed to share, sell, or trade power with the local Distribution Company (DISCO), functions essentially as a decentralized, interconnected Virtual Power Plant (VPP)[11]. This presents a highly feasible solution to several critical challenges facing modern energy infrastructure. Specifically, this approach offers a strong answer to the growing problem of reverse power flow in traditional distribution networks. This occurs when local energy resources like rooftop solar generate more power than is being consumed locally, pushing surplus electricity back into the grid. This reverse flow can destabilize the system, challenge current safety systems, and reduce the main grid's power quality.

Beyond addressing technical grid challenges, Swarm grids are an ideal model for achieving widespread rural electrification, particularly in remote and isolated areas where extending the central transmission and distribution network is too expensive, logistically complex, or environmentally difficult. A detailed technical and economic analysis is performed in Chapter

[8] PRIED's ground survey estimates 2025

[9] https://www.scribd.com/document/999015167/sectoral-analysis-2024-25

[10] https://nepra.org.pk/publications/State%20of%20Industry%20Reports/State%20of%20Industry%20Report%202025.pdf

[11] https://agendaelectrical.com/swarm-hubone-virtual-power-plantinstallation/#:~:text=And%20in%20a%20climate%20of,technologies%2C%20such%20as%20solar%20panels.

3 to further assess the financial viability of swarm grids and compare them with the models mentioned above. The following case studies help in understanding these challenges.

2.5- Practical Case Studies: What International Experience Confirms

i- Evolution of Swarm Grids in Bangladesh

Like Pakistan, Bangladesh has experienced a rapid spread of Solar Home Systems (SHSs). But unlike Pakistan, it was largely driven by government-backed subsidies and financing from Infrastructure Development Company Limited (IDCOL). Under the programme, over 4 million SHSs were installed, making it one of the largest deployments globally. However, many households with SHSs generated excess unused electricity, while nearby homes remained without electricity. This highlights what is currently happening in Pakistan, though on a smaller scale.

In 2014, Dr. Sebastian Groh identified the potential of connecting SHSs so that owners (producers) could sell excess electricity to neighbors (consumers) without needing to buy their own system. This approach was called Swarm Electrification (SE). To make this system sustainable in the long run, it requires monitoring and evaluation tools. To commercialize this idea systematically, Groh founded ME (micro energy) SOLshare in 2014. Key technology developments for swarm electrification included:

- SolBox – an IoT-based device installed in each connected home to:
  - Monitor power flows
  - Enable peer-to-peer (P2P) energy trading
  - Control transactions using mobile money
- SolBazaar – a software platform for managing payments and dynamic pricing

Next-generation SolBox upgrades now allow:

- Higher power throughput for larger appliances
- Higher voltage for longer-distance distribution
- Integration of AWS AI for load forecasting and pricing optimization

Typical configuration:

- SHS-equipped homes connect to neighbors without SHSs
- Controllers in each home regulate and log electricity trading
- Mobile payments ensure transparent transactions

As of late 2021, ME SOLshare had installed 90 swarm grids across Bangladesh. Additionally, in rural Bangladesh, ME SOLshare's swarm grids have turned underused Solar Home Systems into income-generating community assets, enabling SHS owners to sell excess power to neighbors via the IoT-based SolBox and mobile money payments. Across multiple installations, households have reported extended evening study hours for children, improved indoor air quality, reduced fuel expenses, and the ability to run small appliances like fans and sewing machines, creating micro-enterprise opportunities without requiring expensive new infrastructure.

The importance of this model lies not in the specific technology, but in the institutional and market design that enables peer-to-peer energy exchange in off-grid communities. Evidence from these deployments suggests that surplus solar generation can be monetized, while consumers without generation assets can access electricity services on a pay-as-you-use basis.

ii- India – Swarm Grid Feasibility & Productive Energy Use[12]

In 2017, India undertook a comprehensive study, *"Assessing Feasibility of Fostering Productive Energy Use of Swarm Electrified Microgrids in Rural Communities,"* to explore whether swarm electrification -- interconnecting Solar Home Systems (SHSs) via smart controllers - could support productive-use appliances (PEUs), such as grain milling machines, in rural Indian communities.

Key Highlights of the study:

- Location: Bochai Colony, India— the data used to model the swarm grid was collected using an AC microgrid.
- Methodology: Used Solshare's simulation to test the integration of two wheat milling machines (750 W and 7.5 kW) into a theoretical swarm grid.

Results:

- The small 750 W mill could run ~334 days/year.
- The larger 7.5 kW mill could operate ~44 days/year.
- Both showed a payback period under 3 years—a viable threshold for such equipment.

Economic Comparison: Swarm microgrids with new SHSs had a comparable capital cost to traditional AC microgrids. However, swarm systems offered more affordable microloan repayment terms for households using just a couple of LED lights and a phone charger, making them more adaptable to expected growth in household electricity needs.

These insights from the two countries in the South Asian region are particularly relevant when considering decentralized electrification approaches in remote or weak-grid regions of Pakistan, where conventional grid infrastructure expansion remains economically and technically challenging. Models such as swarm electrification highlight how linking these distributed assets through smart controllers and simple digital metering could enable shared electricity use and support small productive loads—such as grain milling, water pumping, sewing machines, or refrigeration—without requiring costly grid expansion. Equally important is the modular financing structure, which allows households to begin with small systems for basic lighting and phone charging while gradually scaling up their participation in local electricity networks as demand and incomes grow.

[12] https://upcommons.upc.edu/entities/publication/db0ae550-e661-47dc-90be-b060152a9573

Chapter 3: Feasibility Assessment

This swarm grid is an entirely novel concept for the case of Pakistan. While global examples cite it as a success case, its suitability to Pakistan's context requires further assessment. For the feasibility assessment, we chose two distinct landscapes, i.e., an urban city and two rural regions.

3-1: Methodology

This study employs a mixed-methods approach, combining qualitative and quantitative analyses to develop a comprehensive case for electrification through swarm grids in Pakistan. The methodology is designed to assess:

a) Household electricity needs
b) Community willingness to adopt this grid type
c) Compare the techno-economic feasibility against standalone solar home systems.

Additionally, the potential of a decentralized, market-responsive model suited to Pakistan's current socio-dynamic and energy transition context is assessed. The steps are outlined below:

1. Qualitative Analysis

a. Literature Review

A targeted review of global swarm grid models was conducted to establish a foundational understanding of decentralized rural electrification models and their application in similar socio-economic contexts. The literature review included:

1. Academic and technical studies on swarm grids, mini-grids, and solar home systems globally, with emphasis on their application in rural South Asia and SubSaharan Africa

2. Policy and regulatory documents on rural electrification in Pakistan, including NEPRA guidelines on mini/micro grids as well as national renewable energy policies and targets.

b. Primary Data Collection

Fieldwork was conducted in two villages — *Khario* and *Thario* (Thar district). The primary reason to assess Thar as a case study was the abundant high solar irradiance in the area, as well as the scattered population with a very huge class divide; therefore, an accessibility divide is present between households.

Sample Size: 51 participants.

For the urban case study, the survey was conducted across the commercial and residential areas in G-13 Islamabad. The reason for choosing this area was essentially due to the high solar penetration in this sector. ***Sample Size: 55 participants***.

Data Collection process: A semi-structured questionnaire was developed, which focused on:

- Socio-Economic Condition of the areas
- Basic household electricity consumption assessment for low, medium, and high demand segments
- Existing solar PV installations and system performance.
- Willingness to join swarm grids and perceived benefits/barriers
- Willingness to participate in a virtual power plant in the urban area

2. Quantitative Analysis

a. Techno-Economic Feasibility Assessment

Using the primary data collected from the two villages, we developed demand and cost profiles to compare the technical and financial performance of the swarm grid under three different scenarios with different source backups; First Swarm electrification with the grid as a backup; the second scenario uses diesel generators as a backup; and the third scenario consists of localized solar rooftop combined with BESS only operating in Island mode.

b. Key Evaluation Metrics: For each model, five key performance metrics were calculated based on the following evaluation methods:

1. Power Flow analysis to ensure none of the power constraints are violated.
2. Electricity generation profiles based on the installed systems and the irradiance profile of the areas to assess temporal and spatial generation profiles.
3. P2P Sharing revenue for financial outlay.
4. Net Savings by replacing grid power usage with swarm grid power supply to assess financial feasibility parameters.
5. Efficiency Gains – Optimized the usage of power generated by individual solar home systems

The techno-economic comparison is carried out by developing and using a "Swarm Grid Simulator," an interactive HTML/JavaScript tool that models peer-to-peer (P2P) energy sharing within a residential cluster. It runs an hourly (24-hour) dispatch engine driven by sitespecific solar irradiance data (NASA POWER GHI), household appliance data and their usage from the surveys, redistributed based on the IESCO and HESCO hourly load consumption of the subsequent months in which the surveys were carried out, and configurable battery and diesel-generator parameters. Since all three scenarios use the same dispatch model and household data, differences in cost, self-sufficiency, and curtailment result only from the choice of source backup used in the architecture. This provides a consistent basis for assessing feasibility across rural and urban cases. The detailed methodology is attached in Annexure 1.

Dispatch Sequence

For every hour of the day, the simulator resolves each house's energy balance through the following fixed merit order:

1. Solar/load first — each *house* serves its load through its own rooftop generation..
2. Battery second — any remaining deficit is drawn from that house's own battery, if it has one.
3. Peer-to-peer (P2P) sharing third — *houses* still short of energy are matched against houses still holding surplus solar directly, without tapping stored energy.
4. Neighbour-battery sharing fourth — a deficit *house/Commercial unit* may draw from a neighbouring house's battery if surplus solar is exhausted.
5. Backup dispatch last — any remaining deficit or surplus is handed to the scenariospecific backup: grid import/export (with reverse power flow addressed through net metering), diesel generation, or the common BESS/common solar.

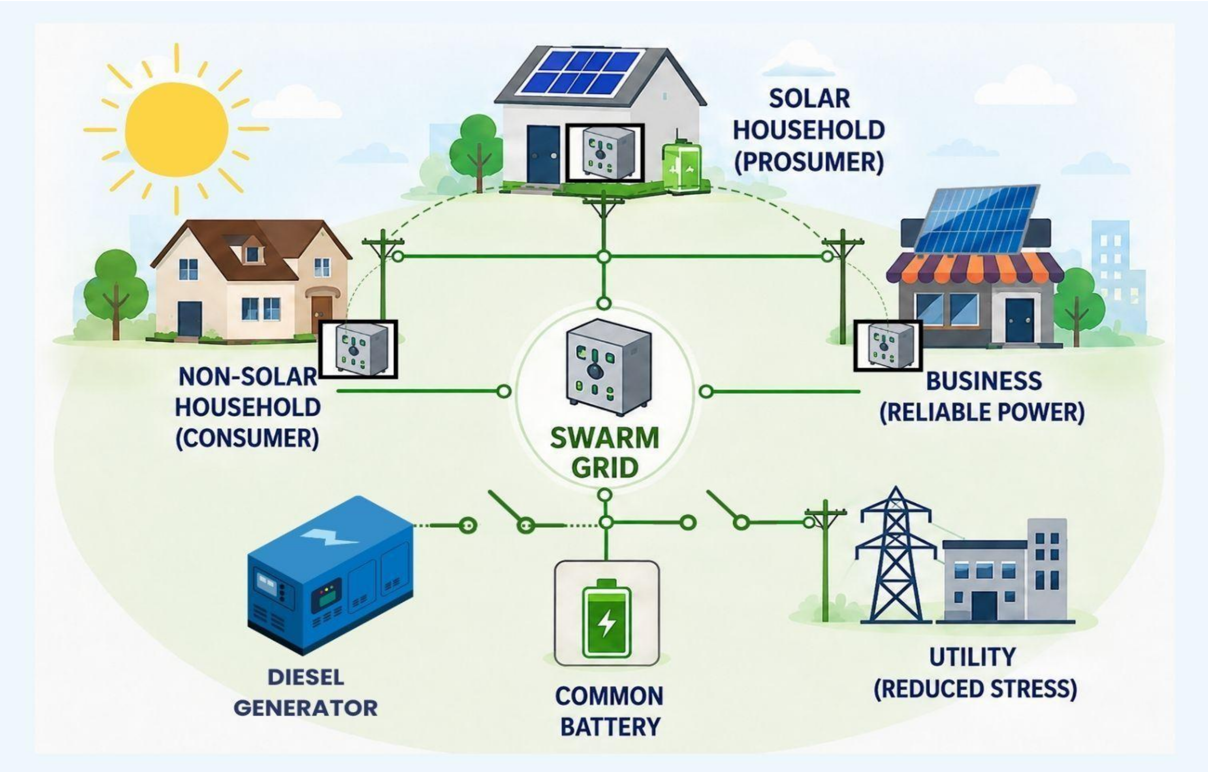
3.Scenarios

The same cluster, day, and houses are evaluated under three backup arrangements so their performance can be compared under the same conditions:

Table 2: Scenarios

Aspect	Scenario 1 — Grid-Connected	Scenario 2 — Diesel Generator	Scenario 3 — Common BESS + Solar
Backup source	National grid/NGC grid	Cluster diesel generator	Shared battery bank + shared solar array
Surplus handling	Exported to grid under net metering	Unused / not exported (no sink) / no reverse power flow	Charges the common BESS first
Governing constraint	Import/export always available	Minimum load factor, kVA × PF	State of charge, charge/discharge kW limits

Unmet demand	Never occurs	Never occurs (assumed always available)	Recorded explicitly as curtailment



The detailed methodology is added to Annexure 1 of the report. The subsequent sections mainly discuss the main results of the feasibility assessment.

3.2- Rural Electrification in Thar

Based on the demographic profile of Tharparkar derived from the Pakistan Bureau of Statistics (PBS) Census 2023, the district exhibits significant development gaps. Household electrification stands at just above 20 percent, reflecting extremely low electricity access and highlighting the urgent need for targeted policy intervention. Tharparkar also falls within the 30.1 percent –40 percent literacy bracket, indicating persistently low educational attainment in the region. Moreover, the district is part of the group where over 60 percent of children are out of school, underscoring deep-rooted social marginalization and the need for urgent policy measures.

Geographically, Tharparkar—situated in the sunny desert region of Sindh—offers exceptional solar potential. The district has annual Global Horizontal Irradiation (GHI) levels of 5–7 kWh/m²/day, receives more than 2,300 hours of sunlight per year, and features high Direct Normal Irradiance (DNI) in its southern belt.[13] This combination makes it one of the most

[13] https://www.researchgate.net/publication/379500744_Solar_Energy_Potential_in_Pakistan_A_Review

suitable regions in Pakistan for solar deployment, supporting both large-scale solar projects and decentralized, off-grid solar systems for rural electrification. These factors present a compelling case for renewable-based electrification in Tharkparkar. As illustrated in Figure 4, settlements in the region are organized in clusters. This spatial arrangement is particularly suitable for swarm grids, which require minimal distribution infrastructure and can effectively serve small, tightly knit communities. Premised on that, we conducted surveys in two villages of Tharparkar district to assess the feasibility and design of a swarm grid.

Figure 4: The rural clusters in Tharparkar and an after-transition vision under swarm electrification

The results indicated that both regions had mostly low- to middle-income households with very low baseload, with the majority willing to join a swarm network. These findings — spatial clustering, low baseload demand, and majority willingness to participate — collectively inform the technical sizing and the feasibility assessment presented in the next section, while also raising the question of what interventions might improve adoption among the remaining respondents.

3.3 Thario Village (Tharparkar, Sindh)

Before presenting the load-flow results, it is important to understand the demand profiles of households. The following chart presents the hourly demand profile of the surveyed households cumulatively over the full day.

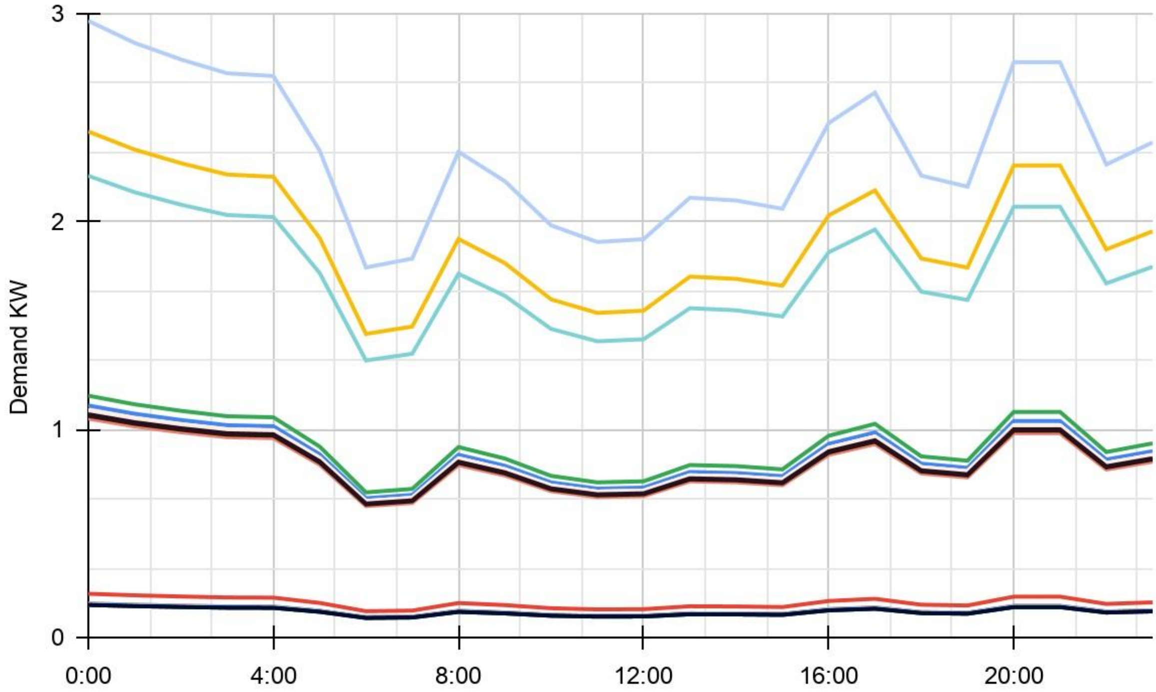


Figure 5: Hourly Electricity load profile Thario

Electricity consumption across the region remained relatively low, with a clear divide between day-time and night-time usage across household categories. In terms of household distribution, high-load households made up approximately **18%** of the sample, medium-load households accounted for roughly **41%**, and low-load households represented the majority at approximately **41%**.

This pattern indicated that while most households fall into lower consumption brackets, the high-consumption segment — though smaller in number — disproportionately drives the night-time peak at 20.00 hrs, as visible in Figure 5.

Participants' Solar & Battery Asset Profile

Some households have two 360 W solar panels and a 1.63 kWh battery. Most use this power mainly for a fan and one or two lights, with solar serving daytime loads and the battery providing limited energy after sunset. Most households in this area do not have appliances such as refrigerators, water pumps, or other high-power domestic equipment. Therefore, the relatively low and variable household loads seen in the load-flow results reflect the actual electricity-use conditions of the area.

Table 3 illustrates the solar panel wattage and battery capacity recorded for each of the 28 surveyed households in Thario. 96% of households reported having solar panels installed, with 93% having batteries installed as well.

Table 3: Solar and battery stats (Thario)

Participant	Solar Capacity/ W	Battery (kWh)
HH1	360	1.68
HH2	360	1.68
HH3	360	1.68
HH4	360	no
HH5	360	1.68
HH6	360	1.68
HH7	360	1.68
HH8	360	1.68
HH9	360	1.68
HH10	700	1.68
HH11	No	No
HH12	700	1.68
HH13	360	3.36
HH14	360	1.68
HH15	360	1.68
HH16	360	1.68
HH17	360	1.68
HH18	360	1.68
HH19	360	1.68
HH20	360	1.68
HH21	360	1.68
HH22	360	1.68
HH23	360	1.68
HH24	360	1.68
HH25	360	1.68
HH26	360	1.68

HH27	360	1.68
HH28	360	1.68

i: Network Load-Flow Snapshots, Cross-Referenced Against Participants' Assets

Based on these loads and the solar and battery capacity installed across each *participant*, we performed a load flow assessment. The detailed methodology can be found in Annexure 1; the subsequent sections will mostly focus on the results.
After incorporating the demand profile of the area and the essential distribution network specifications, we extracted two snapshots from the 24-hour dispatch engine: 12:00 (solar noon) and 22:00 (evening/night).

Sign convention: a negative net bus power denotes the house in deficit for the hour, drawing on P2P transfer and/or grid import; a positive value denotes the house in surplus, exporting into the local network. Similarly, a negative net bus power denotes the house in deficit for the hour, drawing on P2P transfer and/or grid import; a positive value denotes the house in surplus, exporting into the local network. Green shows surplus and red shows a deficit.

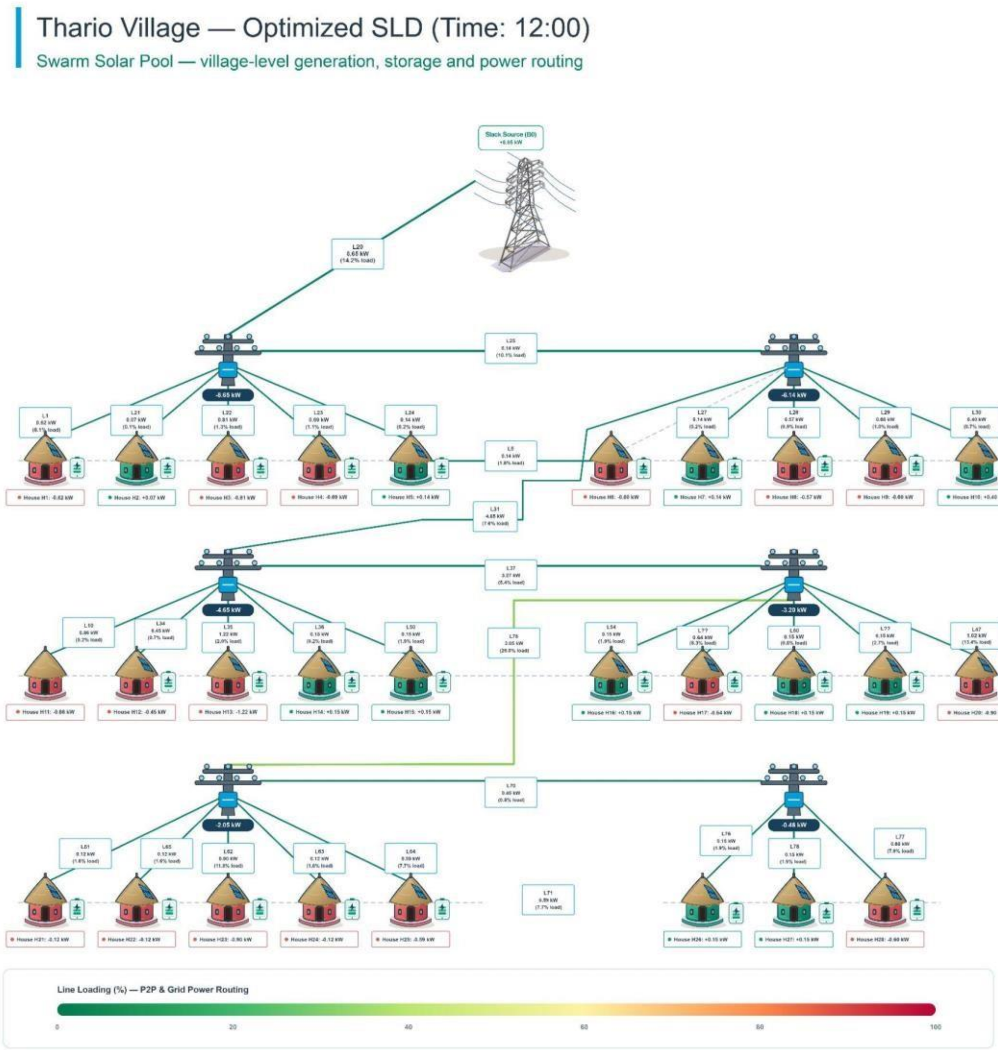


Figure 6 — Thario Village SLD, Time 12:00.

