Jana Nexus: Journal of Computer Science
ISSN(O):3108-1916
Journal Homepage: jananexuscs.com
JN:JNCS *Volume 02 Issue 07* *12-22*

| RESEARCH ARTICLE

Article DOI:10.21474/JNCS01/142
DOI URL: http://dx.doi.org/10.21474/JNCS01/142

VOLTWISE 2.0: AN INTEGRATED SMART HOME ENERGY MANAGEMENT SYSTEM FOR LOAD-SHEDDING-PRONE ENVIRONMENTS

Millius Nkhoma Liswaniso and Santhi Kunaran

Corresponding Author:**Millius Nkhoma Liswaniso**

| ABSTRACT

Recurrent load shedding forces households to manage limited backup energy while maintaining essential services, controlling unnecessary demand, and remaining aware of the cost implications of grid consumption. This paper presents VoltWise 2.0, a Smart Home Energy Management System developed to support intelligent residential energy use in load-shedding-prone environments. The system integrates a Flutter mobile application, a FastAPI backend, and an SQLite database to provide real-time visibility of household demand, battery condition, grid availability, appliance activity, accumulated energy savings, prepaid electricity status, and residential tariff information.

| KEYWORDS

Smart home energy management; load shedding; appliance prioritisation; energy savings; tariff awareness.

| ARTICLE INFORMATION

RECEIVED: 04 May 2026 ACCEPTED: 12 June 2026 PUBLISHED: July 2026

Abstract - Recurrent load shedding forces households to manage limited backup energy while maintaining essential services, controlling unnecessary demand, and remaining aware of the cost implications of grid consumption. This paper presents VoltWise 2.0, a Smart Home Energy Management System developed to support intelligent residential energy use in load-shedding-prone environments. The system integrates a Flutter mobile application, a FastAPI backend, and an SQLite database to provide real-time visibility of household demand, battery condition, grid availability, appliance activity, accumulated energy savings, prepaid electricity status, and residential tariff information. Users assign appliances HIGH, MEDIUM, or LOW priority and configure battery thresholds according to household requirements. VoltWise responds through NORMAL, SAVING, CRITICAL, and EMERGENCY operating modes, progressively disconnecting lower-priority loads as battery capacity declines while preserving essential appliances. The system retains the user's most recent manual appliance decision, preventing automated recovery from restoring appliances that were deliberately switched off. A dedicated energy-savings mechanism records each load-control session and calculates both the instantaneous power removed in watts and the accumulated energy avoided in kilowatt-hours. Only appliances disconnected by VoltWise are included in the savings record, enabling accurate attribution of savings to automated control rather than to devices already switched off by the user. The system further separates savings achieved during grid and battery operation, identifies the appliances contributing most to reduced consumption, and reports the number of control actions and appliances managed. Its rate-analysis module tracks monthly grid-energy consumption, identifies the applicable residential tariff tier, estimates electricity cost, calculates the remaining energy before entry into the next tariff band, monitors prepaid electricity units, and generates warnings when household consumption approaches a higher rate threshold. Battery-supplied consumption is excluded from grid-energy and tariff calculations to prevent inaccurate utility-cost estimates. Controlled simulation showed that active demand decreased from 225 W to 165 W in SAVING mode, representing a 26.7% reduction. Under CRITICAL and EMERGENCY conditions, VoltWise maintained a 15 W high-priority communication load while disconnecting 210 W of non-essential demand. These results demonstrate the potential of VoltWise 2.0 to protect critical household loads, preserve available backup energy, provide traceable evidence of energy savings, reduce avoidable electricity consumption, and improve household understanding of prepaid units, tariff progression, and electricity costs during load shedding. Future work will integrate physical meters,

batteries, inverters, sensors, and switching devices to evaluate actual energy consumption, financial savings, and battery-runtime improvement in operational households.

Introduction:-

Recurrent load shedding transforms household electricity use from a routine consumption activity into a constrained allocation problem. A household supplied by a battery or inverter cannot assume that every connected appliance can remain active until grid service returns. It must decide which services are essential, which loads can be deferred, how rapidly the backup reserve is being depleted, and when intervention is required. This challenge is particularly significant where communication, lighting, refrigeration, security, study, and home-based work depend on the same limited backup resource. Smart Home Energy Management Systems (SHEMSs) provide mechanisms for observing demand, coordinating appliances, and supporting demand-side flexibility [1], [2]. Established research has concentrated mainly on electricity-cost minimisation, peak shaving, renewable-energy coordination, and time-based scheduling [3]-[5]. These objectives remain important, but recurrent load shedding introduces a different operational priority: preserving selected services while the available supply is temporarily constrained. Resilience-oriented studies demonstrate the value of coordinating batteries with critical loads [6], while international energy analysis increasingly recognises demand flexibility as a resource for reliability, efficiency, and consumer cost management [7], [8].

Within the Zambian context, national energy planning emphasises reliable and affordable access, resilient infrastructure, improved utility performance, diversified supply, and stronger use of energy information [9]. At household level, however, the immediate response to an outage is commonly manual. Users inspect an inverter display, estimate appliance demand, and switch devices on or off without a unified record of priorities, previous decisions, accumulated savings, prepaid units, or tariff implications. The result is a reactive process in which low-priority loads may consume scarce backup capacity before essential household services are protected.

VoltWise 2.0 was developed to address this operational gap through a mobile-first system that links household priorities, appliance state, battery conditions, attributable energy savings, prepaid status, and grid-rate analytics within a common data model. Rather than treating the system as an automatic switch alone, the design separates four responsibilities: monitoring establishes what is happening; control allows the household to define appliance states and priorities; optimisation applies transparent load-allocation rules as battery conditions change; and analytics converts events into energy, savings, prepaid, and tariff information.

Problem statement:-

Households operating under recurrent grid outages lack an integrated and explainable mechanism for allocating limited backup energy. Manual control is reactive and depends on the user being continuously present. Monitoring-only applications reveal consumption but do not act when the battery reserve is deteriorating. Automation-only approaches may disconnect appliances without preserving the user's last decision, may restore devices that were intentionally left off, and may provide limited evidence of how a reported saving was produced. In addition, instantaneous demand reduction is frequently confused with accumulated energy savings, while battery-supplied consumption may be incorrectly included in grid-energy and electricity-cost calculations. The research problem is therefore the absence of a user-governed residential energy-management framework that can combine outage-aware load scheduling, appliance-priority management, manual-intent preservation, traceable energy-savings accounting, and grid-rate awareness in one coherent software artefact. The required system must translate changing battery conditions and household priorities into auditable decisions while maintaining accurate distinctions among active demand, avoided energy, grid consumption, prepaid balance, and tariff progression.

Aim, Objectives, and Research Questions:-

The study aimed to design, implement, and evaluate VoltWise 2.0 as an integrated Smart Home Energy Management System for load-shedding-prone households. The specific