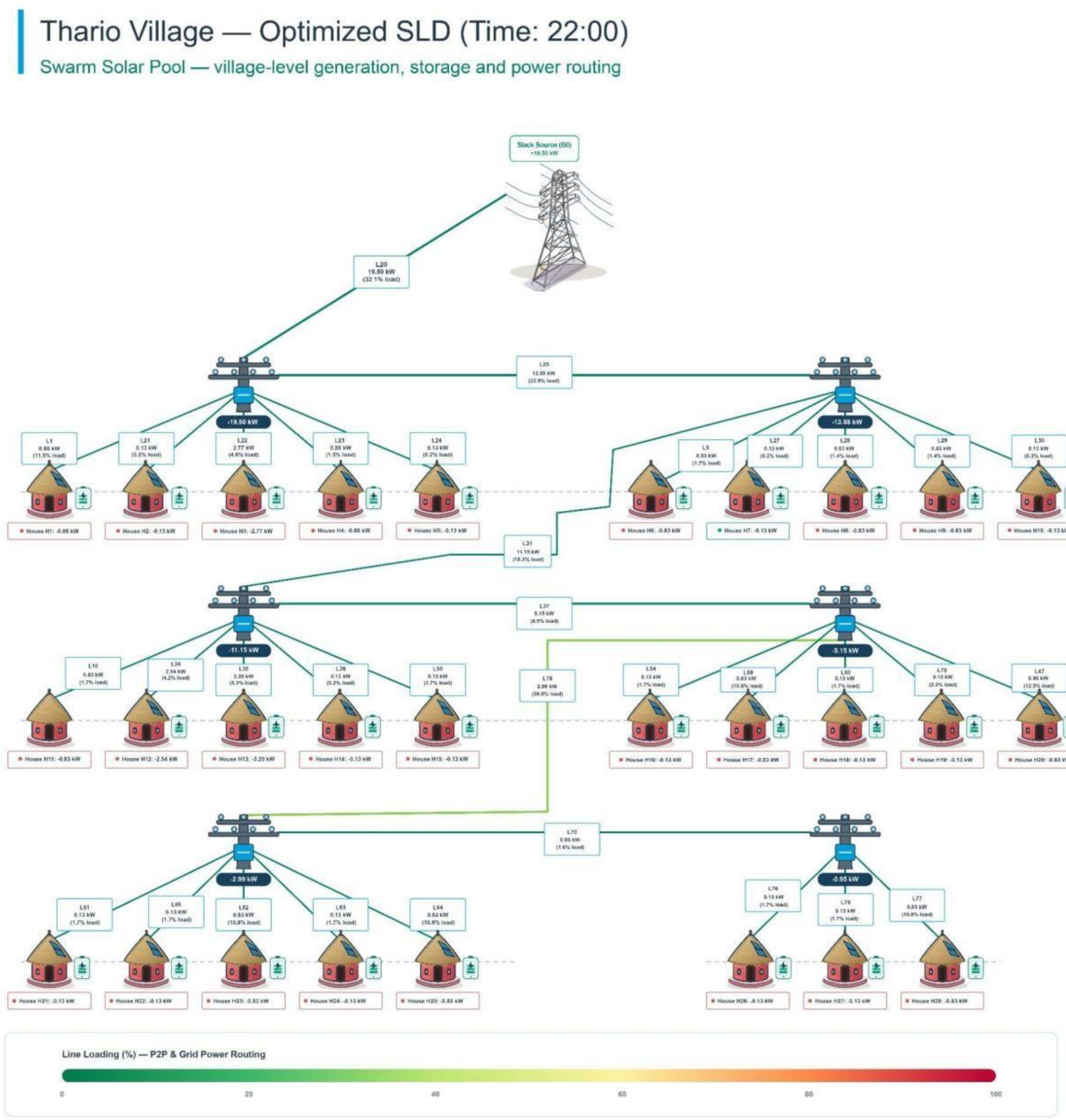


Figure 7 — Thario Village SLD, Time 22:00.

ii: Daily Cluster Energy-Dispatch Profile

The cluster's load is met almost entirely by grid import throughout the day — a small yellow band (Solar) appears only between roughly 07:00 and 15:00, and even at its peak covers just a fraction of the load (~2.5 kWh at most). There is no visible BESS discharge, P2P sharing (only a few kWh shared through peer-to-peer), or grid export at any hour — the cluster never generates a surplus large enough to export, so the lower "Grid Export (NM)" band is essentially flat/absent. Demand stays highest (20–22 kW) overnight and in the early-evening hours

(19:00–23:00), and dips only modestly during the solar window (down to ~7–8 kW), with grid import remaining the dominant source in every hour of the day.

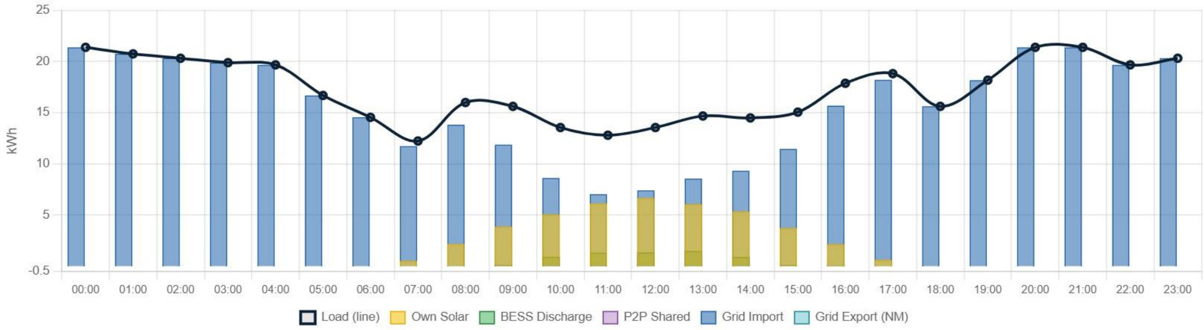


Figure 8: Thario Cluster, 24-Hour Energy Dispatch Profile

Table 4— Household Asset Profile and Status at Each Snapshot (Thario)

Household #	Solar (W)	Battery (kWh)	Net kW @12:00	Status @12:00	Net kW @22:00	Status @22:00
HH1	360	1.68	**-0.62**	Deficit — imports from grid/P2P	**-0.88**	Deficit — imports from grid/P2P
HH2	360	1.68	**0.07**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH3	360	1.68	**-0.81**	Deficit — imports from grid/P2P	**-2.77**	Deficit — imports from grid/P2P
HH4	360	1.68	**-0.69**	Deficit — imports from grid/P2P	**-0.88**	Deficit — imports from grid/P2P
HH5	360	1.68	**0.14**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH6	360	1.68	**-0.60**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH7	360	1.68	**0.14**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH8	360	1.68	**-0.57**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P

HH9	360	1.68	**-0.60**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH10	700	1.68	**0.40**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH11	360	1.68	**-0.86**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH12	700	1.68	**-0.45**	Deficit — imports from grid/P2P	**-2.54**	Deficit — imports from grid/P2Ps
HH13	360	3.36	**-1.22**	Deficit — imports from grid/P2P	**-3.20**	Deficit — imports from grid/P2P
HH14	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH15	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH16	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH17	360	1.68	**-0.64**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH18	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH19	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH20	360	1.68	**-0.90**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P

HH21	360	1.68	**-0.12**	Deficit — imports from grid/P2P	**-0.13**	Deficit — imports from grid/P2P
HH22	360	1.68	**-0.12**	Deficit — imports from grid/P2P	**-0.13**	Deficit — imports from grid/P2P
HH23	360	1.68	**-0.90**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH24	360	1.68	**-0.12**	Deficit — imports from grid/P2P	**-0.13**	Deficit — imports from grid/P2P
HH25	360	1.68	**-0.59**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P
HH26	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH27	360	1.68	**0.15**	Surplus — exports to network	**-0.13**	Deficit — imports from grid/P2P
HH28	360	1.68	**-0.60**	Deficit — imports from grid/P2P	**-0.83**	Deficit — imports from grid/P2P

The table provides a snapshot of household load profiles within the swarm grid, showing how generation, storage, grid imports, and peer-to-peer (P2P) exchanges vary throughout the day. Rather than operating as isolated units, households act as dynamic nodes. At any given hour, a household may meet its demand using its own solar and battery, import power from a neighbouring household or the grid when in deficit, or share excess generation with a neighbouring household when in surplus.

ii: Household-Level Economic Analysis

The economic analysis now builds on the load flow analysis by examining each participant's energy use, solar generation, P2P exchanges, grid dependence, and associated costs and savings. Table 5 provides the economic performance and potential savings for households participating in the swarm grid. The cost of sharing also includes transmission and distribution costs. These will initially fund the additional infrastructure needed for swarm grids, before the system starts generating revenue for a swarm grid operator.

Table 5: Household Economic level analysis (Thario)

Participant	Day Energy (kWh)	Night Energy (kWh)	Solar Gen. (kWh)	P2P Shared Out (kWh)	P2P Received (kWh)	Grid Import (kWh)	Grid Export (kWh)	Grid electricity supply cost (Rs)	NM Earnings (Rs)	Sharing Revenue (Rs)	Sharing Cost (Rs)	Net Saving (Rs/day)
HH1	11	11	1	0	3	16	0	691	0	0	− 65	133
HH2	2	2	1	0	0	3	0	111	0	2	− 0	59
HH3	13	33	1	0	3	42	0	1763	0	0	− 54	121
HH4	11	11	1	0	1	20	0	836	0	0	− 14	77
HH5	2	2	1	0	0	2	0	87	0	7	− 0	50
HH6	10	10	1	0	0	19	0	791	0	0	− 1	63
HH7	2	2	1	0	0	2	0	87	0	7	− 0	50
HH8	10	10	1	0	0	19	0	778	0	0	− 0	61
HH9	10	10	1	0	0	19	0	791	0	0	− 0	61
HH10	1	2	3	1	0	2	0	76	0	29	− 0	77
HH11	10	10	7	1	0	14	0	596	0	12	− 0	266
HH12	12	31	3	0	0	39	0	1650	0	0	− 0	119
HH13	18	38	1	0	0	55	0	2301	0	0	− 0	62
HH14	1	2	1	0	0	2	0	83	0	8	− 0	50
HH15	1	2	1	0	0	2	0	83	0	8	− 0	50
HH16	1	2	1	0	0	2	0	83	0	8	− 0	50
HH17	11	10	1	0	0	19	0	810	0	0	− 0	61
HH18	1	2	1	0	0	2	0	83	0	8	− 0	50
HH19	1	2	1	0	0	2	0	83	0	8	− 0	50
HH20	11	10	1	0	0	19	0	810	0	0	− 0	61
HH21	1	2	1	0	0	2	0	83	0	8	− 0	50
HH22	1	2	1	0	0	2	0	83	0	8	− 0	50

HH23	11	10	1	0	0	19	0	810	0	0	− 0	61
HH24	1	2	1	0	0	2	0	83	0	7	− 0	49
HH25	11	10	1	0	0	19	0	810	0	0	− 0	61
HH26	1	2	1	0	0	2	0	83	0	8	− 0	50
HH27	1	2	1	0	0	2	0	83	0	8	− 0	50
HH28	10	10	1	0	0	19	0	794	0	0	− 0	61

1. P2P sharing splits households into two clear roles: net receivers vs. net exporters.
    - Receivers (large-tier households): HH1 (receives 3.25 kWh, 0 exported), HH 3 (2.72 kWh received), HH6 (0.07 kWh), HH 13 (0.02 kWh). It also shows a negative Sharing Cost (money owed to the exporting participant) rather than revenue.
    - Exporters (small-tier households): HH(2, 5, 7, 10, 14–16, 18, 19, 21, 22, 24, 26, 27) — each consistently exports ~0.37 -- 0.39 kWh/day and earns 7–8rupees per day in sharing revenue. HH 10 is the exception at 1.43 kWh exported (its solar generation is also above-average at 2.83 kWh), and HH 11 exports 0.62 kWh on 6.80 kWh solar generation.
    - Several large HH(4, 8, 9, 12, 17, 20, 23, 25, 28) show zero P2P activity in either direction — solar output equals baseline (1.46 kWh) but isn't routed anywhere, and they don't draw from peers either.

2. P2P revenue is small in absolute terms but proportionally significant for small participants. 7–8 rupees per day in sharing revenue is only ~1–2 percent of what large households pay in **Cost of Grid electricity supply**, but for small households it's ~9–10 percent of their own ~ 83 rupees grid cost — a real, if modest, offset.
3. P2P "cost" for receiving households is negligible against their grid electricity bill. HH 1's − 65 rupees"Sharing Cost" against a 691 rupees grid electricity cost is under 10% — receiving 3.25 kWh via P2P. This is still far cheaper than the equivalent grid import, resulting in net savings rather than an added expense.
4. Net savings correlate with P2P/solar participation, not household size. The clearest evidence:
    - HH 11 — the only household combining above-average solar generation (6.80 kWh) *with* active P2P export (0.62 kWh) — posts 266 rupees/day, roughly 3–5 times every other household in the dataset.

- HH 1 — no export, but the *largest* P2P receipt (3.25 kWh) — posts the second-highest saving at 133rupees per day, ahead of similarly-sized peers (3, 4, 6, 8, 9) that saved only 61–121 rupees per day with zero P2P exchange.
- HH 13 — largest consumer in the cluster (Rs 2,301 grid electricity cost) but almost no P2P exchange (0.02 kWh received, nothing exported) — saves only 62 rupees per day, on par with households consuming a fraction of its load.

5. Net metering does not provide any financial benefit to the households in this analysis. All 28 households have zero NM earnings, meaning that P2P sharing is the only way surplus solar generates direct financial savings. It shows that under the current setup, net metering is non-existent in the territory and contributes nothing (Rs 0 across all 28 participants), so P2P is the *only* mechanism turning solar surplus into cash savings. That makes P2P participation — not household size, and not solar capacity alone — the real r determining factor in terms of who benefits economically from the system. A household can be small and still out-save a much larger one, purely by being an active node in the P2P exchange.

iii: Sensitivity Analysis: Cost Savings Comparison: Diesel-Backed vs. BESS-Backed P2P Sharing

The same simulations with the same assumption set with a diesel generator and BESS as a backup source were performed, and the following results were observed.

Table 6: P2P Sharing With Diesel Generator as the slack source (Thario)

House	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Diesel Received	Diesel Cost (share)	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving/ day
1	11	11	1	0	3	16	1317	0	65	889	-493
2	2	2	1	0	0	3	210	2	0	168	-41
3	13	33	1	0	3	42	3358	0	54	1939	-1474
4	11	11	1	0	1	20	1592	0	14	927	-679
5	2	2	1	0	0	2	165	7	0	130	-28
6	10	10	1	0	0	19	1507	0	1	855	-653
7	2	2	1	0	0	2	165	7	0	130	-28
8	10	10	1	0	0	19	1482	0	0	839	-642
9	10	10	1	0	0	19	1507	0	0	852	-655
10	1	2	3	1	0	2	146	29	0	125	8
11	10	10	7	1	0	14	1134	12	0	849	-273
12	12	31	3	0	0	39	3143	0	0	1769	-1374

13	18	38	1	0	0	55	4383	0	0	2363	-2021
14	1	2	1	0	0	2	158	8	0	125	-25
15	1	2	1	0	0	2	158	8	0	125	-25
16	1	2	1	0	0	2	158	8	0	125	-25
17	11	10	1	0	0	19	1542	0	0	871	-671
18	1	2	1	0	0	2	158	8	0	125	-25
19	1	2	1	0	0	2	158	8	0	125	-25
20	11	10	1	0	0	19	1542	0	0	871	-671
21	1	2	1	0	0	2	158	8	0	125	-25
22	1	2	1	0	0	2	158	8	0	125	-25
23	11	10	1	0	0	19	1542	0	0	871	-671
24	1	2	1	0	0	2	158	7	0	125	-25
25	11	10	1	0	0	19	1542	0	0	871	-671
26	1	2	1	0	0	2	158	8	0	125	-25
27	1	2	1	0	0	2	158	8	0	125	-25
28	10	10	1	0	0	19	1513	0	0	855	-658

Table 7: P2P Sharing With BESS as the slack source (Thario)

House	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Common BESS Received	Daily CB cost share	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving
1	11	11	1	0	3	16	444	0	65	889	380
2	2	2	1	0	0	3	71	2	0	168	98
3	13	33	1	0	3	42	1133	0	54	1939	751
4	11	11	1	0	1	20	537	0	14	927	375
5	2	2	1	0	0	2	56	7	0	130	82
6	10	10	1	0	0	19	509	0	1	855	345
7	2	2	1	0	0	2	56	7	0	130	82
8	10	10	1	0	0	19	500	0	0	839	339
9	10	10	1	0	0	19	509	0	0	852	344

10	1	2	3	1	0	2	49	29	0	125	104
11	10	10	7	1	0	14	383	12	0	849	479
12	12	31	3	0	0	39	1061	0	0	1769	708
13	18	38	1	0	0	55	1479	0	0	2363	883
14	1	2	1	0	0	2	53	8	0	125	79
15	1	2	1	0	0	2	53	8	0	125	79
16	1	2	1	0	0	2	53	8	0	125	79
17	11	10	1	0	0	19	521	0	0	871	350
18	1	2	1	0	0	2	53	8	0	125	79
19	1	2	1	0	0	2	53	8	0	125	79
20	11	10	1	0	0	19	521	0	0	871	350
21	1	2	1	0	0	2	53	8	0	125	79
22	1	2	1	0	0	2	53	8	0	125	79
23	11	10	1	0	0	19	521	0	0	871	350
24	1	2	1	0	0	2	53	7	0	125	79
25	11	10	1	0	0	19	521	0	0	871	350
26	1	2	1	0	0	2	53	8	0	125	79
27	1	2	1	0	0	2	53	8	0	125	79
28	10	10	1	0	0	19	510	0	0	855	345

Across the 28-participant community, the slack source was changed from grid to diesel and BEES and a comparison of both scenarios produces a dramatic swing in economic outcomes, even though the underlying load, solar generation, and P2P sharing patterns are identical in both scenarios.

Backup energy cost: In the diesel scenario, the cost of drawing backup energy (18.84–54.79 kWh per day per house-equivalent) is billed at the diesel rate, driving the aggregate daily backup cost share to roughly 29,368 rupees across all 28 participants. With the BESS in place, the same backup energy draw is served from the shared battery instead of a generator, and the aggregate daily cost share drops to roughly 9,913 rupees— a reduction of about 19,455, or nearly two-thirds (~66percent) lower backup energy cost for an essentially identical consumption profile.

Net saving flips from loss to gain: Because diesel is expensive relative to the grid-equivalent benchmark, almost every house in the diesel scenario shows a negative net saving — i.e., participating in the diesel-backed system costs more than simply buying from the grid. Houses with heavy night-time draw and low solar self-sufficiency (e.g., HH13: –2,020.68 rupees; HH3: –1,474.08 rupees; HH12: –1,373.74 rupees) are hit hardest, and only one house (participant 10, a small consumer with a higher solar share) shows a marginal net saving (+7.74). Summed across all houses, the diesel-backed system runs a net loss of about –11,947 rupees relative to grid pricing.

With BESS as the backup source, the same houses swing decisively into positive territory: every single house records a positive net saving, and the community-wide total flips to roughly +7,508. The largest beneficiaries are the same high-consumption houses that suffered the biggest losses under diesel — House 13 improves from Rupees –2,020.68 to +883.19, HH3 from –1,474.08 to +750.86 rupees, and HH 12 from –1,373.74 to +708.36 rupees— illustrating that the households most exposed to backup costs gain the most from switching to battery storage.

3.4 Khario Village (Tharparkar, Sindh)

The subsequent sections will take us through the load profile of the surveyed Thario households and their battery and solar capacity. Following these, we'll discuss the results and analysis of the simulation for swarm electrification in Khario.

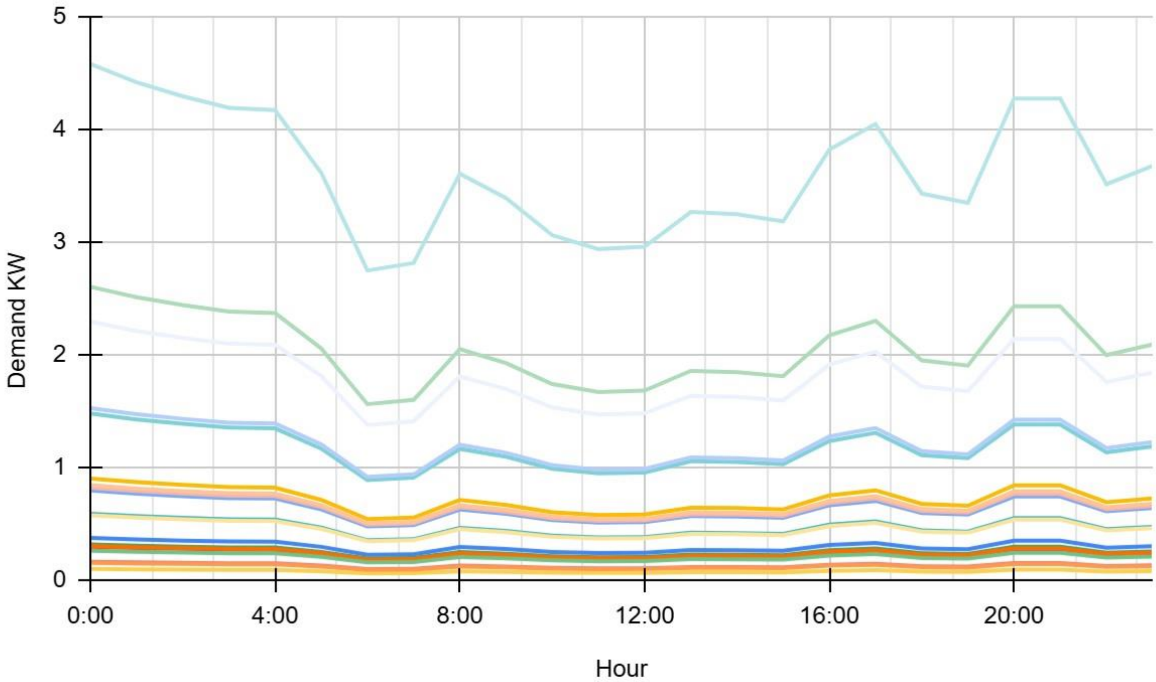


Figure 9: Hourly Electricity Load profile Khario

Overall electricity consumption across the region remained relatively low compared to national or urban benchmarks, reflecting the area's predominantly residential and lowintensity load profile. To better understand usage behavior, we developed hourly load profiles based on survey data reflecting demand driven by lighting, heating/cooling, and household appliance use. Out of the total surveyed households, 79% had solar installed, with 74% among them having lead-acid batteries installed with it.

Households were also classified into three consumption tiers — high, medium, and low — based on their average daily load. The distribution was skewed toward lower consumption brackets, consistent with the region's limited residential appliance use and modest income levels. Specifically:

High-load households accounted for approximately 11percent of the sample, typically characterized by extended evening usage, multiple appliances, and in some cases, commercial or semi-commercial activity conducted from the home. Medium-load households represented roughly 39percent, showing moderate and fairly consistent consumption across both day and night periods. Low-load households made up the majority at approximately 50percent, with usage concentrated around essential lighting and minimal appliance operation, particularly during night-time hours.

Household Solar & Battery Asset Profile

Table 8 below lists the solar panel wattage and battery capacity recorded for each of the 28 surveyed households in Khario. None of the households were net-metered. All the households have lead-acid tubular batteries.

Table 8: Household solar and battery stats (Khario)

participant	Solar PV capacity / W	Battery energy storage capacity/kWh
HH5	nil	
HH6	580	
HH7	360	1.68
HH8	180	1.68
HH9	nil	nil
HH10	nil	nil
HH11	360	1.68
HH12	nil	nil
HH13	180	1.68
HH14	160	1.68
HH15	580	1.68
HH16	480	1.68
HH17	180	1.68
HH18	nil	nil
HH19	360	1.68

In Khario, 14 participants own solar panels ranging from 0.16 kW to 0.58 kW with batteries of around 1.68 kWh. Five of the 19 surveyed participants have no solar panel, while 2 households have unknown battery capacity; for analysis, we used a battery size of 1.68 kWh. Compared to the Thario village, this rural setting has significantly low solar adoption. The recorded solar generation therefore is not sufficient to reliably support swarm grid operation. The analysis that follows should consequently be interpreted within the context of this limited solar penetration and storage capacity.

i: Network Load-Flow Snapshots, Cross-Referenced Against Household Assets

Similar to the Thario case study, two snapshots were extracted from the 24-hour dispatch engine for Khario: 12:00 (solar noon) and 22:00 (evening/night), with the same sign convention that is defined in the previous case study

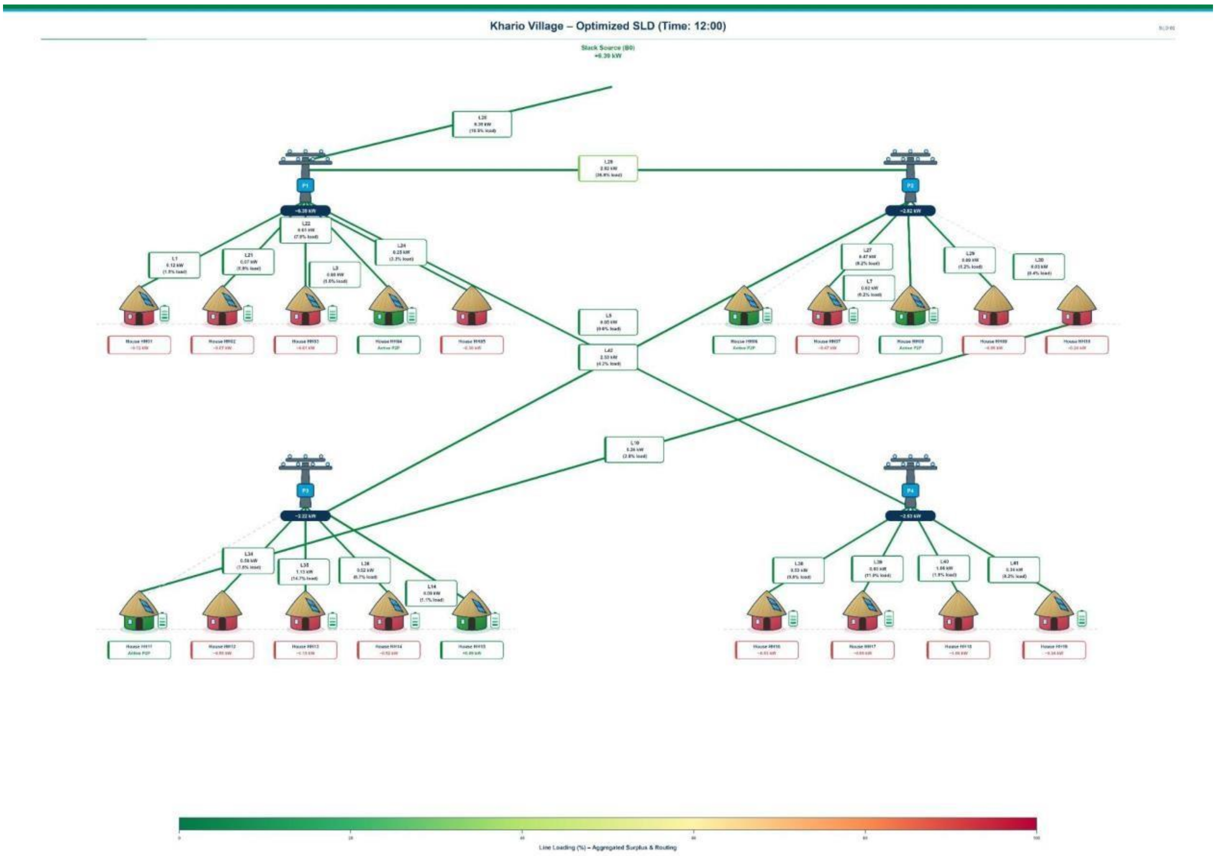


Figure 10: Khario Village SLD, Time 12:00. Grid Import: 6.39 kW.

At solar noon, five of the nineteen houses register a small surplus and are shown actively exporting: HH04, sharing 0.08 kW peer-to-peer with neighbouring HH03, HH06, HH08, HH11 (+0.20 kW, shared onward to HH01 and HH15,-+0.09 kW. The remaining fourteen houses are in deficit, the largest being HH13, −1.1 kW. Cluster-wide import at the slack source is 6.39 kW, which is only 10.5% of the main feeder's rated capacity. This import level is consistent with the small solar systems recorded in the asset survey, which range from 160 W to 580 W per participant. These systems can meet some daytime participant demand and produce a small surplus, but they are not large enough to make the cluster self-sufficient, even around midday.

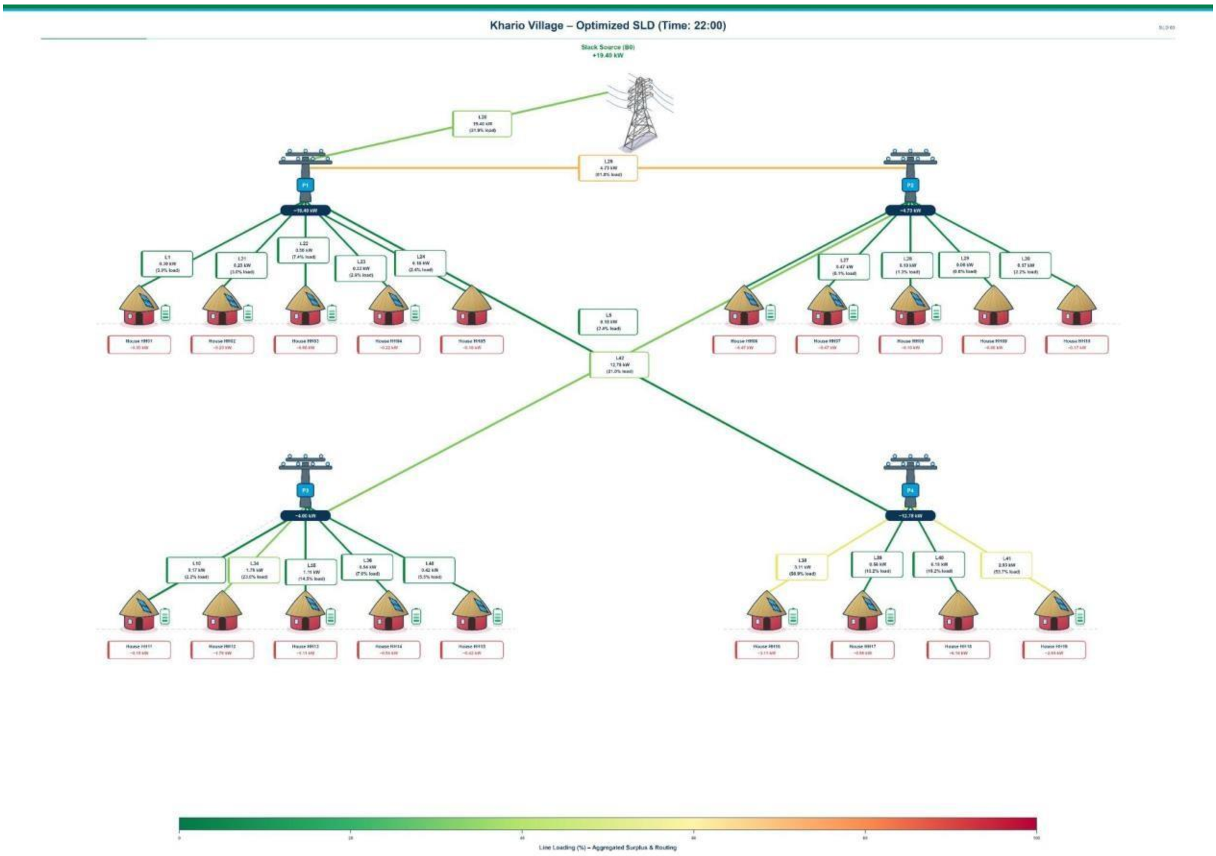


Figure 11: Khario Village SLD, Time 22:00. Grid Import: 19.4 kW.

By 22:00, all participants in the cluster are in deficit because solar generation has stopped. Most participant batteries have only 1.68 kWh of storage, which is not enough to cover the full evening demand.

As a result, slack-source imports rose to 19.40 kWh, about three times the noon level and equal to 31.9% of line capacity. The deficit is mainly concentrated in three households: HH16, −3.1 kW, HH18, −6.1 kW, and HH19, −2.93 kW. Together, they account for 12.1 kW, or nearly two-thirds of the cluster's total evening import.

ii: Daily Cluster Energy-Dispatch Profile

The cluster's load is met almost entirely by grid import throughout the day — a small yellow band (Solar) appears only between roughly 07:00 and 15:00, and even at its peak covers just a fraction of the load (~2.5 kWh at most). There is no visible BESS discharge, P2P sharing (only a few kWh shared through peer-to-peer), or grid export at any hour — the cluster never generates a surplus large enough to export, so the lower "Grid Export (NM)" band is essentially flat/absent. Demand stays highest (23–25 kWh) overnight and in the earlyevening hours (19:00–23:00), and even dips only modestly during the solar window (down to ~11–15 kWh), with grid import remaining the dominant source in every hour of the day.

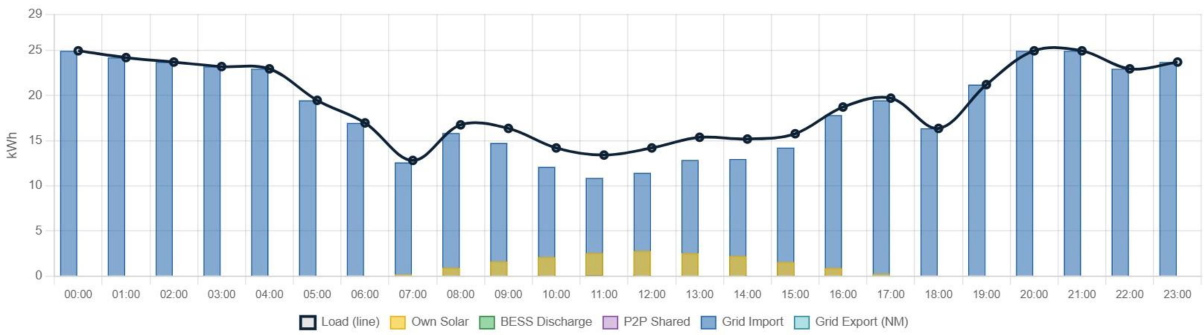


Figure 12: Khario Cluster, 24-Hour Energy Dispatch Profile

Table 9 below cross-references each household's recorded solar and battery assets against its net power and status at both snapshot hours.

Table 9: Household Status at Each Snapshot, Cross-Referenced with Solar/Battery Ownership (Khario)

Participant	Solar	Battery	Net kW @12:00	Status @12:00	Net kW @22:00	Status @22:00
HH1	180 W	1.68 kWh	-0.10	Deficit — imports from grid/P2P	-0.30	Deficit — imports from grid/P2P
HH2	180 W	1.68 kWh	-0.03	Deficit — imports from grid/P2P	-0.20	Deficit — imports from grid/P2P
HH3	180 W	None	-0.61	Deficit — imports from grid/P2P	-0.50	Deficit — imports from grid/P2P
HH4	360 W	1.68 kWh	+0.08	Surplus — exports (P2P to participant03)	-0.20	Deficit — imports from grid/P2P
HH5	None	None	-0.30	Deficit — imports from grid/P2P	-0.18	Deficit — imports from grid/P2P
HH6	580 W	1.69 kWh	+0.04	Surplus — exports to network	-0.40	Deficit — imports from grid/P2P
HH7	360 W	1.69 kWh	-0.40	Deficit — imports from grid/P2P	-0.40	Deficit — imports from grid/P2P
HH8	180 W	1.69 kWh	+0.02	Surplus — exports to network	-0.10	Deficit — imports from grid/P2P
HH9	None	None	-0.02	Deficit — imports from grid/P2P	-0.03	Deficit — imports from grid/P2P
HH10	None	None	-0.24	Deficit — imports from grid/P2P	-0.17	Deficit — imports from grid/P2P
HH11	360 W	1.68 kWh	+0.20	Surplus — exports (P2P to participant01)	-0.10	Deficit — imports from grid/P2P

HH12	None	None	-0.50	Deficit — imports from grid/P2P	-1.70	Deficit — imports from grid/P2P
HH13	180 W	3.36 kWh	-1.10	Deficit — imports from grid/P2P	-1.10	Deficit — imports from grid/P2P
HH14	160 W	1.68 kWh	-0.60	Deficit — imports from grid/P2P	-0.50	Deficit — imports from grid/P2P
HH15	580 W	1.68 kWh	+0.09	Surplus — exports to network	-0.42	Deficit — imports from grid/P2P
HH16	480 W	1.68 kWh	-0.50	Deficit — imports from grid/P2P	-3.10	Deficit — imports from grid/P2P
HH17	180 W	1.68 kWh	-0.60	Deficit — imports from grid/P2P	-0.50	Deficit — imports from grid/P2P
HH18	None	None	-1.00	Deficit — imports from grid/P2P	-6.10	Deficit — imports from grid/P2P
HH19	360 W	1.68 kWh	-0.34	Deficit — imports from grid/P2P	-2.93	Deficit — imports from grid/P2P

One result merits particular attention: HH16 and HH19, despite owning 480 W and 360 W solar arrays respectively — among the larger installations in the sample — post two of the largest evening deficits in the cluster. This is not an inconsistency once cross-checked against the economic table below: both households' night-time demand (42.27 kWh and 38.45 kWh) is more than double their day-time demand (18.24 kWh and 13.26 kWh) and far exceeds what a 1.68 kWh battery could carry through to 22:00, pointing to unusually high night-time consumption relative to the rest of the Khario sample. The same reversed day/night pattern is visible, even more sharply, for HH18, 18.97 kWh day vs 78.27 kWh night, and HH12, 13.55 kWh day vs 25.59 kWh night— both non-solar households.

iii: Household-Level Economic Analysis

Table 10 below illustrates the household-level techno-economic simulation output for the 19 participants of the Khario sample, for the representative day.

Table 10: Household economic analysis (Khario)

Participant	Day Energy (kWh)	Night Energy (kWh)	Solar Gen. (kWh)	P2P Shared Out (kWh)	P2P Received (kWh)	Grid Import (kWh)	Grid Export (kWh)	Cost of Grid electricity supply (Rs)	NM Earnings (Rs)	Sharing Revenue (Rs)	Sharing Cost (Rs)	Net Saving (Rs/day)
HH1	3.52	3.57	0.73	0	0.29	6.07	0	255	0	0	-6	**37**

HH2	2.91	2.71	0.73	0	0	4.89	0	205	0	0	0	**31**
HH3	9.88	6.96	0.73	0	0	16.11	0	677	0	0	0	**31**
HH4	5.91	2.67	1.46	0	0	7.12	0	299	0	0	0	**61**
HH5	6.14	2.18	0	0	0	8.33	0	350	0	0	0	**0**
HH6	12.85	9.76	2.35	0	0	20.27	0	851	0	0	0	**99**
HH7	12.04	5.62	1.46	0	0	16.20	0	681	0	0	0	**61**
HH8	6.73	5.31	0.73	0	0	11.31	0	475	0	0	0	**31**
HH9	1.99	1	0	0	0	2.99	0	126	0	0	0	**0**
HH10	2.90	2.06	0	0	0	4.95	0	208	0	0	0	**0**
HH11	1.69	1.21	1.46	0.29	0	1.80	0	76	0	6	0	**52**
HH12	13.55	25.59	0	0	0	39.14	0	1644	0	0	0	**0**
HH13	21.52	17.44	0.73	0	0	38.23	0	1606	0	0	0	**31**
HH14	13.05	9.12	0.73	0	0	21.44	0	901	0	0	0	**31**
HH15	9.73	7.79	2.35	0	0	15.18	0	637	0	0	0	**99**
HH16	18.24	42.27	1.94	0	0	58.57	0	2460	0	0	0	**82**
HH17	13.92	11.25	0.73	0	0	24.44	0	1027	0	0	0	**31**
HH18	18.97	78.27	0	0	0	97.24	0	4084	0	0	0	**0**
HH19	13.26	38.45	1.46	0	0	50.25	0	2111	0	0	0	**61**

Across the nineteen households, total demand for the representative day was 462.0 kWh cumulatively (188.8 kWh day, 273.2 kWh night), of which solar met only 17.6 kWh — under

4percent of demand, and grid import covered the remaining 444.5 kWh; the remaining 96 percent stay dependent on the grid.

Peer-to-peer transfer, at 0.29 kWh (a single active link, HH1 to HH11, redistributed under 2% of the day's already-small solar output. No house recorded a grid export on the representative day, so net-metering earnings are zero across the entire sample. This is a direct, quantified illustration of the point made qualitatively in the asset profile above: at the 160–580 W panel and roughly 1.68 kWh battery sizes currently installed in Khario, individual systems generate barely enough surplus to offset their own owner's load. Hence not sufficient to create a meaningful peer-to-peer market between neighbours.

Despite this, every household that owns any solar capacity records a positive net saving relative to a grid-only baseline — from 31 rupees per day (HH2, HH3, HH8, HH13, HH14 and HH17) up to 99 rupees per day HH6 and HH15, two of the larger installations in the sample) — While the five households with no solar (HH5, HH9, HH10, HH12, and HH18) show zero net savings because others do not have enough energy for these houses via the P2P network, these houses still meet the demand through the grid network.

iv: Sensitivity Analysis: Cost Savings Comparison: Diesel-Backed vs. BESS-Backed P2P Sharing

The same simulations with the same assumption set with a diesel generator and BESS as a backup source were performed, and the following results were observed.

Table 11: P2P Sharing With Diesel Generator (Khario)

participant	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Diesel Received	Diesel Cost (share)	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving
HH1	4	4	1	0	0	6	486	0	6	298	-194
HH2	3	3	1	0	0	5	391	0	0	236	-155
HH3	10	7	1	0	0	16	1289	0	0	707	-582
HH4	6	3	1	0	0	7	570	0	0	360	-209
HH5	6	2	0	0	0	8	666	0	0	349	-317
HH6	13	10	2	0	0	20	1622	0	0	950	-672
HH7	12	6	1	0	0	16	1296	0	0	742	-554
HH8	7	5	1	0	0	11	905	0	0	506	-399

HH9	4	4	1	0	0	6	486	0	6	298	-194
HH10	3	3	1	0	0	5	391	0	0	236	-155
HH11	10	7	1	0	0	16	1289	0	0	707	-582
HH12	6	3	1	0	0	7	570	0	0	360	-209
HH13	6	2	0	0	0	8	666	0	0	349	-317
HH14	13	10	2	0	0	20	1622	0	0	950	-672
HH15	12	6	1	0	0	16	1296	0	0	742	-554
HH16	7	5	1	0	0	11	905	0	0	506	-399
HH17	4	4	1	0	0	6	486	0	6	298	-194
HH18	3	3	1	0	0	5	391	0	0	236	-155
HH19	10	7	1	0	0	16	1289	0	0	707	-582

Table 12: P2P Sharing With BESS (Khario)

participant	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Common BESS Received	Daily CB cost share	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving/ day
HH1	4	4	1	0	0	6	164	0	6	298	128
HH2	3	3	1	0	0	5	132	0	0	236	104
HH3	10	7	1	0	0	16	435	0	0	707	272
HH4	6	3	1	0	0	7	192	0	0	360	168
HH5	6	2	0	0	0	8	225	0	0	349	125
HH6	13	10	2	0	0	20	547	0	0	950	402
HH7	12	6	1	0	0	16	437	0	0	742	304
HH8	7	5	1	0	0	11	305	0	0	506	200
HH9	2	1	0	0	0	3	81	0	0	126	45
HH10	3	2	0	0	0	5	134	0	0	208	75

HH11	2	1	1	0	0	2	49	6	0	122	79
HH12	14	26	0	0	0	39	1057	0	0	1644	587
HH13	22	17	1	0	0	38	1032	0	0	1636	604
HH14	13	9	1	0	0	21	579	0	0	931	352
HH15	10	8	2	0	0	15	410	0	0	736	326
HH16	18	42	2	0	0	59	1581	0	0	2541	960
HH17	14	11	1	0	0	24	660	0	0	1057	397
HH18	19	78	0	0	0	97	2625	0	0	4084	1459
HH19	13	38	1	0	0	50	1357	0	0	2172	815

The easiest comparison is between Houses 1–8. In both datasets, these houses have the same electricity use, solar generation, and energy sharing. The only thing that changes is the backup source. Therefore, any difference in the results is caused by the different backup source, not by changes in electricity consumption.

Backup energy cost. Across those eight matched households, both systems draw the same 90.3 kWh of aggregate backup power. Diesel bills that energy at a flat rate of 80/kWh, producing a combined cost share of 7,224. The common BESS supplies the identical 90.3 kWh at 27/kWh, bringing the cost share down to 2,438.10 — a savings of 4,785.90, or roughly a 66% cut in backup energy cost for households whose consumption didn't change at all.

Net saving flips from red to black. Because diesel sits well above the grid-equivalent benchmark, every one of these eight households shows a loss under diesel — from –155.16 rupees for the lightest consumer (HH 2) to –671.98 rupees for the heaviest (HH 6), totaling –3,081.88 rupees across the group. Switch the backup source to BESS, and the same eight households turn uniformly positive: Rupees +104.01 for House 2 up to +402.33rupees for House 6, for a combined +1,704.02 rupees. That's a swing of +4,785.90 rupees— matching the backup-cost reduction almost exactly, since P2P revenue and the grid benchmark stay unchanged.

As per the analysis, both the rural cases are technically feasible.

3.4.2 Willingness to Join Swarm Grid Khario & Thario

One of the most critical points of any new model is its acceptance by the community it is installed for. The last portion of our questionnaire assessed knowledge about P2P and willingness of the locals to join a swarm grid. Figure 13 sums up the main findings from the survey. Some of the households were already informally sharing electricity with their neighbours. From a simple yes-or-no perspective, i.e., whether they would be willing to join a swarm grid, 53 percent of respondents said yes and 47 percent said no — a nearly even split. To understand the strength of this willingness, respondents were asked to rate their interest on a 1–5 scale (1 = not interested, 5 = very strongly interested). Treating a rating of 3 or above as "willing" produces an almost identical figure (53.1 percent), confirming that the two questions are consistent rather than contradictory.

However, looking at the full distribution of ratings reveals a more nuanced picture than the binary yes/no figure suggests. Responses are polarized rather than moderate: roughly a third of respondents (33%) gave the lowest rating of 1, and nearly a third (31%) gave the highest rating of 5, while only 6% chose the neutral midpoint of 3. In other words, opinion is split almost evenly between strong supporters and strong skeptics, with very few people sitting on the fence. This suggests that willingness to participate is driven by firm underlying positions — trust or distrust in shared/peer-to-peer energy arrangements — rather than by general uncertainty about the concept.

It is also worth noting that not all "high interest" responses stem from the same motivation. Some respondents expressed genuine trust in the community-sharing model, while others were skeptical of relying on their neighbors' equipment or contributions. At least one respondent — a representative from a local school — indicated strong willingness primarily because participation could bring access to better IT equipment for the institution, rather than because of confidence in the swarm grid concept itself.

Moreover, they were more interested in the concept if it develops local entrepreneurship and brings them an extra source of fixed income.

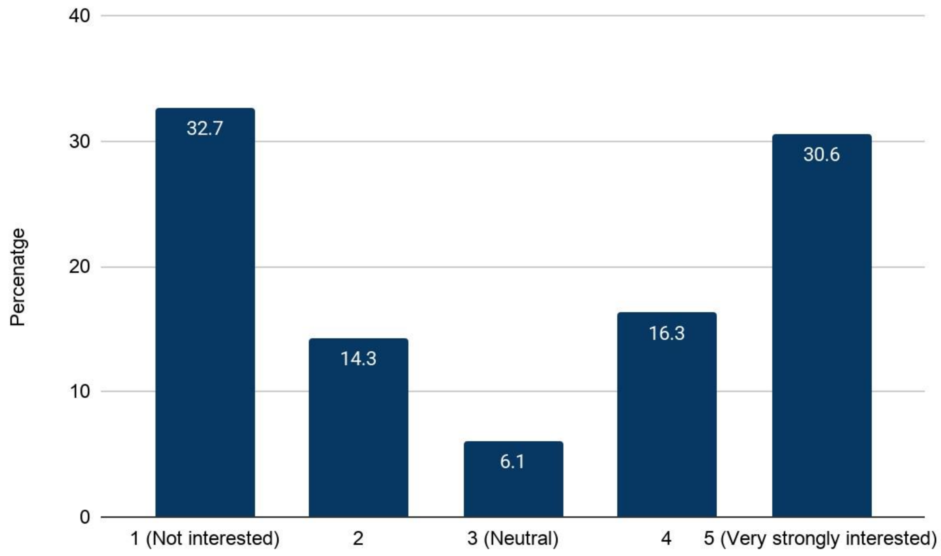


Figure 13: Willingness to Join Swarm Grid Khario & Thario

3.5- Case 2: Feasibility Analysis of an Urban Centre- Islamabad

The selection of this location is informed by the case study discussed in Chapter 1, which highlighted reverse power flow issues within the IESCO region. This challenge, compounded by the duck curve phenomenon, is commonly observed in urban centers with high solar photovoltaic (PV) penetration. Sector G-13, Islamabad, was identified as a representative site due to its notably high solar adoption rate among residential and commercial consumers.

The sector is predominantly composed of middle- to high-income households, a demographic profile often associated with greater capacity for solar PV investment. To capture a representative cross-section of energy consumption and solar usage patterns, a sample of households and nearby commercial shops within 1 KM in the sector was selected for the survey. The following battery and solar installation and demand ranges were used in the subsequent analysis.

Note that the G-13/1 and G-13/3 samples had some commercial units as well as households, but for convenience of the model, HH and participant was most commonly used to present them all.

3.5.1Sub-Cluster G-13-1 (Sector G-13, Islamabad)

This section presents the results of the Swarm Grid Simulator for Cluster G-13-1, a 4-busbar, 19-house cluster modelled within Sector G-13, Islamabad.

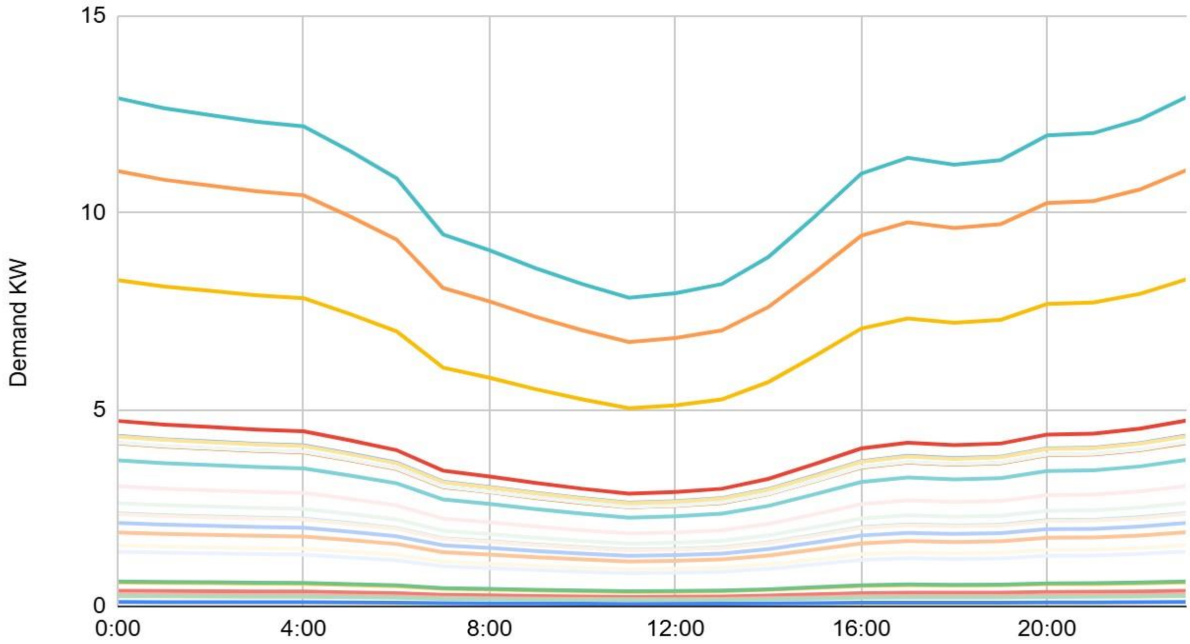


Figure 14: Hourly Electricity Load profile G-13-1

Solar PV & Battery Statistics G-13/1

Table 13: Household solar and battery stats (G-13/1)

participant	Solar Capacity (kW)	Solar Type	Battery Type
HH1	N/A	N/A	N/A
HH2	N/A	N/A	N/A
HH3	30	On-grid (Net Metered)	N/A
HH4	N/A	N/A	N/A
HH5	20	On-grid (Net Metered)	N/A
HH6	20	On-grid (Net Metered)	N/A
HH7	5	On-grid (Non-Net Metered)	N/A
HH8	N/A	N/A	N/A
HH9	N/A	N/A	N/A
HH10	5	On-grid (Net Metered)	Tubular

HH11	12	On-grid (Net Metered)	N/A
HH12	N/A	N/A	Lead Acid
HH13	N/A	N/A	N/A
HH14	N/A	N/A	N/A
HH15	20	On-grid (Net Metered)	N/A
HH16	N/A	N/A	N/A
HH17	10	On-grid (Net Metered)	N/A
HH18	5	On-grid (Net Metered)	N/A
HH19	N/A	N/A	N/A
HH20	8	Hybrid (battery + solar+ grid)	Lithium-ion
HH21	N/A	N/A	N/A
HH21	12	On-grid (Net Metered)	N/A
HH22	10	On-grid (Net Metered)	Lithium-ion
HH23	12	On-grid (Net Metered)	N/A

The above Figure 14 and Table 13 represent the household solar and battery stats as well as the load patterns. Most participants had a moderate load, with the peak reaching around 12KW for an individual household/shop. The high peak generally came from the commercial shops that were part of the survey.

Two elements of the model output are reported: (i) network load-flow snapshots, extracted at 12:00 (representative daytime and solar peak hours) and 23:00 (representative evening/night hour) and (ii) a 20-household techno-economic analysis, computed for the same representative day, covering energy balances, peer-to-peer (P2P) transactions, and cost outcomes for every participating household.

i: Network Load-Flow Snapshot

The G-13-1 network is represented as four house busbars (B20–B24), each aggregating four to five House Bus nodes, connected through a single slack source (B0) representing the point of interconnection with the IESCO distribution network. At each snapshot hour, the diagram reports the net power at every house bus after the swarm-layer merit order has been resolved, which also includes the resulting import at the slack source.

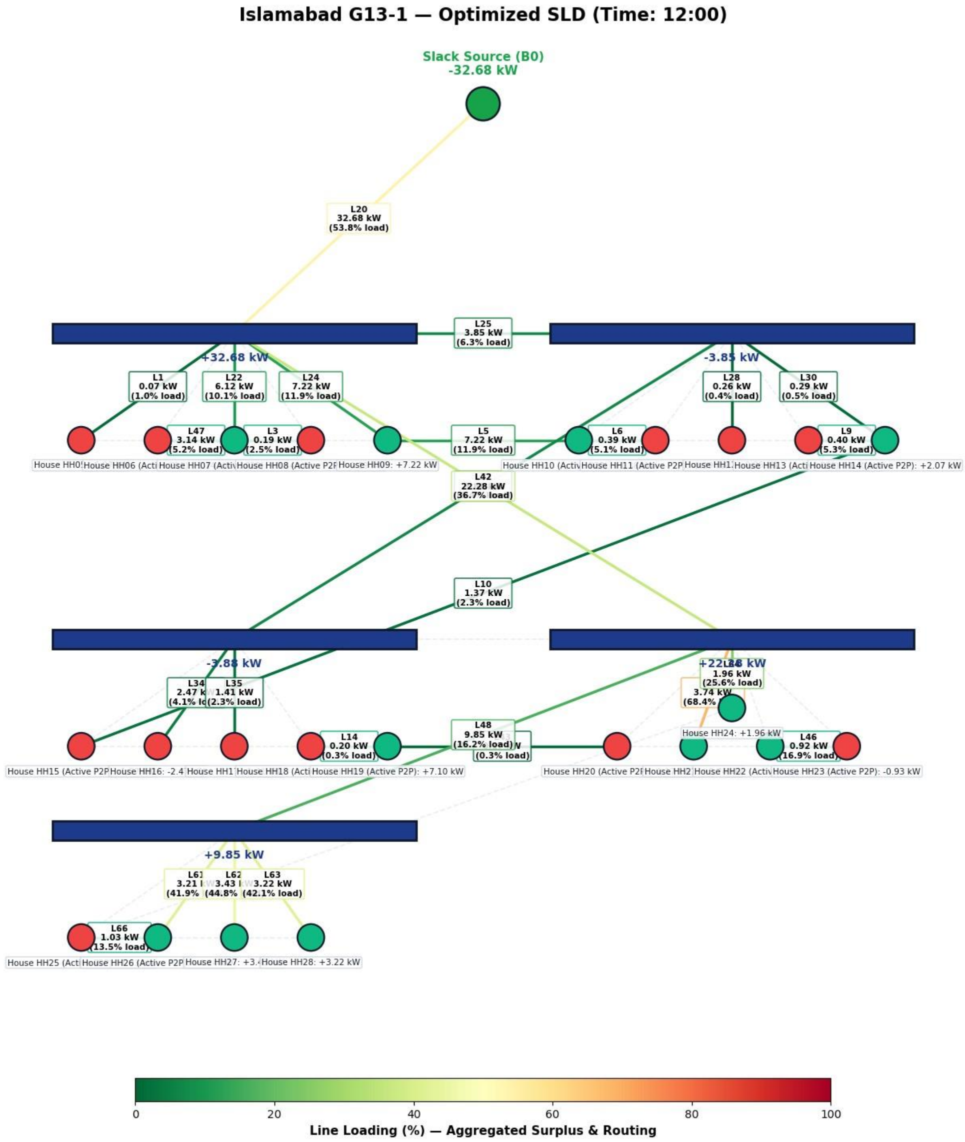


Figure 15 — G-13-1, 4-Busbar Single-Line Diagram, Snapshot 12:00.

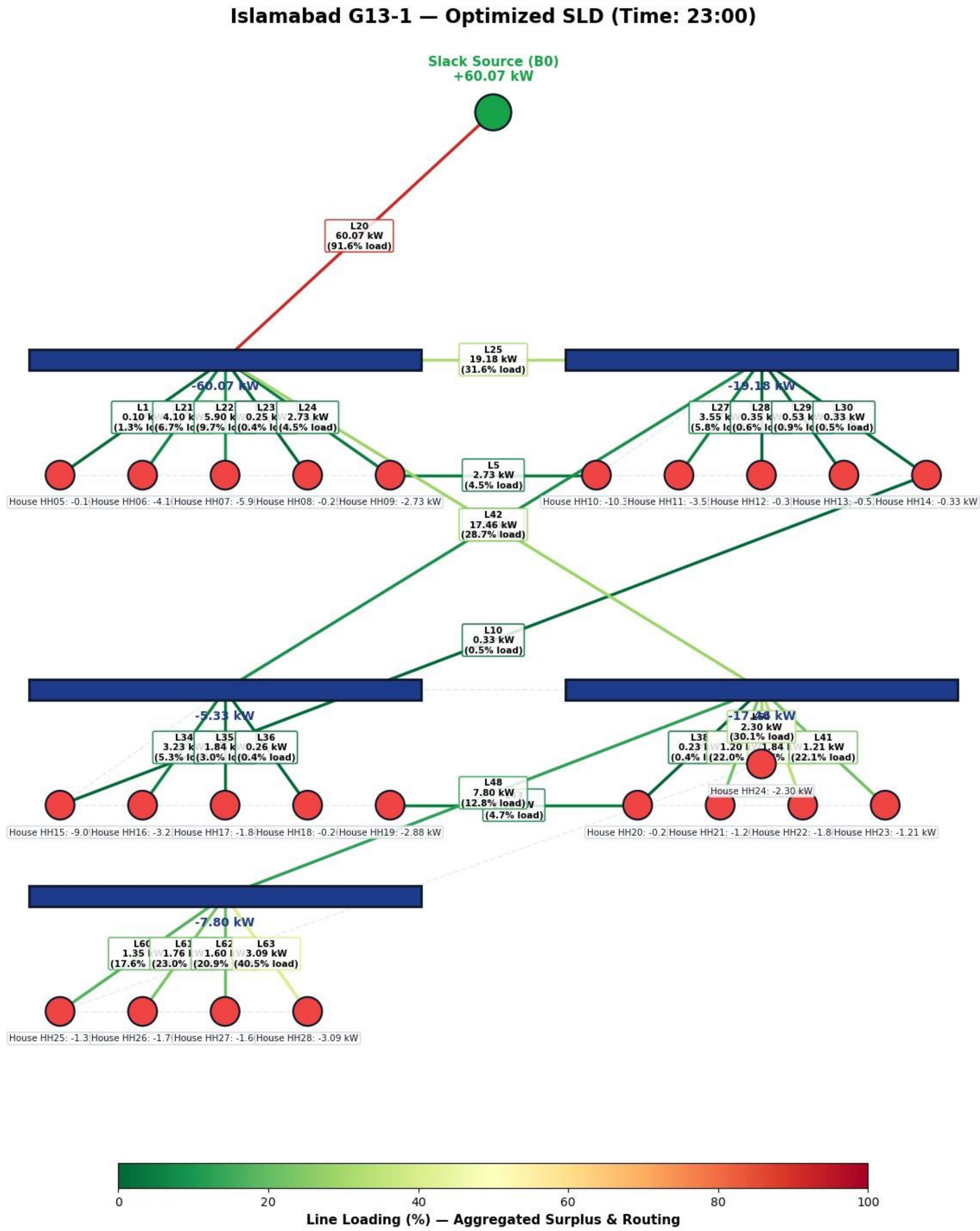


Figure 16 — G-13-1, 4-Busbar Single-Line Diagram, Snapshot 22:00

Comparison of the two snapshots shows that grid import at the slack source swings from 32.68 kW (export) at 12:00 to +60.07 kW (import) at 23:00, while individual house buses in the cluster show mixed surplus/deficit at both hours — some houses remain net importers even during the midday export period, and all houses shift to deficit by 23:00. This indicates that, for this particular representative day and this particular cluster, self-consumption and

P2P transfer reduce but do not eliminate the network's reliance on grid import, even around noon when the cluster as a whole is exporting. This finding should be read together with the cluster-level daily energy-balance profile which shows solar generation exceeding cluster load and exporting to the grid during the 09:00–16:00 window; the two results are not contradictory (the cluster can be a net exporter overall while individual buses remain net importers at the same hour, depending on how load and generation are distributed across houses).

Table 14: Household Status at Each Snapshot, Cross-Referenced with Solar/Battery Ownership (G13/1)

Participant	Solar	Battery	Net kW @12:00	Status @12:00	Net kW @23:00	Status @23:00
HH5	None	None	−0.07	Deficit — imports from grid	−0.10	Deficit — imports from grid
HH6	None	None	−3.14	Deficit — imports via P2P (from hh07)	−4.10	Deficit — imports from grid
HH7	30 kW	None	+9.4	Surplus — exports to bus (+6.12) and via P2P to H06 (+3.14) and H08 (+0.19)	−5.90	Deficit — imports from grid
HH8	None	None	−0.19	Deficit — imports via P2P (H07)	−0.25	Deficit — imports from grid
HH9	20 kW	None	+7.22	Surplus — exports to bus	−2.73	Deficit — imports from grid
HH10	20 kW	None	+0.39	Surplus — exports via P2P to H11	~−10.3	Deficit — imports from grid (large commercial night load)
HH11	5 kW	None	−0.39	Deficit — imports via P2P (from H10)	−3.55	Deficit — imports from grid
HH12	None	None	−0.26	Deficit — imports from grid	−0.35	Deficit — imports from grid
HH13	None	None	-0.40	Deficit	−0.53	Deficit — imports from grid
HH14	5 kW	4.8 kWh	+2.07	Surplus — exports to bus, incl. P2P to H13 (+0.40)	−0.33	Deficit — imports from grid
HH15	12 kW	None	-1.37	Deficit	~−9.0	Deficit — imports from grid (large commercial night load)
HH16	None	none	~−2.47	Deficit — imports from grid	~−3.2	Deficit — imports from grid

HH17	None	None	−1.41	Deficit — imports from grid	~−1.8	Deficit — imports from grid
HH18	None	None	−0.20	Deficit — imports via P2P (from H19)	~−0.2	Deficit — imports from grid
HH19	20 kW	None	+7.10	Surplus — exports to bus, incl. P2P to H18 (+0.20)	−2.88	Deficit — imports from grid
HH20	None	None	-0.166	Deficit	~−0.2	Deficit — imports from grid
HH21	10 kW	None	+3.74	Surplus — exports to bus	~−1.2	Deficit — imports from grid
HH21	5 kW	None	+0.92	Surplus — exports via P2P to H23	~−1.8	Deficit — imports from grid
HH22	None	None	−0.93	Deficit — imports via P2P (from H22)	−1.21	Deficit — imports from grid
HH23	8 kW	8kwh	+1.96	Surpl us — exports to bus	−2.30	Deficit — imports from grid
HH24	None	None	−1.03	Deficit — imports via P2P (from H26)	−1.35	Deficit — imports from grid
HH26	12 kW	None	+4.24*	Surplus — exports to bus (+3.21) and via P2P to H25 (+1.03)	−1.76	Deficit — imports from grid
HH27	10 kW	15 kWh	+3.43	Surplus — exports to bus	−1.60	Deficit — imports from grid
HH28	12 kW	None	+3.22	Surplus — exports to bus	−3.09	Deficit — imports from grid

Key patterns

1. At 12:00 pm, the cluster is mixed, not uniformly in surplus. Of 24 participants, 11 are in surplus (~46%), and 13 are already in deficit even at peak solar hours. Solar penetration does not mean universal self-sufficiency, even at midday —HHs with no PV (05, 06, 08, 12, 13, 16, 17, 18, 20, 23, 25) are structurally locked into deficit regardless of time of day, since they have no generation source at all and depend entirely on grid or P2P imports.

2. At 23:00, since solar generation is zero, every single participant is in deficit, and only the battery, grid, or P2P can serve load.

3. Deficit magnitude at night is not uniform. Most residential/small households sit around −0.10 to −1.80 kW, but HH**10** (~−10.3 kW) and HH **15** (~−9.0 kW) post deficits 5–10

times larger than the rest of the cluster — both are commercial loads (a pharmacy/bakery and a separate commercial site) with great night-time operational demand. HH**07** (−5.90 kW) and HH**06** (−4.10 kW) are also well above the rest of the houses.

4. Batteries are rare and concentrated among commercial nodes. Only three participants — HH**14** (4.8 kWh), HH **24** (8 kWh), and HH**27** (15 kWh) — have any storage, and all three post comparatively modest night deficits relative to their daytime surplus (e.g., HH 27 swings from +3.43 kW at noon to just −1.60 kW at night). This suggests storage is meaningfully flattening the evening drop for the households with batteries, while the 21 participants without batteries fall straight back to grid/P2P dependence once the sun goes down.

5. Solar-only households (surplus by day, no cushion by night) show the sharpest swings. HH07, 09, 10, 15, and 19 all post large midday surpluses (+9.4, +7.22, +0.39, +7.10 kW) purely from PV with no battery, then flip to some of the largest deficits in the table after dark (−5.90, −2.73, ~−10.3, ~−9.0, −2.88 kW). These systems drive daytime export capacity, but without storage, it does nothing to soften the household's own night-time position.

Table 14 shows a cluster where solar generation is unevenly distributed, storage is scarce and concentrated in a few nodes, and P2P exchange operates only at small, localized scale. That combination means the evening deficit — even added together across all the small households — is lower than the two large commercial night loads (HH10, HH15) alone, pointing toward grid dependence or shared/community-level storage as the likely gap-filler rather than P2P redistribution.

ii: Daily Cluster Energy-Dispatch Profile

The chart shows, for each hour of the day, where the G-13-1 cluster gets its electricity from. It shows electricity supplied by solar panels, batteries, nearby houses/commercial through P2P sharing, and the main grid. When there is extra solar power, the surplus is sent back to the grid and shown below the zero line.

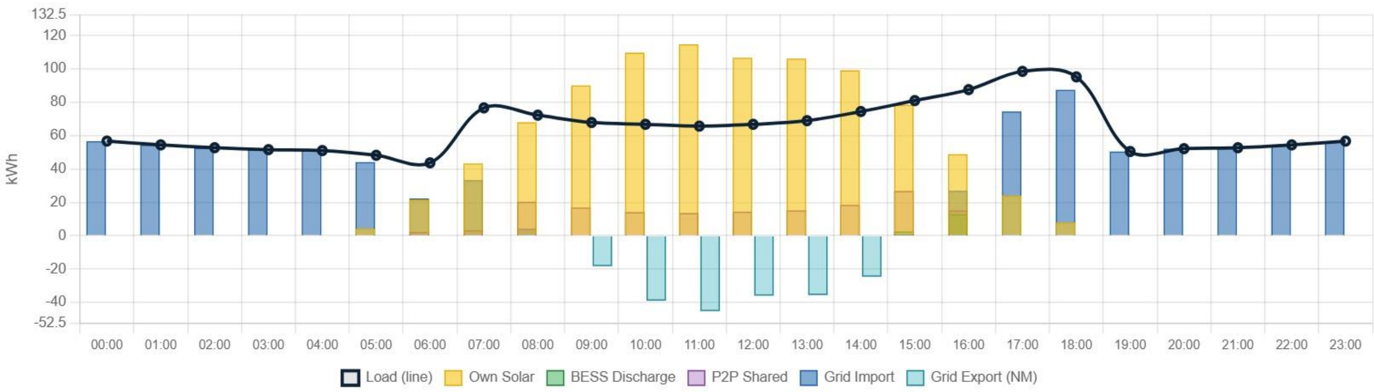


Figure 17— G-13-1 Cluster, 24-Hour Energy Dispatch Profile (Scenario 1: Grid-Connected with Net Metering).

[14] note: if our system follows the exact merit order of the swarm grid then we get the graph like this.

The cluster load is met almost entirely from the grid during the night and early-morning hours (00:00–06:00), then shifts onto solar generation. This shows the cluster becoming a net exporter to the grid between roughly 09:00 and 17:00. In this time slot, solar output exceeds the cluster's simultaneous demand. At 17:00, grid import resumes as solar output goes down and continues through the evening peak, consistent with the duck-curve pattern discussed in Chapter 1.

iii: Household-Level Economic Analysis

Table 15 below shows the household-level techno-economic simulation output for the 20 surveyed/modelled houses (participant-1 to participant-20) of the G-13-1 economic case, for the representative day used in this analysis (June profile, per Section 3.2). Figures are drawn directly from the project's economic model without alteration.

Table 15: Household economic level analysis (G-13/1)

Participant	Day Energy (kWh)	Night Energy (kWh)	Solar Gen. (kWh)	P2P Shared Out (kWh)	P2P Received (kWh)	Grid Import (kWh)	Grid Export (kWh)	Grid electricity supply cost (Rs)	NM Earnings (Rs)	Sharing Revenue (Rs)	Sharing Cost (Rs)	Net Saving (Rs/day)
HH5	1.03	1.17	0.00	0.00	0.63	1.57	0.00	66	0	0	-13	14/day
HH6	56.81	37.13	0.00	0.00	36.47	57.46	0.00	2413	0	0	-729	802/day
HH7	111.83	53.46	166.7	71.42	1.69	68.31	0.00	2869	0	1428	-34	5467/day
HH8	4.13	1.61	0.00	0.00	2.59	3.15	0.00	132	0	0	-52	57/day
HH9	46.22	36.42	111.1	39.21	0.00	39.26	28.6	1649	314	784	-0	2920/day
HH10	137.47	119.92	111.1	0.00	12.65	147.9	14.3	6210	157	0	-253	4504/day
HH11	50.30	36.06	27.78	0.00	8.93	49.64	0.00	2085	0	0	-179	1363/day
HH12	5.37	2.57	0.00	0.00	3.33	4.61	0.00	194	0	0	-67	73/day
HH13	8.40	3.72	0.00	0.00	5.19	6.93	0.00	291	0	0	-104	114/day
HH14	10.32	2.29	27.78	7.48	0.00	3.22	10.0	135	110	150	-0	654/day
HH15	108.97	111.49	66.68	0.00	14.82	139.5	0.57	5860	6	0	-296	3109/day
HH16	46.25	27.77	0.00	0.00	29.60	44.42	0.00	1865	0	0	-592	651/day
HH17	26.48	15.73	0.00	0.00	17.51	24.70	0.00	1038	0	0	-350	385/day
HH18	2.52	3.46	0.00	0.00	1.56	4.42	0.00	186	0	0	-31	34/day
HH19	60.16	25.84	111.1	11.54	0.00	32.35	45.9	1359	505	231	-0	2990/day
HH20	4.22	1.00	0.00	0.00	2.53	2.68	0.00	113	0	0	-51	56/day
HH21	25.99	11.51	55.57	5.91	0.00	14.01	26.2	588	288	118	-0	1393/day

HH21	29.78	17.32	27.78	0.00	0.25	24.67	5.60	1036	62	0	-5	999/day
HH22	17.31	10.40	0.00	0.00	10.59	17.12	0.00	719	0	0	-212	233/day
HH23	42.69	18.12	27.78	0.00	2.28	31.50	0.75	1323	8	0	-46	1194/day
HH24	16.66	14.27	0.00	0.00	9.57	21.36	0.00	897	0	0	-191	211/day
HH26	33.53	18.78	66.68	5.94	0.00	21.91	30.4	920	334	119	-0	1729/day
HH27	26.64	20.06	55.57	16.17	0.00	22.20	12.8	932	141	323	-0	1493/day
HH28	48.42	34.51	66.68	2.54	0.00	42.50	23.7	1785	261	51	-0	2009/day

Table 15 presents household-level techno-economic simulation results for 24 surveyed/modelled houses (participant-5 to participant-28) under the G-13-1 economic case, using the representative June-profile day set out in Section 3.2. In this configuration, the grid itself serves as the backup source: any shortfall after solar generation and P2P sharing is met through grid import at standard tariff, while surplus solar is exported and credited back via net metering (NM).

Two household types are visible in the data. Twelve of the households — HH-7, 9, 10, 14, 15, 19, 21, 22, 24, 26, 27, and 28 — have their own solar generation and therefore show non-zero NM earnings, sharing revenue, or both. participant-7 is the largest of these, generating 166.70 kWh of solar and sharing 71.42 kWh peer-to-peer, which brings in rupees 1,428 in sharing revenue and drives its net saving to rupees 5,467 rupees per day, the highest figure in the table. participant-9, participant-19, and participant-26 follow a similar pattern at a smaller scale, earning both NM credits.

The other twelve households — HHs -5, 6, 8, 11, 12, 13, 16, 17, 18, 20, 23, and 25 — have no solar generation of their own. Their NM earnings and sharing revenue are both zero, and they instead carry a sharing cost for the P2P energy they receive from solar-equipped neighbours

iv: Sensitivity Analysis: Cost Savings Comparison: Diesel-Backed vs. BESS-Backed P2P Sharing

The same simulations with the same assumption set with a diesel generator and BESS as a backup source were performed, and the following results were observed.

Table 16: P2P Sharing With Diesel Generator as the slack source (G-13/1)

Participant	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Diesel Received	Diesel Cost (share)	Sharing Revenue	Sharing Cost	Grid equivalent cost	Net Saving/ day
HH1	1	1	0	0	1	2	126	0	13	92	-46
HH2	57	37	0	0	37	57	4584	0	729	3945	-1368
HH3	112	54	167	71	2	68	5442	1428	34	6942	2894
HH4	4	2	0	0	3	3	251	0	52	241	-62
HH5	46	36	111	39	0	39	3133	784	0	3471	1122
HH6	137	120	111	0	13	148	11800	0	253	10810	-1243
HH7	50	36	28	0	9	50	3961	0	179	3627	-512
HH8	5	3	0	0	3	5	367	0	67	333	-100
HH9	8	4	0	0	5	7	553	0	104	509	-148
HH10	10	2	28	7	0	3	256	150	0	530	423
HH11	109	111	67	0	15	139	11140	0	296	9259	-2177
HH12	46	28	0	0	30	44	3543	0	592	3109	-1026
HH13	26	16	0	0	18	25	1970	0	350	1773	-548
HH14	3	3	0	0	2	4	354	0	31	251	-134
HH15	60	26	111	12	0	32	2577	231	0	3612	1266
HH16	4	1	0	0	3	3	214	0	51	219	-45
HH17	26	12	56	6	0	14	1116	118	0	1575	577
HH18	30	17	28	0	0	25	1968	0	5	1978	5
HH19	17	10	0	0	11	17	1366	0	212	1164	-414
HH20	43	18	28	0	2	31	2511	0	46	2554	-3
HH21	17	14	0	0	10	21	1706	0	191	1299	-598
HH22	34	19	67	6	0	22	1747	119	0	2197	569

HH23	27	20	56	16	0	22	1771	323	0	1961	514
HH24	48	35	67	3	0	42	3390	51	0	3483	143

Economically, the DG-based case is unfeasible due to high operational and fuel costs exceeding grid-equivalent tariffs.

Table 17: P2P Sharing With BESS as the slack source (G-13/1)

Participant	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Common BESS Received	Daily CB cost share	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving
HH1	1	1	0	0	1	2	42	0	13	92	37
HH2	57	37	0	0	36	57	1551	0	729	3945	1665
HH3	112	53	167	71	2	68	1844	1428	34	6942	6492
HH4	4	2	0	0	3	3	85	0	52	241	104
HH5	46	36	111	39	0	39	1060	784	0	3471	3195
HH6	137	120	111	0	13	148	3992	0	253	10810	6565
HH7	50	36	28	0	9	50	1340	0	179	3627	2108
HH8	5	3	0	0	3	5	124	0	67	333	142
HH9	8	4	0	0	5	7	187	0	104	509	218
HH10	10	2	28	7	0	3	87	150	0	530	592
HH11	109	111	67	0	15	140	3767	0	296	9259	5196
HH12	46	28	0	0	30	44	1199	0	592	3109	1318
HH13	26	16	0	0	18	25	667	0	350	1773	756
HH14	3	3	0	0	2	4	119	0	31	251	101
HH15	60	26	111	12	0	32	873	231	0	3612	2969
HH16	4	1	0	0	3	3	73	0	51	219	96
HH17	26	12	56	6	0	14	378	118	0	1575	1315
HH18	30	17	28	0	0	25	666	0	5	1978	1307
HH19	17	10	0	0	11	17	462	0	212	1164	490

HH20	43	18	28	0	2	32	851	0	46	2554	1658
HH21	17	14	0	0	10	21	577	0	191	1299	531
HH22	34	19	67	6	0	22	592	119	0	2197	1724
HH23	27	20	56	16	0	22	600	323	0	1961	1685
HH24	48	35	67	3	0	43	1148	51	0	3483	2386

The two tables compare the economic performance of a 24-household decentralized energy system under two configurations: (i) diesel-generator (DG)-based supply and (ii) solar PV integrated with a common battery energy storage system (BESS). The main distinction is that the DG case relies heavily on diesel generation to meet residual demand, whereas the BESS case stores and redistributes available solar energy, reducing dependence on diesel and lowering the cost of electricity supply.

1. DG-based case

The first table 16 presents the energy flows and economic outcomes when the system uses a diesel generator as the primary backup source. Each household's daily demand is divided into daytime and nighttime consumption. Solar generation is available for some households, and surplus solar energy is shared with other households through the P2P mechanism.

Participants with solar generation—particularly Participants (3, 5, 10, 15, 17, 18, 22, 23, and 24)—can share part of their excess generation with other households. This generates P2P sharing revenue for the supplying Participants while reducing the amount of energy that must be supplied through diesel generation. However, households without sufficient solar generation continue to rely substantially on diesel.

The major economic problem is the high diesel fuel cost. For example, Participant 6 incurs a diesel cost share of 11,800 rupees, while HH 11 incurs 11,140 rupees. Consequently, despite the revenue obtained from P2P electricity sharing, many households record negative net savings. Only a limited number of solar-producing households achieve positive savings, with HH3 achieving the highest net saving of 2,894.38 rupees.

Overall, the DG configuration demonstrates that P2P energy sharing alone is insufficient to overcome the high operating and fuel costs associated with diesel generation. The negative net savings observed for a large proportion of households indicate that the DG-based configuration is economically unattractive compared with the grid-equivalent supply cost.

2. BESS-based case

The second Table 17 introduces a common BESS, which allows excess solar generation to be stored and subsequently supplied to households when solar generation is unavailable, particularly during nighttime hours. The table therefore replaces the large diesel dependence of the previous case with a common BESS energy allocation and its associated daily cost share.

The impact is substantial. The common BESS reduces the need for diesel generation, while the cost of stored energy is distributed among participating Participants. Importantly, all 24 Participants show positive net savings under this configuration.
Solar-producing Participants continue to benefit from P2P trading. For instance, HH 3 generates 166.7 units of solar energy, shares 71.42 units through P2P, earns 1,428.4 rupees in sharing revenue, and achieves a net saving of 6,492.41. Even participants without their own solar generation benefit because they can access stored energy through the common BESS at a lower effective cost than the grid-equivalent alternative.

The BESS therefore changes the economic structure of the system: rather than using diesel to compensate for the temporal mismatch between solar generation and household demand, solar energy can be shifted from periods of surplus generation to periods of higher demand.

3.5.2: P2P (Grid as a backup) vs Net Metering vs Net Billing

The net-metered households in this cluster share 358.95 units through P2P, generating 7179 rupees in revenue at the assumed P2P rate of 20/unit. If the same quantity were instead exported to the grid, revenue would be 3948.45 rupees in total under net billing at 11 rupees per unit and 8973.75 rupees in total under net metering at 25 rupees per unit.

Thus, net metering provides the highest direct revenue, approximately 20% higher than P2P, while net billing provides roughly 45 percent lower revenue than P2P.

	Net Metering @ Rs 22/kWh (Rs/day)	P2P Saving (Rs/day)	Net Billing @ Rs 11/kWh (Rs/day)	P2P Advantage vs NM	P2P Advantage vs NB
HH7	1785.5	1428.4	785.62	-357.1	642.78
HH9	1694	1355.2	745.36	-338.8	609.84
HH10	356.25	285	156.75	-71.25	128.25
HH14	437.25	349.8	192.39	-87.45	157.41
HH15	14.25	11.4	6.27	-2.85	5.13
HH19	1437	1149.6	632.28	-287.4	517.32
HH21	801.75	641.4	352.77	-160.35	288.63
HH22	140	112	61.6	-28	50.4
HH24	18.75	15	8.25	-3.75	6.75
HH26	907.25	725.8	399.19	-181.45	326.61
HH27	725.25	580.2	319.11	-145.05	261.09
HH28	656.5	525.2	288.86	-131.3	236.34
Total	8973.75	7179	3948.45	-1794.75	3230.55

Table 18: P2P (Grid as a backup) vs Net Metering vs Net Billing

The results therefore indicate that P2P is economically more attractive than low-rate net billing but somewhat less attractive than net metering for the individual prosumer. Nevertheless, unlike grid export, P2P keeps the electricity within the local energy network, allowing the surplus generated by prosumers to directly serve other households. **Table 19: P2P vs Standalone solar home systems**

Scenario	Total Export/Shared Energy	Rate	Total Revenue	Difference vs P2P
P2P	358.95	20	7179	—
Net Billing	358.95	11	3948.45	3230.55
Net Metering	358.95	22	8973.75	-1794.75

The G-13-1 results provide direct, cluster-level evidence for two of the problems defined in Chapter 1. First, the household table shows that P2P transfer redistributed 358 kWh of solar generation directly between neighbouring houses on the representative day, energy that, in the absence of a swarm arrangement, would either have been exported to the grid under net metering (as occurs for the remaining 198.74 kWh, 21.5% of total solar generation) or remain unused. One important point noted here is that when we make a standalone system, our P2P units do not denote only the unit shared by each other. In fact, this unit is shared by each other and the grid export unit.

Second, the economic table shows that P2P sharing revenue (3,204 Rupees day, concentrated in a small number of prosumer households such as HH07, HH09, HH27 and HH 19) and netmetering earnings (2,186 rupees per day) both flow disproportionately to houses with larger installed solar capacity, while every house, including those with little or no solar of their own, such as HH05, HH06, HH08, HH12, HH13, HH16 and HH20, records a positive net saving relative to a grid-only baseline. This is consistent with the swarm-grid logic set out in Section 1.1: prosumers recover part of their investment by selling surplus generation locally, while non-solar and low-solar households gain access to cheaper electricity than continuous gridonly supply, without bearing the upfront cost of their own installation.

For the swarm grid simulator, we use a peer-to-peer tariff is 20 rupees per unit because majority of responded purpose that they will join the swarm grid network if this network provide the tariff of peer to peer tariff averagely 20 rupees per unit and use the grid import and export tariff according to NEPRA tariff.

The 12:00 and 23:00 load-flow snapshots (Section 3.8.1), read together with the 24-hour dispatch profile (Section 3.9), indicate that individual houses in the cluster show mixed surplus/deficit behaviour at 12:00 — with some houses remaining net importers even during the midday export period — while at 23:00 every house and bus revert to deficit and draw from the grid. This distinction between individual-house behaviour and cluster-level surplus is a useful diagnostic for sizing any future common-BESS or common-solar component (Scenario 3): it suggests that a shared storage asset sized to the cluster's mid-day surplus could reduce the number of individual houses drawing on the grid during peak evening hours, and is flagged here as a candidate follow-on analysis.

3.5.3 Sub-Cluster G-13-3 (Sector G-13, Islamabad)

This section reports results for Cluster G-13-3, a second urban sample within Sector G-13, Islamabad, complementing the G-13-1 results presented in the previous Sections. The underlying sample comprises 14 surveyed households (HH 1 to HH 14), for which both a solar/battery asset profile and a full techno-economic simulation are available. The network load-flow model represents the same cluster as an extended busbar diagram with 15 housebus nodes (HH1–HH15) across three busbars (B20–B22) plus one additional.

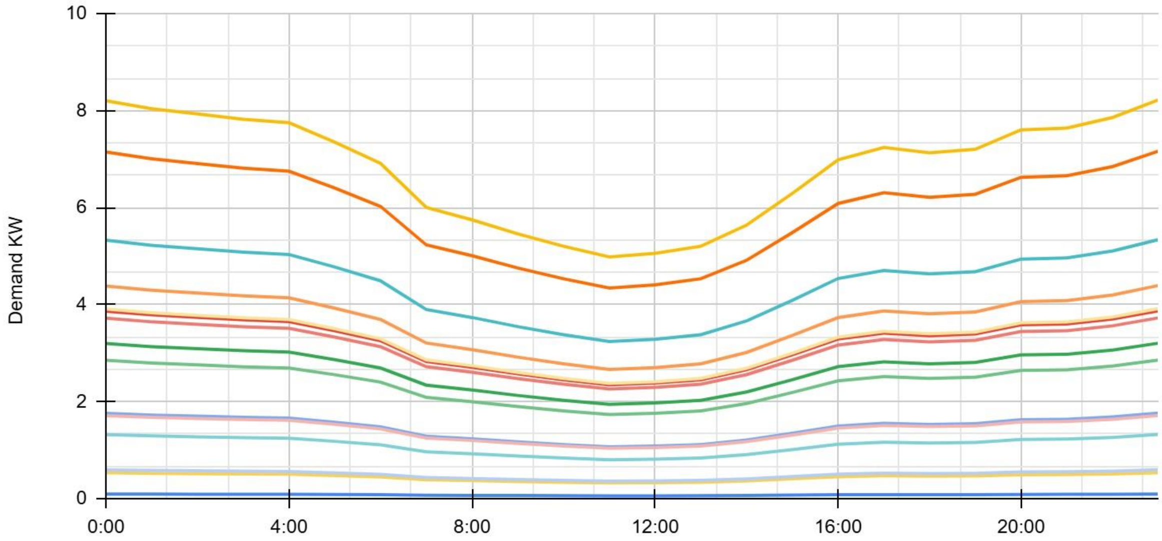


Figure 18: Hourly Electricity Load Profile G13-3

The above Figure 18 and Table 20 below represent the household solar and battery stats as well as the load profile. Out of the 15 households, about 20 percent are high-load (peak 5–8 kW), 40 percent medium-load (peak approximately 2–5 kW), and 40 percent low-load (peak under 2 kW). The single highest individual peak demand recorded is 8.2 kW, coming from one of the high-load households.

Household Solar & Battery Asset Profile

The following Table 20 and Figure 18 above are the situational overview of the load and generation for the region obtained from the data from the survey.

Table 20: Household solar and battery stats (G-13/3)

Name	Solar Capacity (kW)	Solar Type	Battery Type	Battery Capacity
HH1	N/A	N/A	N/A	N/A
HH2	N/A	N/A	N/A	N/A
HH3	30	On-grid (Net Metered)	N/A	N/A

HH4	N/A		N/A	N/A
HH5	20KW	On-grid (Net Metered)	Lithium-ion	25kWh
HH6	N/A		N/A	N/A
HH7	15 KW	On-grid (Net Metered)	N/A	N/A
HH8	15KW	On-grid (Net Metered)	N/A	N/A
HH9	N/A		N/A	N/A
HH10	12KW	On-grid (Net Metered)	Lithium-ion	15 kWh
HH11	7KW	On-grid (Net Metered)	Tubular	10kWh
HH12	5KW	Hybrid (battery + solar+ grid)	Tubular	8KWh
HH13	N/A		N/A	N/A
HH14	12KW	Hybrid (battery + solar+ grid)	Lithium-ion	18kWh

i: Network Load-Flow Snapshots

As with G-13-1, two snapshots were extracted from the 24-hour dispatch engine: 12:00 (daytime) and 22:00 (nighttime).

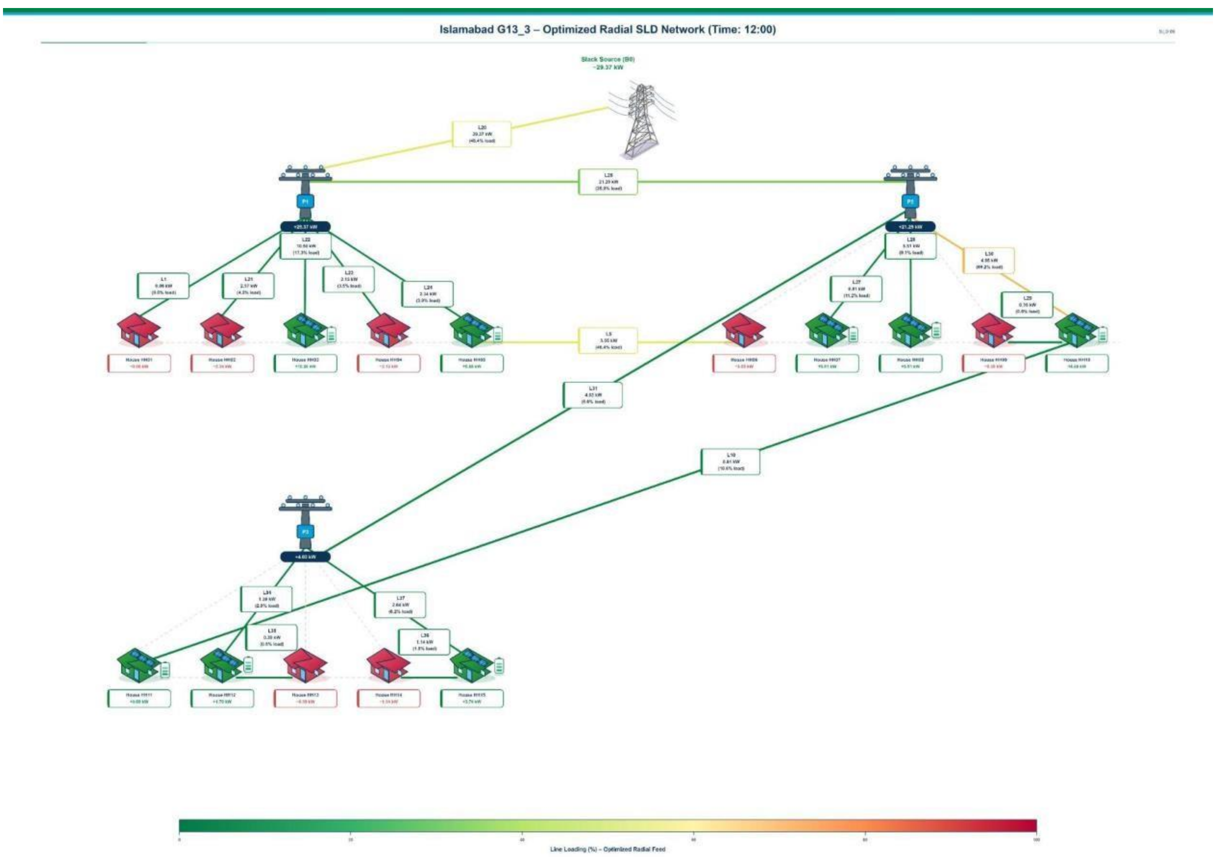


Figure 19 — G-13-3, SLD Network, Snapshot 12:00.

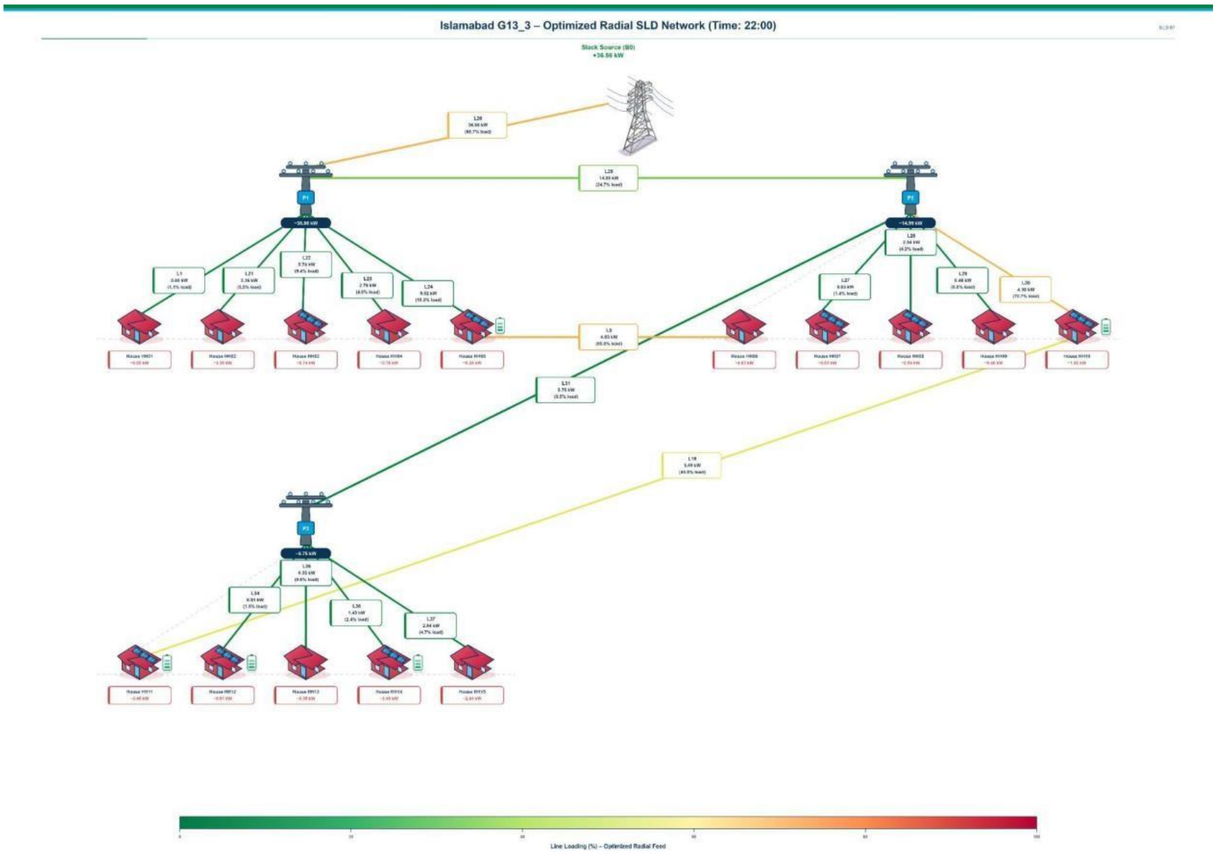


Figure 20 — G-13-3, Extended Busbar Orthogonal SLD, Snapshot 22:00. Grid Import: 36.0 kW.

Table 21 — Household Status at Each Snapshot, Cross-Referenced with Solar/Battery Ownership

#	Household	Solar	Battery Storage	Net kW @12:00	Status @12:00	Net kW @22:00	Status @22:00
1	HH1	None	None	**-0.1**	Deficit — imports from grid/P2P	**-0.1**	Deficit — imports from grid/P2P
2	HH2	None	None	**-2.5**	Deficit — imports from grid/P2P	**-3.3**	Deficit — imports from grid/P2P
3	HH3	30 kW	None	**10.5**	Surplus — exports to network	**-5.7**	Deficit — imports from grid/P2P
4	HH4	None	None	**-2.1**	Deficit — imports from grid/P2P	**-2.7**	Deficit — imports from grid/P2P
5	HH5	20 kW	Li-ion, 25 kWh	**5.88**	Surplus — exports to network	**-5.28**	Deficit — imports from grid/P2P
6	HH6	None	None	**-3.5**	Deficit — imports from grid/P2P	**-4.6**	Deficit — imports from grid/P2P

7	HH7	15 kW	None	**6.81**	Surplus — exports to network	**-0.8**	Deficit — imports from grid/P2P
8	HH8	15 kW	None	**5.51**	Surplus — exports to network	**-2.5**	Deficit — imports from grid/P2P
9	HH9	None	None	**-0.3**	Deficit — imports from grid/P2P	**-0.4**	Deficit — imports from grid/P2P
10	HH10	12 kW	Li-ion, 15 kWh	**4.49**	Surplus — exports to network	**-1.92**	Deficit — imports from grid/P2P
11	HH11	7 kW	Tubular, 10 kWh	**0.8**	Deficit — imports from grid/P2P	**-3.4**	Deficit — imports from grid/P2P
12	HH12	5 kW	Tubular, 8 kWh	**1.78**	Deficit — imports from grid/P2P	**-0.9**	Deficit — imports from grid/P2P
13	HH13	None	None	**-0.3**	Deficit — imports from grid/P2P	**-0.5**	Deficit — imports from grid/P2P
14	HH14	12 kW	Li-ion, 18 kWh	**-1.1**	Deficit — imports from grid/P2P	**-1.4**	Deficit — imports from grid/P2P

Table 21 below lists, for each of the 14 sampled households, whether the household owns a rooftop solar system and/or battery storage, drawn directly from the household equipment survey. 9 Participant(HH3, HH5, HH7, HH8,HH10, HH11,HH12 and HH14) out of 14 Participants report owning a solar PV system, ranging from 5 kW to 30 kW installed capacity, and, 5 solar households (HH5, HH10, HH12 and HH14) report owning battery storage (a mix of lithiumion and tubular lead-acid batteries, 8–25 kWh). The remaining 5 participants (HH1, HH2, HH4, HH6, HH9 and HH13) report neither solar nor battery and are fully grid-dependent.

Reading the two columns together shows a consistent, physically sensible pattern. At 12:00, the six houses in surplus are HH5 (20 kW solar + battery), HH7 (15 kW solar), HH8 (15 kW solar), HH10 (12 kW solar + battery), and HH3(30kW solar). All three identified surplus houses are solar owners, and their solar generation at noon(solar peak hours) exceeds their own load by enough to export into the network — exactly the behaviour the swarm grid model is intended to capture. By 22:00, every household in the sample, including all five houses that own battery storage, has returned to a net deficit; this is consistent with the 3–5 hour backup duration reported for these batteries in the household survey, One result merits particular attention: participant03 holds the single largest installed solar capacity in the sample (30 kW) but is in deficit, not surplus, at 12:00 (−9.2 kW). This is because participant03's combined day-and-night household demand (152.14 kWh) exceeds his solar generation (111.13 kWh). The premises are in fact a commercial gym rather than a residential household.

ii: Daily Cluster Energy-Dispatch Profile

The chart below aggregates the 24-hour dispatch engine's output for the full G-13-3 cluster under Scenario (grid-connected, net metering).

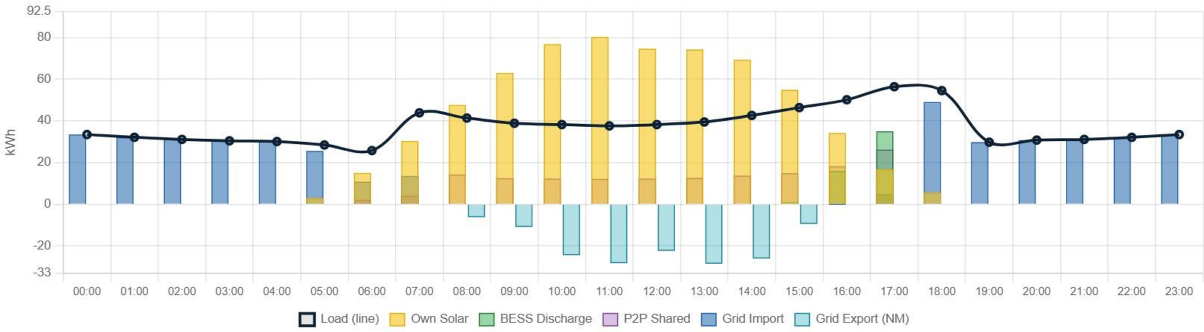


Figure 22— G-13-3 Cluster, 24-Hour Energy Dispatch Profile

As shown in Figure 22, G-13-3, the cluster gets its electricity from the grid during the night. From around 07:00, solar generation starts meeting more of the load. During the middle of the day, solar produces more electricity than the cluster needs, so the extra power is exported to the grid. In the evening, solar generation decreases, and the cluster starts importing electricity from the grid again. This creates the same duck-curve pattern discussed in Chapter 1, but here it is shown for this specific 14-household cluster.

iii: Household-Level Economic Analysis

Table 22 below reproduces, in full, the household-level techno-economic simulation output for the 14 households of the G-13-3 sample, for the representative day used throughout this analysis. The empirics are drawn directly from the project's economic model.

Table 22: Household-level economic analysis

Particip ant	Day Energy (kWh)	Night Energy (kWh)	Solar Gen. (kWh)	P2P Shared Out (kWh)	P2P Receiv ed (kWh)	Grid Import (kWh)	Grid Export (kWh)	Cost of Grid electricity supply	NM Earning s (Rs)	Sharing Revenue (Rs)	Sharing Cost (Rs)	Net Savings by replacing grid with solar (Rs/day)
HH1	1.56	1	0	0	1.42	1.13	0	48	0	0	-28	**31**
HH2	54.91	35.76	0	0	54.9	35.7	0	1500	0	0	-1099	**1209**

HH3	103.69	48.46	166.7	75.37	16.0	46.1	1.38	1939	15	1507	-321	**5653**
HH4	37.96	30.64	0	0	36.2	32.3	0	1360	0	0	-724	**797**
HH5	68.64	57.74	111.1	30.66	5.34	53.2	26.41	2234	291	613	-107	**3871**
HH6	49.14	36.79	0	0	46.9	39.0	0	1639	0	0	-938	**1032**
HH7	14.62	5.13	83.35	28.36	0.5	4.7	40.44	198	445	567	-10	**1634**
HH8	40.2	28.57	83.35	7.72	4.55	27.3	38.7	1146	426	154	-91	**2231**
HH9	7.33	4.17	0	0	6.27	5.23	0	220	0	0	-125	**138**
HH10	29.84	25.07	66.68	18.33	0.06	22.0	24.58	925	270	367	-1	**2016**
HH11	48.9	33.21	38.9	4.44	5.63	35.7	0	1499	0	89	-113	**1925**
HH12	15.76	10.97	27.78	8.58	0	9.65	6.53	405	72	172	0	**961**
HH13	18.2	16.96	0	0	14.4	20.8	0	872	0	0	-288	**317**
HH14	36.3	33.69	66.68	19.25	0.4	29.3	18.02	1232	198	385	-8	**2283**

Table 22 presents a **household-level energy and financial assessment of a decentralized solar and** peer-to-peer (P2P) energy-sharing system across 14 houses. It compares each household's daytime and nighttime electricity demand with its solar generation, P2P energy transactions, and interaction with the conventional grid. Table 22 also quantifies the resulting financial benefits, including grid electricity costs, net-metering (NM) earnings, P2P sharing revenues and costs, and the overall daily savings achieved by replacing grid electricity with locally generated solar energy.

The results show considerable variation among households depending on their electricity demand and solar capacity. Houses without solar generation remain primarily dependent on grid electricity and P2P energy received from other households, while solar-equipped households can meet part of their own demand, share surplus electricity through P2P transactions, and export excess generation to the grid. House 3 records the highest daily net savings of 5,653 rupees, followed by HH 5 (3,871 rupees), HH 14 (2,283rupees), and HH (

2,231rupees). Overall, Table 22 demonstrates that combining rooftop solar, P2P energy sharing, and net metering can substantially reduce household dependence on grid electricity and improve the economic value of distributed renewable energy.

The G-13-3 sample reinforces the G-13-1 findings with an added layer of household-level explanatory detail. The surplus solar generation is concentrated in exactly the households that own solar PV. and that the advantage of battery ownership in HH5, and HH10) is time-limited to a few hours after sunset given the 3–5 hour backup durations reported in the survey. This provides a clear illustration of the potential benefits of swarm-grid P2P energy sharing during daytime operation, when four to five houses simultaneously have surplus generation available for sharing. In contrast, during nighttime operation, all houses shifted back to grid import. This highlights the role of coordinated P2P energy exchange in improving the utilization of locally available surplus energy within the swarm grid.

Economically, the cluster recorded a total net saving of Rs 24,660 per day across the 14 participants, with an average of 1761 per day per household. This saving accrues to solar and non-solar households alike. Five out of the nine non-solar households (HH1, HH2, HH4, HH6, HH9, HH13) still register a positive net saving purely through P2P access and reduced grid tariff exposure.

As per the analysis, both the urban cases are technically feasible.

iv: Sensitivity Analysis: Cost Savings Comparison: Diesel-Backed vs. BESS-Backed P2P Sharing

The same simulations with the same assumption set with a diesel generator and BESS as a backup source were performed, and the following results were observed.

Table 23: P2P Sharing With Diesel Generator (G-13/3)

Participants	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Diesel Received	Diesel Cost (share)	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving
HH1	1.6	1	0	0	1.4	1.1	88	0	28	107.5	-8.5
HH2	54.9	35.8	0	0	54.97	34.5	2757.6	0	1099	3808.1	-48.5
HH3	103.7	48.5	166.7	75.4	16.0	44.1	3529.6	1507	321	6390.	4047
HH4	37.96	30.6	0	0	36.2	31.5	2521.6	0	724	2881.z	-364.4
HH5	68.6	57.7	111.1	30.7	5.34	51.9	4148	613	107	5307.9	1666.2
HH6	49.1	36.8	0	0	46.9	37.9	3033.6	0	938	3609.06	-362.5
HH7	14.6	5.1	83.4	28.4	0.5	4.5	362.4	567	10	829.5	1024.3
HH8	40.2	28.6	83.4	7.7	4.6	26.5	2122.4	154	91	2888.34	829.3
HH9	7.3	4.2	0	0	6.3	5.1	404.8	0	125	483	-46.8
HH10	29.8	25.1	66.7	18.3	0.06	21.5	1718.4	366	1	2306.2	953.4

HH11	48.9	33.2	38.9	4.4	5.6	34.7	2773.6	889	113	3448.6	650.8
HH12	15.8	10.97	27.8	8.6	0	9.4	748	171	0	1122.6	546.3
HH13	18.2	16.96	0	0	14.4	20.4	1628	0	288	1476.7	-439.3
HH14	36.3	3379	66.7	19.3	0.4	28.6	2290.4	385	8	2939.58	1026.2

Table 24: P2P Sharing With BESS (G-13/3)

House	Day Energy (07:00–18:59 · 12 h)	Night Energy (19:00–06:59 · 12 h)	Solar Generation	P2P Shared Out	P2P Received	Common BESS Received	Daily CB cost share	Sharing Revenue	Sharing Cost	Gridequivalent cost	Net Saving
HH1	1.56	1	0	0	1.42	1.13	30.51	0	28.4	107.52	48.61
HH2	54.9	35.8	0	0	54.97	35.71	964.17	0	1099.4	3808.14	1744.57
HH3	103.7	48.5	166.7	75.37	16.03	46.16	1246.32	3334	320.6	6390.3	8157.38
HH4	37.9	30.6	0	0	36.22	32.38	874.26	0	724.4	2881.2	1282.54
HH5	68.6	57.7	111.1	30.66	5.34	53.2	1436.4	2222.6	106.8	5307.96	5987.36
HH6	49.1	36.8	0	0	46.9	39.02	1053.54	0	938	3609.06	1617.52
HH7	14.6	5.1	83.4	28.36	0.5	4.71	127.17	1667	10	829.5	2359.33
HH8	40.2	28.6	83.4	7.72	4.55	27.29	736.83	1667	91	2888.34	3727.51
HH9	7.3	4.2	0	0	6.27	5.23	141.21	0	125.4	483	216.39
HH10	29.8	25.1	66.7	18.33	0.06	22.03	594.81	1333.6	1.2	2306.22	3043.81
HH11	48.9	33.2	38.9	4.44	5.63	35.7	963.9	778	112.6	3448.62	3150.12
HH12	15.8	10.97	27.8	8.58	0	9.65	260.55	555.6	0	1122.66	1417.71
HH13	18.2	16.96	0	0	14.4	20.77	560.79	0	288	1476.72	627.93
HH14	36.3	33.7	66.7	19.25	0.4	29.32	791.64	1333.6	8	2939.58	3473.54

With Diesel Generator

This scenario evaluates the 14-household system when diesel generation is used to meet the remaining electricity demand that cannot be supplied through solar generation, P2P energy sharing, or the grid. The results show that households without solar generation generally experience negative net savings, as the relatively high cost of diesel generation outweighs the benefits of P2P energy sharing. HH 1, 2, 4, 6, 9, and 13 therefore record net losses ranging from approximately 8 to 439 rupees per day. In contrast, solar-generating households benefit from both solar generation and P2P energy sales, with House 3 achieving the highest net saving of 4,047 rupees per day, followed by HH 5 at 1,666 rupees day. Overall, the results demonstrate that reliance on diesel significantly increases the cost of supplying nighttime and residual electricity demand and reduces the economic benefits of decentralized renewable energy.

With Battery Energy Storage System (BESS)

The BESS scenario demonstrates the economic advantage of using a common battery energy storage system to store surplus solar generation and supply electricity when solar production is unavailable. Compared with diesel generation, the BESS substantially reduces the cost of meeting nighttime demand while allowing greater utilization of locally generated solar energy. As a result, all 14 households achieve positive net savings, with HH 3 recording the highest saving of Rs 8,157/day, followed by HH 5 at Rs 5,987rupees per day, HH 8 at Rs 3,728 rupees per day, and HH 14 at 3,474 rupees per day. Even households without their own solar generation benefit from access to the shared BESS through lower-cost energy availability compared with diesel generation. The results therefore indicate that communitylevel battery storage can significantly improve the economic performance of a decentralized solar-P2P system while reducing dependence on expensive diesel-based backup generation.

3.6.2:P2P (Grid as a backup) vs Net Metering vs Net Billing

Using the data above, we can make a basic daily comparison of P2P sharing, conventional net metering at Rs 25/kWh, and net billing at Rs 11/kWh for the eight net-metered households.

Table 25: P2P (Grid as a backup) vs Net Metering vs Net Billing

HH	Net Metering @ Rs 22/kWh (Rs/day)	P2P Saving (Rs/day)	Net Billing @ Rs 11/kWh (Rs/day)	P2P Advantage vs NM	P2P Advantage vs NB
3	1918.75	1535	844.25	-383.75	690.75
5	1426.75	1141.4	627.77	-285.35	513.63
7	1720	1376	756.8	-344	619.2
8	1160.5	928.4	510.62	-232.1	417.78
10	1072.75	858.2	472.01	-214.55	386.19
11	111	88.8	48.84	-22.2	39.96
12	377.75	302.2	166.21	-75.55	135.99
14	931.75	745.4	409.97	-186.35	335.43

Total	8719.25	6975.4	3836.47	-1743.85	3138.93

The net-metered households in this cluster share 348.77 units through P2P, generating 6975.4 rupees in revenue at the assumed P2P rate of 20/unit. If the same quantity were instead exported to the grid, revenue would be 3836.47 under net billing at 11/unit and 8719.25 rupees under net metering at 25/unit.

Thus, net metering provides the highest direct revenue, approximately 20% higher than P2P, while net billing provides roughly 45% lower revenue than P2P.

This highlights an important distinction: P2P is particularly valuable when surplus solar can be sold directly to other households at a rate that captures more value than simply exporting it to the grid. Where a household has a large surplus and receives a relatively favorable netmetering rate, conventional net metering can remain competitive. This pattern is also very different from G-13/1 results, as we see better revenue from P2P, so this also means that the revenue depends upon both demand and generation.

3.6.3: Willingness to Join Swarm Grid- Willingness to participate in a virtual power plant

The results from the ground survey show a clear preference for the Swarm Grid model over the VPP model — nearly two-thirds of respondents are willing to join a Swarm Grid, while the VPP model faces strong resistance, with about three-quarters of respondents unwilling to participate. We observed during the survey that people trust their neighbors, but a significant trust deficit remains between the citizens and the government. This suggests the Swarm Grid concept has significantly stronger grassroots buy-in in urban areas, which is a meaningful signal for prioritizing it as the near-term rollout model over a VPP structure.

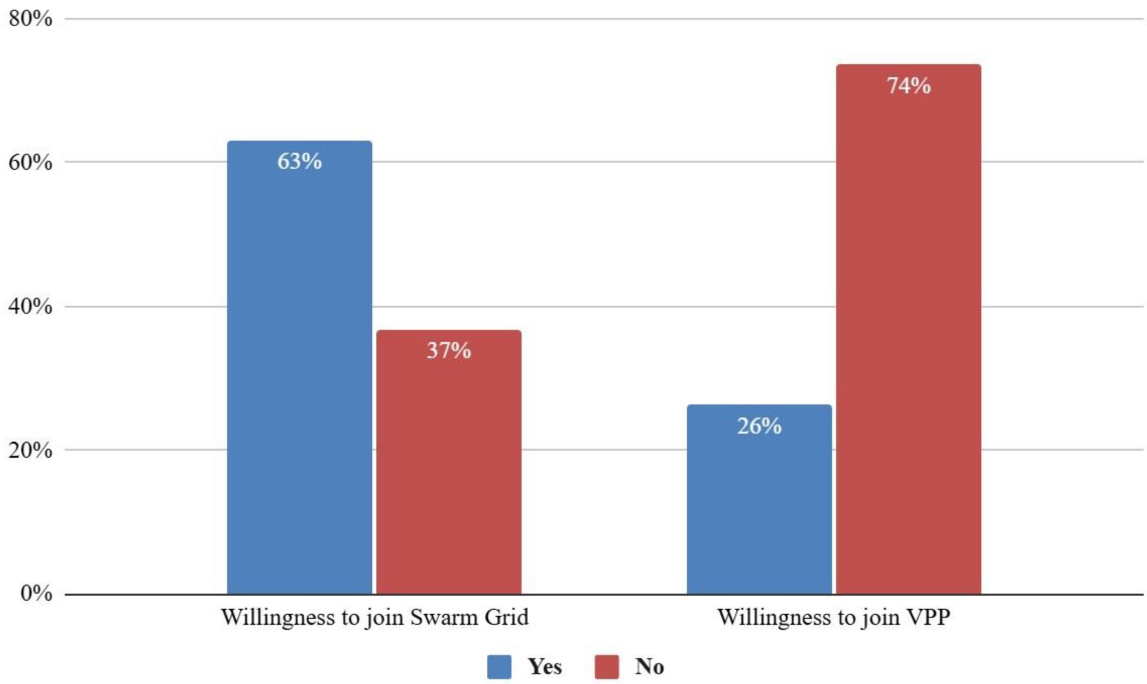


Figure 23: Comparison of willingness to join a swarm grid or a virtual power plant

Chapter 4: SOLBOX

SOLbox[15] is a machine-to-machine (M2M) and IoT-enabled, bi-directional DC smart electricity meter developed by SOLshare (Bangladesh) that serves as the interconnection node of a peer-to-peer (P2P) solar micro-grid. Operating at 12V DC (up to 1000W in its nextgeneration version), it performs two layered functions simultaneously: at the **M2M level**, it continuously senses its own node's real-time energy surplus or deficit and automatically routes power directly to or from neighboring SOLboxes on the local micro-grid — executing and settling trades via mobile money (e.g., bKash) without any human negotiating each exchange; at the **IoT level**, it stays connected to SOLshare's cloud backend (SOLweb), continuously reporting usage and trading data for remote monitoring, fault detection, and fleet-wide analytics across all deployed micro-grids. In short, M2M is what lets each SOLbox make autonomous, real-time trading decisions with its immediate neighbors, while IoT is what lets SOLshare centrally monitor, manage, and improve the entire network of boxes at scale — together turning a cluster of standalone rooftop solar systems into a self-balancing, remotely supervised local energy market.

The wider system built around the SOLbox is often called SOLbazaar or the SOLgrid, comprising three layers: the SOLbox (hardware node), the SOLapp (customer/payment management), and SOLweb (the backend platform for monitoring, analytics, and dynamic pricing). SOLshare refers to "swarm electrification".

2. How It Functions

- **Interconnection:** SOLboxes at neighboring households/businesses are wired together over low-voltage DC lines (historically 12V/24V DC, with a newer 1000W "SOLbox NG" generation for higher loads), forming a local P2P micro-grid independent of the national grid. But for the urban cases we study, we can develop an IOT device with a better power factor and higher voltage.
- **Bi-directional metering:** Each SOLbox continuously measures import and export at that node, so a household with solar surplus can push power out to the shared line, while a deficit household can pull power in — the same behavior seen in the swarm-

[15] [1] SOLshare — SOLgrid: P2P microgrid technology overview — https://solshare.com/solgrid/
[2] Siemens Stiftung — SOLbox: Empowering People Network profile — https://empowering-people-network.siemensstiftung.org/solutions/solbox/
[3] Andan Foundation — SOLshare/SOLbox program description — https://www.andan.org/livelihood-economic-inclusion-1/solshare
[4] The Business Standard — "SOLshare: Using the Uber model to share solar power" — https://www.tbsnews.net/feature/panorama/solshare-using-uber-model-share-solar-power-195445
[5] Grameen Shakti / SOLshare — UNDESA Solar PV Program for Rural Areas presentation — https://www.un.org/sites/un2.un.org/files/2020/11/grameen_shakti-_solshare_presentation.pdf
[6] SOLshare — 2020 Annual Report (definitions, swarm electrification, impact figures) — https://solshare.com/wpcontent/uploads/2022/07/2020_SOLshare_Annual_Report-1.pdf
[7] ScienceDirect — "Peer to peer solar energy sharing system for rural communities" (feasibility study, IoT-enabled P2P) — https://www.sciencedirect.com/science/article/pii/S2772783123000523
[8] Allume Energy — unrelated "SolShare" AC solar-splitting product (for disambiguation only) — https://allumeenergy.com/uk/howsolshare-works-technical-uk/

grid tables in the above sections (surplus nodes exporting to bus/neighbors; deficit nodes importing via P2P or grid).

- **Automated trading:** The M2M(Machine-to-Machine) layer detects real-time supply/demand imbalances and routes electricity between nodes without manual intervention, prioritizing the cheapest/nearest available surplus before falling back to the grid or diesel backup.
- **Mobile-money settlement:** Every kWh traded is priced and settled automatically through mobile financial services (e.g., bKash in Bangladesh), so surplus producers ("prosumers") are paid directly, and deficit consumers pay only for what they draw — converting a normal net-metering "savings" model into an actual income stream.
- **Roles in the network:** SOLshare defines three participant types — Prosumers (own an SHS, both produce and consume), Producers (net sellers), and Consumers (no SHS, buy only) — mirroring the surplus/deficit household roles seen in swarm-grid data.

3. Where It Is Functional

- **Bangladesh (core market):** the origin and largest deployment. Reporting from SOLshare and UNDESA's "Solar PV Program for Rural Areas" puts the network at roughly 500+ SOLboxes across 20+ P2P micro-grids, reaching 4,000+ beneficiaries, with 40% of end-users being women and children.
- **Refugee and displacement settings:** SOLshare has piloted SOLbox-based micro-grids in Rohingya refugee camps in Cox's Bazar, Bangladesh, extending electrification to displaced populations with no formal grid access.
- **India:** SOLshare has cited early-stage/pilot expansion of the P2P model into rural India, alongside Bangladesh, as regions where mini-grid electricity is otherwise unavailable.
- **Broader South Asia relevance:** the swarm-grid data we've been analyzing (Pakistani households/commercial nodes trading solar surplus and deficit via P2P) reflects the same underlying architecture and economic logic SOLshare pioneered — solar-rich nodes exporting to solar-poor or high-load neighbors, settled through a shared ledger rather than the public grid.

Note: a separate, unrelated product also named "SolShare" is sold by Allume Energy (Australia/UK/US) — an AC-side device that splits a single embedded solar system across multiple separately-metered apartments in multi-tenant buildings. It solves a different problem (behind-the-meter solar splitting within one building) and is not a P2P trading platform between independent prosumers)

4. **Evidence, Impact Data & References**

Documented outcomes from SOLshare's SOLbox deployments (SOLshare/UNDESA/Siemens Stiftung reporting):

- P2P trading has delivered ~75 MWh of additional energy to 600+ households and microbusinesses.
- Prosumers selling surplus energy earned additional income of roughly USD $16,000 cumulatively from ~24–25 MWh of energy sold.

- 95+ microbusinesses (including women-owned businesses) reported additional income worth over USD $6,000 through reliable energy access.
- 84% of end-users live on less than USD $5/day, underscoring the base-of-the-pyramid target segment.
- Academic modeling of comparable rural P2P solar-sharing systems (peer-reviewed, IoT-enabled architectures) found P2P sharing increased community self-sufficiency by ~13.7% and self-consumption by ~11.2% versus isolated household systems — directionally consistent with the pattern in your swarm-grid tables, where P2P closes small local gaps but cannot fully offset large deficits without storage or grid backup.

4:1:Tariff Structures for Electricity Trade

The final input parameters of the model incorporate a set of tariffs governing electricity trade within the swarm grid. Five tariff structures are implemented, each suited to different consumer profiles, income patterns, and grid conditions.

i: Pay-as-You-Go (PAYG) Model

The Pay-as-You-Go tariff is a flexible pricing model in which consumers pay only for the electricity they actually consume, with no fixed or base charges applied. This structure is especially significant for low-income and rural communities where affordability is a primary barrier to energy access. Because users prepay for energy credits before consumption, the model eliminates the risk of debt accumulation and keeps financial exposure low.

Beyond affordability, PAYG functions as an implicit demand-side management (DSM) tool. Since consumers are spending from a finite prepaid balance, they naturally become more conscious of their consumption habits, which helps regulate load on the grid. This makes it particularly well-suited to communities with irregular or seasonal income patterns, where committing to fixed monthly payments would be impractical.[14] **ii. Subscription-Based Model**[15]

The Subscription-Based tariff structure bills consumers on the basis of three distinct cost components: a fixed price, an energy cost, and an overconsumption cost.

The fixed price consists of two parts: a flat annual fee that applies regardless of the subscription tier chosen, and a subscription fee that varies depending on the capacity tier the consumer selects. The energy cost is intentionally kept low and constant, designed only to recover the marginal operating cost of the grid rather than generate surplus revenue. The overconsumption charge is applied when a consumer's power import exceeds their subscribed capacity limit, and its purpose is to deliver a short-term price signal that encourages the consumer to reduce their demand and stay within their chosen tier. This pricing structure

[14] https://documents1.worldbank.org/curated/en/687851468320946678/pdf/93786-REVISED-LW34-fin-logoOKR.pdf
[15] https://www.researchgate.net/publication/330557459_Testing_Time-of-Use_and_Subscription_based_grid_tariff_structures_using_a_Prosumer_model#pf16

economically motivates consumers to either adjust their consumption habits or invest in battery energy storage to remain in their subscription tier.

iii. Commission-Based Model (Platform Fees)

The Commission-Based model operates as a platform fee applied to peer-to-peer (P2P) energy transactions within the swarm grid. Rather than charging a fixed or consumptionbased fee, the operator levies a small percentage, typically between 1% and 5%, on the value of each energy transaction settled through the platform. This model imposes no fixed financial commitment on participants, making it accessible to prosumers who trade surplus generation intermittently. Revenue to the operator scales directly with trading activity, meaning it is best suited to grids with active and frequent P2P energy exchange.

iv. Hybrid Billing Model

The Hybrid Billing Model combines multiple charge streams into a single integrated billing framework. It draws together P2P energy trading prices, battery storage access fees, and grid backup standby charges, each billed as a distinct component. This structure is designed for more complex swarm grid communities where consumers, prosumers, and storage owners all interact. While the Hybrid model offers the most comprehensive cost recovery mechanism for operators, it places greater demands on consumer financial literacy and requires a more sophisticated metering and billing infrastructure.

v. Dynamic Time-of-Use (d-TOU) Tariff [16]

The Dynamic Time-of-Use tariff is a time-differentiated pricing structure in which the operator sets different energy prices based on anticipated demand patterns, informed by historical load data and the grid's generation profile. Since peak demand periods typically occur in the morning hours and the post-work evening period places the greatest strain on the grid, prices during these windows are set higher to discourage non-essential consumption. Conversely, off-peak hours carry lower prices, encouraging consumers to shift flexible loads away from congested periods.

A key advantage of this model is that the price signal reflects the condition of the grid as a whole, not just the behaviour of any individual consumer. The dynamic-TOU model is also considered more intuitive for consumers, since billing is based on energy consumed in kilowatt-hours (kWh) rather than power capacity in kilowatts (kW) as done in the subscription model, and involves fewer cost components to track.

The tariff is structured around three LCOE-derived pricing tiers:

- **Off-peak hours** — nominal electricity prices, reflecting low demand and high renewable availability

[16] https://www.researchgate.net/publication/330557459_Testing_Time-of-Use_and_Subscription_based_grid_tariff_structures_using_a_Prosumer_model#pf16

- **Mid-peak hours** — mid-range prices, reflecting moderate grid stress
- **Peak hours** — the highest prices, applied during periods of maximum demand

The specific tariff values within each tier are determined by a combination of factors: the timezone-based renewable generation profile, the observed load profile, operations and maintenance (O&M) costs, and non-technical miscellaneous costs such as employee wages and salaries, cabling, metering equipment, and accessories.

4.2:What Our Model Suggests: (For Grid as the slack source)

The proposed model is a commission-based tariff for a swarm grid operating company. Rather than charging participants a fixed subscription or consumption-based fee, the operator earns a small commission — typically 1–5% — on the value of every peer-to-peer (P2P) energy transaction settled through the platform; in our case, this will be part of the PKR 20/KWh received by the prosumer. Prosumers trading surplus solar generation pay nothing upfront; the seller shares a small portion of the agreed per-unit rate with the operator to cover platform maintenance and margin. Operator revenue scales directly with P2P trading activity, making the model best suited to grids with active, frequent energy exchange.

In the pilot cluster, buyers and sellers have agreed on a real, live P2P rate of Rs 20/unit (this is not an illustrative figure — it is the operating tariff). Beneath this commission layer sits a second, capital-heavy cost: transmission & distribution (T&D) infrastructure, which must largely be built out before transaction volume is sufficient to fund it. Commission revenue (or investor bridge capital) is what carries the operator through this pre-revenue infrastructure phase.

Figures below are drawn from one swarm grid cluster of 14 houses of G-13/3, for a single day. The urban demand case is modelled on peak summer conditions (June); a winter/off-peak demand profile has not yet been collected, so an annualized revenue model cannot be built yet.
8 of the 14 houses have solar generation; P2P commission revenue is driven by prosumer density, not house count alone — this ratio should be treated as a pilot-stage assumption, not a scaling constant.

Table 25: Cluster Snapshot (14 houses, 1 summer day(June), G-13/3)

Metric	Total
Solar generation (kWh)	644.6
P2P energy shared out (kWh)	192.7
P2P energy received (kWh)	192.7

Gross P2P transaction value (Rs) @ Rs 20/unit	3,854
Net metering earnings (Rs)	1,717
Cost of equivalent grid supply (Rs)	15,217
Net household savings vs. all-grid case (Rs)	24,098

Table 26: Commission Revenue — Pilot Scale At
Rs 3,854 gross P2P value/day for this cluster:

Commission rate	Daily revenue (Rs)	Monthly revenue (Rs)	Annual revenue (PKR)*
1%	38.5	1,156	14,067
3%	115.6	3,469	42,201
5%	192.7	5,781	70,336

**Annualised by straight-line extrapolation of the June figure only — treat as an upper-bound placeholder until winter demand data is available.*

4. Scaling Logic (Urban Case)[19]

Holding pilot transaction density constant (~Rs 275 traded/house/day):

Cluster size	Gross P2P value/day (Rs)	Commission/day @ 1–5% (Rs)
100 houses	27,530	275 – 1,377
1,000 houses	275,300	2,753 – 13,765

This commission stream is what an investor would weigh against T&D + platform capex to derive a payback period. Two qualifiers to state plainly to investors: (i) this is a single-day, single-cluster, summer-peak sample — not a validated annual model; (ii) revenue will be seasonal, tracking solar output, and a low/high season range is needed once winter data exists.

[19] **How the Scaling Table numbers were derived:Step 1 — Gross P2P value (independent of commission rate)** Take the pilot's average transaction density and scale it by house count:

- Pilot: Rs 3,854 traded ÷ 14 houses = **Rs 275.3/house/day**
- 100 houses → 275.3 × 100 = **Rs 27,530/day**
- 1,000 houses → 275.3 × 1,000 = **Rs 275,300/day**

This is just "if every house trades like the pilot houses did, how much total value flows through the platform" — the 1–5% commission rate plays no part in this number. **Step 2 — Commission (1–5% applied *to* the gross value from Step 1)**

- 100 houses: 1% of 27,530 = Rs 275 → 5% of 27,530 = Rs 1,377 → range **275–1,377**
- 1,000 houses: 1% of 275,300 = Rs 2,753 → 5% of 275,300 = Rs 13,765 → range **2,753–13,765**

So the table shows the total transaction pie first (Step 1), then how much of that pie the operator keeps at 1% vs. 5% (Step 2). The commission rate never changes the gross column — it only determines the split between operator revenue and seller net proceeds.

Rural Case — A different financing mechanism

The commission model above assumes participants can absorb a small transaction-based fee, which holds for urban prosumers with disposable purchasing power. The rural case is structurally different: rural households generally lack the purchasing power to sustain a feebearing commercial P2P market on their own.

For rural swarm grids, the bankable case is therefore not commission revenue but carbon market financing. The business case rests on positioning the rural swarm grid as an emissions-displacement asset — displacing fossil fuel grid generation with solar P2P exchange — and monetising that displacement through climate finance instruments (carbon credits, results-based climate funds, or blended concessional capital). Climate finance would need to substitute for the commission stream that carries the urban model, effectively subsidising the T&D build-out and early operations until (or unless) local purchasing power and trading volumes rise enough to sustain a fee-based layer.

The swarm grids- especially for the urban case- can be a new revenue stream if the retail market is opened. This will be a new business model for private grid or solar companies to step in.

Chapter 5: Conclusion & Recommendations

This study examines whether a swarm-grid model based on distributed solar generation, peer-to-peer (P2P) electricity trading, flexible demand, and localized energy exchange can be implemented in Pakistan from technical, economic, and institutional perspectives.

The analysis indicates that swarm grids are technically feasible, including in the rural and urban cases examined. The results demonstrate that distributed prosumers can exchange electricity locally and that P2P arrangements can improve the utilization of locally generated solar electricity. However, technical feasibility alone does not ensure commercial or institutional viability. The economic attractiveness of the model depends significantly on the regulatory framework, electricity tariffs, market arrangements, and the availability of appropriate financial incentives.

The analysis also indicates that the rural case requires greater economic support for the model to become commercially viable. This does not necessarily imply that permanent subsidies are required; rather, targeted fiscal incentives, transitional support mechanisms, or other appropriate policy instruments may be required to address the initial economic barriers associated with establishing distributed energy networks. The precise form and duration of such support should be determined through further regulatory and financial assessment rather than assumed in advance.

To put it simply, swarm grids are a technically feasible solution in Pakistan once they receive the required regulatory support and appropriate financial incentives. Based on our analysis, there are a few key recommendations from our end:

1. **Develop entirely new regulations for P2P trading**, including clear rules for participation, transactions, settlement, and responsibilities of the different actors.
2. **Develop and enforce standards for solar equipment** installed on the distribution network, with appropriate penalties for installations that do not comply with NEPRAapproved standards.
3. **Open the retail electricity market** to allow greater participation of prosumers and consumers and facilitate new electricity trading models.
4. **Address remaining reverse power flows.** As per our analysis, reverse power flow is still present in the urban case even after introducing P2P trading. Where technically feasible, this excess power could be redirected toward **EV charging stations and other flexible loads**.
5. **Encourage EV charging during solar peak hours** by providing appropriate signals to EV users as well as prosumers, thereby increasing electricity consumption during periods of high solar generation.
6. **Promote swarm electrification** as a distributed and sustainable energy asset. Such systems can also contribute to energy-system resilience during major disruptions, including supply shocks or other crises.
7. **Develop flexible business models for swarm-grid participants** that provide greater flexibility to both prosumers and consumers. For example, revenue-maximization mechanisms could reward a prosumer who supplies electricity to the grid during

   peak hours before charging their own battery, potentially through a higher tariff or incentive.
8. **Swarm-grid operators should seek to minimize transmission and operational costs** by maximizing local consumption and efficiently coordinating distributed generation, storage, EVs, and flexible demand.
9. **Make swarm-grid operations more gender-inclusive** by providing training to both men and women in households on how to operate, maintain, and manage the relevant systems and technologies.

10. **Strengthen demand-side management** by shifting flexible electricity loads toward periods of higher solar generation.

11. Digitize the Distribution Network. (It is very crucial for p2p, vpp etc.It will allow the real time monitoring and control of the assets)

12. Start with a pilot under regulatory sandboxing, instead of waiting for perfect market and conditions

Annexure1: Detailed Methodology

A 1.1: Methodology

With these objectives set, the next step is to explain how they were actually pursued. This study employs a mixed-methods approach, combining qualitative and quantitative analyses to develop a comprehensive case for electrification through swarm grids in Pakistan. The methodology is designed to assess household electricity needs, evaluate community willingness to adopt swarm grids, and compare the techno-economic feasibility of swarm grids against standalone solar home systems. Additionally, the potential of swarm grids as a decentralized, market-responsive model suited to Pakistan's current energy transition context is assessed. The steps are outlined below, beginning with the qualitative groundwork that informs everything that follows. 1. Qualitative Analysis

a. Literature Review

The qualitative work starts with the literature to ground the study in what is already known before any new data is collected. A targeted review of global swarm grid models was conducted to establish a foundational understanding of decentralized rural electrification models and their application in similar socio-economic contexts. The literature review included:

- Academic and technical studies on swarm grids, mini-grids, and solar home systems globally, with emphasis on their application in rural South Asia and Sub-Saharan Africa.
- Policy and regulatory documents on rural electrification in Pakistan, including NEPRA guidelines on mini/micro grids as well as national renewable energy policies and targets.

b. Primary Data Collection

Building on that literature base, the study then turned to primary data collection in the field to ground the analysis in real household conditions rather than assumptions drawn from other contexts. Fieldwork was conducted in two villages — Khario and Thario (Thar district). The primary reason to assess Thar as a case study was the abundant high solar irradiance in the area, as well as the scattered population with a very large class divide, and therefore an accessibility divide present between households.

Sample size: 51 participants.

For the urban case study, the survey was conducted across the commercial and residential areas in G-13, Islamabad. The reason for choosing this area was essentially the high solar penetration in this sector.

Sample size: 55 participants.

Data collection: A semi-structured questionnaire focused on:

- Socio-economic condition of the areas
- Basic household electricity consumption assessment for low, medium, and high demand segments
- Existing solar PV installations and system performance
- Willingness to join swarm grids and perceived benefits/barriers
- Willingness to participate in a virtual power plant in the urban area

2. Quantitative Analysis

With the qualitative picture in place, the field data was also carried into the quantitative stage of the study, where it was translated into numbers that could be compared and tested.

a. Techno-Economic Feasibility Assessment

Using the primary data collected from the two villages, PRIED's team developed real-world demand and cost profiles to compare the technical and financial performance of swarm grids under three different scenarios:

- Swarm grids with the grid as a backup
- Swarm grids with diesel generators as a backup
- A proposed swarm grid model with optimized solar and BESS installations b. Key

  Evaluation Metrics

To make these three scenarios comparable, each one was scored against the same set of metrics:

- Energy flow patterns
- Electricity generation profiles based on the installed systems and the irradiance profile of the areas
- P2P sharing revenue
- Net savings by replacing grid power usage with swarm grid power supply
- Efficiency gains — optimized usage of power generated by individual solar home systems

c. Data Analysis Tools

Calculating these metrics by hand across three scenarios and two case-study sites would not have been practical, so a dedicated tool was built to run the numbers consistently.
Developed an interactive HTML/JavaScript-based energy simulation tool (“Swarm Grid Simulator”) to model peer-to-peer (P2P) energy sharing within a residential cluster, capable of evaluating three operational scenarios — grid-connected net metering, diesel generator

backup, and common Battery Energy Storage System (BESS) with shared solar — for a configurable cluster of houses.

- Back-end programming: Implemented the complete simulation logic in JavaScript, including an hourly (24-hour) dispatch engine that sequentially resolves selfconsumption, individual house battery charge/discharge, inter-house P2P energy transfer, and scenario-specific backup dispatch (grid import/export, diesel generation, or common BESS supply) for each hour of the day.
- Irradiance profile: Built the solar model on site-specific NASA POWER Global Horizontal Irradiance (GHI) data, with representative daily irradiance profiles compiled for each calendar month of the year, allowing the tool to be adapted to any location by substituting its local irradiance dataset. Since the analysis in this project was based on load survey data collected for June (Islamabad urban case) and April (Thar Rural case), the June and April irradiance profiles were used to simulate a representative day of that month. Similarly, for the Thar case, where the survey was conducted in April, the corresponding April irradiance profile was used to run the simulation, ensuring that the solar generation estimates in each case reflect the seasonal conditions matching the actual survey period.
- Solar generation profile: Derived hourly PV output/generation for each house's rooftop system (and for an optional shared common solar array) from the irradiance data, incorporating a tilt-angle (30° for Islamabad) correction factor, system efficiency (calculated based on inverter degradation factor and overall electrical losses), and panel degradation factor (due to dust and tilt angle), scalable to any installed capacity (kWp).
- Seasonal variation analysis: Incorporated a full year of monthly irradiance data (January–December) into the tool, enabling generation of month-wise solar generation graphs and comparison of seasonal solar generation trends across the year, independent of the single-month scenario used for the present analysis.
- Load profile modelling: Constructed configurable hourly load profiles from surveybased day-energy and night-energy (kWh) inputs, distributing consumption across 12-hour day and night windows using residential, commercial, or flat load shape patterns.
- Battery Energy Storage System (BESS) modelling: Modelled both individual houselevel batteries and a shared common BESS, incorporating hourly state-of-charge (SoC) tracking, round-trip efficiency, depth-of-discharge (DoD) limits, and charge/discharge power-rate constraints.
- Diesel generator modelling: Modelled cluster-level diesel backup generation, accounting for generator capacity (kVA), power factor, minimum load factor, specific fuel consumption (L/kWh), and fixed operation and maintenance (O&M) cost.
- Techno-economic analysis: Computed per-house and cluster-level energy costs and savings across all three scenarios using configurable grid tariff, net metering rate, and

P2P sharing rate, including diesel fuel cost, BESS capital cost, and payback period estimation for BESS versus diesel backup.

- Scenario and parametric sensitivity analysis: Enabled sensitivity analysis of system performance by allowing variation of key input parameters — cluster size, analysis month, tariff structure, diesel generator specifications, and BESS specifications — to observe their impact on self-sufficiency, effective cost per kWh, and energy curtailment.
- Data visualization: Generated dynamic, interactive charts for hourly energy flow, individual house dispatch profiles, and battery SoC trends, along with detailed hourly dispatch tables and P2P sharing matrices for each scenario.

A 1. 2. Synthesis of Findings

Once the qualitative and quantitative strands were both complete, the final step was to bring them back together. By integrating the qualitative field data with the quantitative techno-economic analysis, the study aims to:

- Identify the most viable electrification scenario for rural (Thar) and urban (Islamabad) cases based on cost, efficiency, and community acceptance.
- Provide recommendations for scaling swarm grid models in Pakistan.
- Highlight policy and financing interventions required under which swarm grids can scale.

The flowchart below summarises the overall methodological approach for this study.

A1.3: A Feasibility Design for Swarm Grids in Pakistan

Having outlined how the study was carried out, the discussion now turns to what that methodology was actually applied to: the two settings chosen to test swarm grids in Pakistan. The two distinct case studies focused on a rural context, examining how swarm grids can enhance electrification and expand reliable electricity access. The second explores an urban setting with a high penetration of distributed solar PV (DSPV), evaluating the feasibility of swarm grids in such environments.

In urban centres, swarm grids present a compelling opportunity — not only to mitigate reverse power flow challenges and address high electricity tariffs, but also to enable community-driven demand-side management. By facilitating localized coordination of generation and consumption, swarm grids can improve grid stability, optimize energy use, and empower consumers to play an active role in managing their energy systems. For the rural case, swarm grids can act as a value-addition measure for the communities by developing local entrepreneurship.

A 1.3.1 Analysis

With the rural and urban contexts established, attention now shifts to the simulator itself, the tool that turns those contexts into comparable numbers. This section explains the analytical and programming logic behind the Swarm Grid Simulator, focused on how solar and battery data are turned into hourly generation statistics, how the peer-to-peer (swarm) grid architecture is structured, how the hour-by-hour dispatch loop is built, and how the three backup scenarios differ. Before going into the details, the key technical terms used throughout the model are defined below so that the rest of the analysis can be read without ambiguity.

A 1.3.2 Technical Terminology

Term	Definition
GHI (Global Horizontal Irradiance)	The total solar radiation (direct + diffuse), measured in Wh/m² per hour, received on a horizontal surface at a given location. It is the raw solar-resource input from which panellevel electricity generation is derived.
kWp (kilowatt-peak)	The rated (nameplate) output of a solar PV array under standard test conditions; used as the sizing unit for both household-level rooftop solar and the shared common solar array.
Tilt Factor (F_tilt)	A correction multiplier applied to horizontal irradiance to account for the gain obtained by mounting panels at an inclined angle instead of flat; it peaks at the site's optimum tilt (30° for Islamabad) and reduces at shallower or steeper angles.
System Efficiency (η)	The combined derating applied to account for inverter conversion losses, DC/AC wiring losses, and other balance of system losses between the panel output and usable electricity.
Degradation Factor	A multiplier (<1) that accounts for the gradual loss of panel output over time due to dust accumulation, soiling, and cell ageing.
State of Charge (SoC)	The instantaneous energy stored in a battery, expressed as a percentage (or kWh) of its rated capacity; tracked hour by hour for both house-level batteries and the common BESS.

Depth of Discharge (DoD)	The maximum percentage of a battery's rated capacity that is allowed to be discharged; it defines the usable energy window and protects battery life by preserving a reserve floor.
Round Trip Efficiency	The fraction of energy recovered from a battery relative to the energy originally put into it, capturing conversion and internal losses incurred during one full charge–discharge cycle.
Peer-to-Peer (P2P) Sharing	Direct hour-by-hour transfer of surplus energy from a house with excess generation to a neighbouring house with a deficit, without that energy first passing through the grid or a central storage asset.
Net Metering (NM)	A grid-interconnection arrangement, regulated by NEPRA, under which surplus solar energy exported to the utility grid is credited or purchased at a defined buy-back rate.
Dispatch Engine	The core simulation routine that, for every hour of the day, decides how each unit of load is met and how each unit of surplus generation is absorbed, following a fixed order of priority (merit order).
Curtailment	Load demand that cannot be met by any available source (own solar, own battery, P2P, common BESS, common solar) within an hour, and is therefore left unserved in the commonBESS (off-grid) scenario.
Minimum Load Factor (Diesel)	The lowest fraction of a generator's rated output at which it is permitted to run.

A 1.3.4 Solar Generation Profile & Statistics

With the terminology in place, the first building block of the simulator to walk through is generation, since everything else in the model — battery charging, P2P sharing, backup dispatch — depends on how much solar electricity is available in a given hour. The generation side of the model is built on measured solar-resource data rather than a generic clear-sky assumption. Hourly Global Horizontal Irradiance (GHI) for the project site (33.65°N, 72.97°E — G-13, Islamabad) was obtained from the NASA POWER database for the full year 2025. For each calendar month, a single "representative day" was selected — the day whose total daily GHI is closest to that month's median — so that the hourly shape used in the simulator reflects a typical, cloud-adjusted day rather than an idealised one. This gives twelve distinct hourly irradiance curves (one per month), which is what allows the same tool to be re-used for a different survey month (e.g. February for the Thar case) simply by switching the active profile.

Running this calculation across all 24 hours for every house, plus the optional common solar array in Scenario 3, produces the generation statistics used everywhere else in the tool: total daily kWh generated, the peak generation hour, and the shape of the solar curve relative to the load curve. The seasonal spread in the underlying data is significant — the representative day's total GHI ranges from about 2,715 Wh/m² in December to roughly 7,083 Wh/m² in May — which is why the self-sufficiency and cost results shift noticeably when the analysis month is changed, and why matching the simulation month to the actual load survey month (June for Islamabad, April for Thar) was important for producing realistic figures.

A 1.3.5 Battery Statistics

Once generation is known hour by hour, the next question is what happens to any energy that is not used immediately, which is where storage comes in. Two categories of storage are represented: an individual battery at house level (optional, per house) and, in Scenario 3 only, a single Common BESS shared by the whole cluster. Both are modelled with the same four parameters — usable capacity (kWh), maximum charge rate (kW), maximum discharge rate (kW), round-trip efficiency, and depth of discharge — and both carry an hour-by-hour state-of-charge value that is updated as the simulation steps through the day.

Depth of discharge sets a protected floor below which the battery is never drawn down (for example, at 80% DoD only 80% of rated capacity is ever available for use), and round-trip efficiency is applied whenever energy crosses the battery boundary, so that the kWh delivered to a house or to the cluster is always slightly less than the kWh drawn from storage. House batteries additionally respect a configurable charging window (a start and end hour) that represents daytime charging from that house's own solar surplus, whereas the Common BESS in Scenario 3 can be charged both from any house's leftover surplus after P2P sharing and from the dedicated common solar array. Tracking SoC hourly, rather than only as a daily total, is what allows the tool to flag situations where a battery is technically "large enough" on paper but still runs empty at a particular hour because of how load and generation are timed.

Inverters

Choosing between grid-following and grid-forming inverters is not just a technical preference — it directly affects whether a swarm grid cluster like G13 can stay stable and continue local P2P exchange during grid disturbances. In simple terms, a grid-following inverter behaves like a passenger: it needs the grid (or another strong source) to already be "driving," providing a stable voltage and frequency for it to sync to, and it shuts itself off if that reference disappears. A grid-forming inverter behaves like the driver: it sets its own voltage and frequency, so it can hold a cluster together on its own, restart it after an outage, and keep power flowing between houses even if the main grid trips. For a swarm-grid architecture, where the goal is local resilience and continued P2P sharing under grid stress, at least one grid-forming source per cluster — most practically the common/community BESS — is necessary, while individual rooftop solar inverters can remain grid-following since they simply feed into the voltage/frequency reference the BESS (or the grid) provides.

At the distribution/prosumer level — the level relevant to household inverters in a cluster like G13 — NEPRA's Net-Metering Regulations instead require every grid-connected inverter to comply with the UL 1741 standard (alongside IEEE 1547, IEC 61215, or equivalent EN standards), to carry mandatory anti-islanding protection that trips the inverter's energy flow the moment the grid fails, and to be paired with a lockable interconnection disconnect switch rated for the site's voltage and fault-current levels, accessible to both the owner and the DISCO. In plain terms: the Grid Code's slower, wider tolerances exist to keep large generators and the bulk grid from tripping unnecessarily during brief disturbances, while the Net-Metering Regulations' anti-islanding rule for household inverters exists for the opposite reason — to disconnect immediately and protect utility workers. This is precisely why a gridforming inverter or BESS operating inside a swarm-grid cluster needs certified anti-islanding logic before it can safely take over voltage/frequency formation for the cluster; it cannot simply keep energizing the local network the way a transmission-level generator is allowed to during a brief grid disturbance.

A 1.3.6 Swarm Grid Design

With generation and storage defined at the level of a single house, the next step is to explain how houses interact with each other, which is the defining feature of the model. The “swarm” in Swarm Grid Simulator refers to the fact that the cluster of houses behaves as a decentralised, peer-to-peer micro-grid rather than a set of houses that each deal with the backup source independently. Every house is treated as an equal node that can simultaneously be a supplier (when it has surplus solar or spare battery capacity) and a consumer (when it has a deficit), and energy is allowed to move directly between houses before any external backup — grid, diesel, or common BESS — is called upon.

This is implemented as a strict merit order that is applied identically, hour by hour, in all three scenarios:

- Own solar first — each house consumes its own rooftop generation directly.
- Own battery second — any remaining deficit is drawn from that house's own BESS, if it has one; any remaining solar surplus is used to recharge it.
- Peer-to-peer sharing third — houses still short of energy are matched directly against houses still holding surplus solar, largest deficit against largest surplus first.
- Neighbour-battery sharing fourth — if surplus solar is exhausted, a deficit house may draw from a neighbouring house's battery, provided that battery is not itself still charging.

- Scenario backup last — whatever deficit (or surplus) is still left after the four peerlevel steps is handed to the scenario-specific source: the grid, the diesel generator, or the common BESS/common solar.

Only the last step changes between scenarios; the swarm layer itself (steps 1–4) is common to all three, which is what makes the three scenarios directly comparable — they share exactly the same load, the same solar generation, and the same peer-sharing behaviour, and differ only in how the residual gap is closed.

A 1.3.7 Generation-Based Programming — Loop Development & Sequence

Having described the merit order conceptually, the next step is to show how it is actually implemented in code, hour by hour. The simulation is written as a discrete time-stepped model: a single outer loop runs 24 times, once for each hour of the day (hours = 0 … 23), and the state of every house — load, solar output, battery SoC, and energy already shared — is carried forward from one iteration to the next. Nothing is solved for the whole day at once; each hour is resolved completely before the next one begins, which mirrors how a real micro-grid actually operates and lets the dispatch order genuinely mean something (a house cannot, for instance, be credited with battery energy it has not yet generated).

Inside each hourly iteration, the code executes the five-step merit order described above as an explicit sequence of nested loops:

- Step 1 (self-dispatch) loops once over every house, computing that house's own solar-vs-load balance and its own battery response, and leaves each house holding a remaining deficit (_rem) or remaining surplus (_surp) for that hour.
- Step 2 (P2P matching) builds two lists — deficit houses and surplus houses, sorted from largest to smallest — and then runs a nested loop that pairs the largest remaining deficit against the largest remaining surplus, transferring the smaller of the two amounts and repeating until either list is exhausted. This greedy, largest-first pairing is what keeps the number of matches low while maximising how much of the surplus is actually absorbed within the hour.
- Step 3 (neighbour-battery sharing) re-scans the remaining deficit houses against every other house that owns a battery and is not still in surplus, drawing down that battery within its discharge-rate limit.
- Step 4 (backup dispatch) branches on the scenario mode parameter (“grid”, “diesel”, or “CBESS”) and applies the source-specific rules — grid import/export with net metering, diesel output capped at generator capacity and floored at the minimum load factor, or common-BESS/common-solar dispatch with any unserved remainder logged as curtailment.

Every transfer of energy from one house to another, from a battery, or from a scenario backup, is written into per-house, 24-element arrays (one value per hour) so that the same underlying simulation run can drive the hourly dispatch tables, the stacked energy-flow charts, the P2P sharing matrix, and the daily/annual economics without being recalculated. Peer-to-peer transfers specifically are also recorded into a three-dimensional matrix indexed by hour, sending house, and receiving house, which is what allows the tool to report exactly how much energy moved from any one house to any other house at any hour of the day. Structuring the program this way — one outer 24-hour loop, a fixed inner sequence per hour, and results captured into flat per-hour arrays — keeps the three scenarios as three calls to the same dispatch engine with a different mode flag, rather than three separatelywritten simulations, which is also why the comparison view in section 4.6 can be produced directly from the three result sets without any extra reconciliation logic.

A 1.3.8 Scenarios

With the dispatch engine fully defined, the final piece is to see how it behaves once a specific backup source is plugged into that last step of the merit order. With the swarm layer fixed, the tool evaluates the same cluster, the same day, and the same houses under three different backup arrangements so that their technical and economic performance can be compared on equal footing:

Aspect	**Scenario 1 — Grid-Connected**	**Scenario 2 — Diesel Generator**	**Scenario 3 — Common BESS + Solar**
Backup source	National grid/NGC grid	Cluster diesel generator	Shared battery bank + shared solar array
Surplus handling	Exported to grid under net metering	Unused / not exported (no sink) / no reverse power flow	Charges the common BESS first
Governing constraint	Import/export always available	Minimum load factor, kVA × PF	State of charge, charge/discharge kW limits
Unmet demand	Never occurs	Never occurs (assumed always available)	Recorded explicitly as curtailment

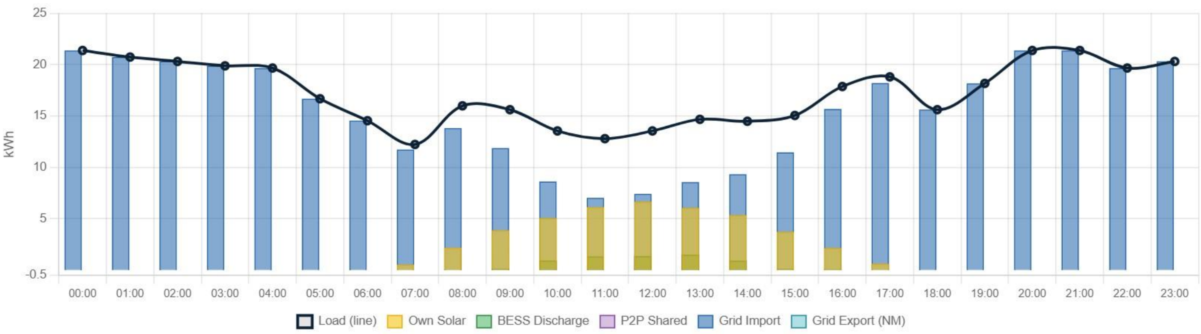
Scenario 1 keeps the cluster connected to the national grid, so any residual deficit after the swarm steps is simply imported at the prevailing tariff, and any residual surplus is exported and credited at the net-metering rate, meaning this scenario never has an unmet-load problem, but its running cost depends on the gap between the import tariff and the NM buyback rate. Scenario 2 removes the grid entirely and substitutes a single cluster-level diesel generator; because diesel generators lose efficiency when lightly loaded, the model enforces a minimum load factor (dispatching at that floor rather than exactly matching the deficit when the deficit is small) and prices the hour's output using a fuel-consumption rate (L/kWh) plus a fixed daily operations-and-maintenance charge. Scenario 3 also removes the grid, but instead of diesel it adds a shared Common BESS and an optional shared solar array sized independently of the houses' own rooftops; any deficit the swarm layer could not resolve is drawn from this shared battery, any spare solar (house-level or common) tops the battery back up, and — because there is now no unlimited backup of any kind — any load that still cannot be met in a given hour is recorded as curtailment rather than silently satisfied, which is the clearest technical signal of whether a proposed battery/solar size is actually adequate for the cluster.

Because all three scenarios are generated from one shared dispatch engine and one shared set of house inputs, the differences reported in the comparison tab — cost per kWh, selfsufficiency, and curtailment — can be attributed entirely to the choice of backup source rather than to any inconsistency in how the underlying load or solar was modelled.

P2P Cluster Tharparkar Example of a household load and consumption:

As shown in the figure below, the household load is highly non-uniform, both across the cluster and across time. Even during peak solar hours (12:00), roughly 60% of households remain in deficit despite generation being at its daily maximum, while by 22:00 every household in the sample is in deficit, since solar output has dropped to zero and only battery storage or grid/external supply can meet demand. As a result, a significant share of the cluster's evening load still falls back on the grid (or would need to be met by aggregated/community-level storage, if the swarm grid is designed with a shared battery rather than only individual household units).

24 Hour dispatch of the cluster



This demonstrates that a swarm grid architecture in Tharparkar cannot rely on P2P trading and individual household batteries alone to achieve energy self-sufficiency. It instead points toward the need for either (a) increased battery capacity per household or at cluster level, (b) continued grid dependency as a backstop.

Annexure 2

Microgrid Eligibility & Licensing by NEPRA 2022:

- Applicants can be individuals, companies, cooperatives, partnerships, or social welfare organizations.
- Must serve an unserved market — at least 5 km away from existing distribution infrastructure and not in the host utility's expansion plan.
- A single unified licence covers generation, distribution, and supply.
- Licence term: Maximum 10 years.
- NEPRA consults the host distribution company, supplier of last resort, and provincial energy department before granting a licence.
- Supply must be offered to all consumers in the licensed area without discrimination (except for load/feasibility limits).
- Tariffs are set bilaterally between developer and consumers, but must be fair and equitable.
- NEPRA can reassess if tariffs appear unjustified.

About SOLBOX:

The SolBox is SOLshare's core hardware innovation — an IoT-based smart power meter and controller installed in each participating home. It:

- Manages energy flows between households (buy, sell, or store).
- Measures usage and battery status in real time.
- Enables payments via mobile money platforms like bKash.
- Supports dynamic pricing and data analytics to optimize trading.

SOLshare is the organization and business model, while the SolBox is the enabling technology that makes the swarm grid possible.

The case of South Africa — Challenges & Emerging Solutions in Swarm Electrification:

In rural South Africa—particularly in Limpopo—studies like Azimoh et al. (2014)[8] revealed that solar home systems (SHSs) were frequently compromised due to theft concerns. For instance, homeowners would place panels incorrectly (e.g., flat on the ground or indoors after sunset), which significantly reduced energy output, battery performance, and system longevity. The study emphasized the need for secure yet performance-preserving setups, such as bench-rack mounting systems, to mitigate theft while maintaining efficiency. Beyond hardware issues, additional challenges undermined SHS effectiveness:

Beyond hardware issues, additional challenges undermined SHS effectiveness:

- Low user awareness and insufficient training led to misuse and abandonment of systems.
- Institutional weaknesses and weak supporting policies created barriers for sustainable solar adoption.

  These problems highlight the risk that even when swarm electrification could be beneficial, it lacks the necessary ecosystem to succeed.

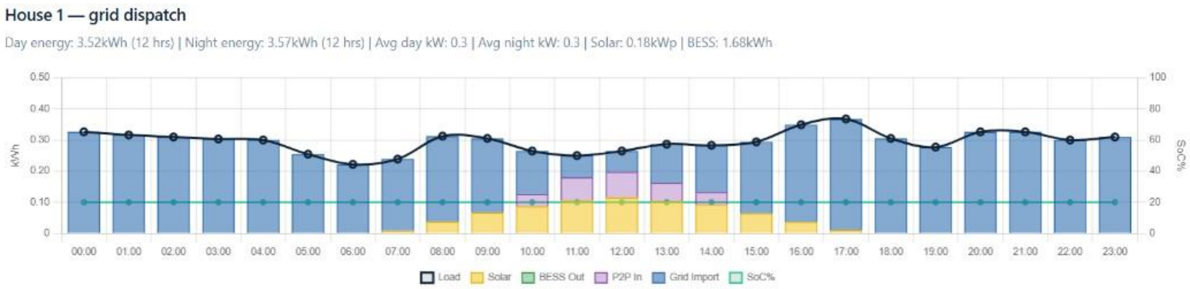
A New Proposal — Long Range (LoRa)-Based Swarm Grid [17]

To address communication challenges in remote areas where GSM networks are unreliable or costly, a 2023 conference paper proposed a novel architecture: a LoRa-based swarm grid for rural electrification in Sub-Saharan Africa. Key highlights include:

- Integrating SHSs into locally interconnected swarm grids to share surplus solar energy efficiently.
- Using LoRa wireless communication instead of GSM for real-time load monitoring and control between prosumers and consumers.
- This approach enables a low-cost, reliable local network that supports smart tariffing and billing mechanisms without reliance on mobile networks.

From the case of South Africa, it is important to note that issues can emerge after deployment, particularly related to system installation and handling. This underscores the need for technically trained installers who can ensure proper system setup and guide users on safe and efficient operation, so that performance is not compromised by security concerns or improper installation practices.

Khario:



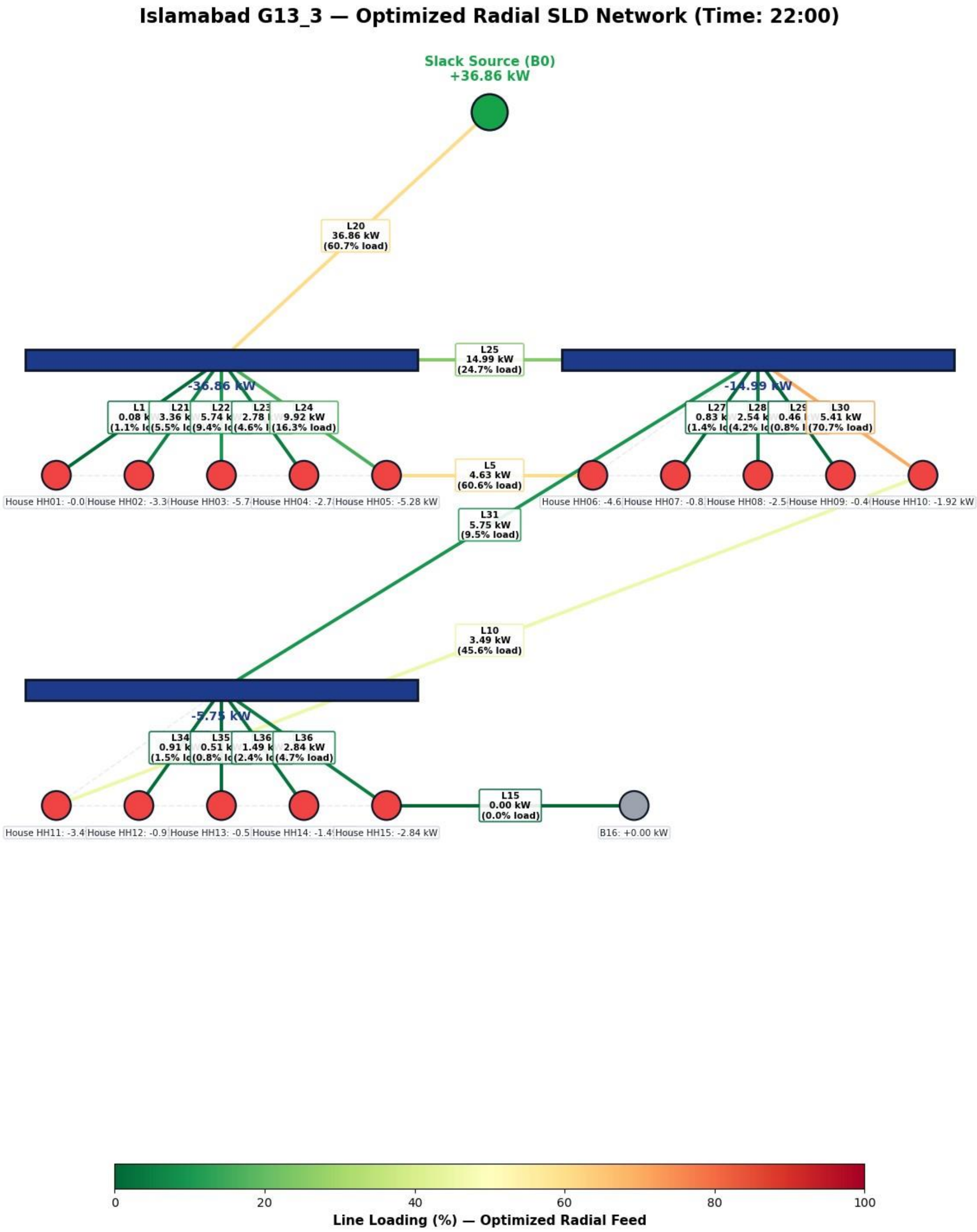
To explain the tabulated data in more detail, the above figure is a snapshot from our analysis of how a household with solar and battery storage load profile varies and how much it imports from the grid, generates itself, and takes from a neighboring household. The load pattern is very non-uniform, and a large chunk of the load is still met by the grid. G-13,1

Aspect	DG-based system	BESS-based system

[17] https://www.researchgate.net/publication/376777095_LoRa-based_Swarm_Grid_Implementation_for_Rural_Electrification_in_Africa

Main backup source	Diesel generator	Common BESS
Diesel dependence	High	Substantially reduced
Fuel cost	Very high	Replaced by BESS cost allocation
P2P trading	Available	Available
Solar utilization	Limited by timing of demand	Improved through storage
Net savings	Negative for many households	Positive for all households
Economic feasibility	Unfeasible	Economically viable once the payback is received
Key benefit	Backup reliability	Solar shifting + lower supply cost

SLDs:



Islamabad G13_3 — Optimized Radial SLD Network (Time: 22:00)
Slack Source (B0)
+36.86 kW
L20
36.86 kW
(60.7% load)
L25
14.99 kW
(24.7% load)
-36.86 kW
-14.99 kW
L24
9.92 kW
(16.3% load)
L30
5.41 kW
(70.7% load)
L5
4.63 kW
(60.6% load)
House HH05: -5.28 kW
House HH10: -1.92 kW
L31
5.75 kW
(9.5% load)
L10
3.49 kW
(45.6% load)
-5.75 kW
L36
2.84 kW
(4.7% load)
L15
0.00 kW
(0.0% load)
House HH15: -2.84 kW
B16: +0.00 kW
0
20
40
60
80
100
Line Loading (%) — Optimized Radial Feed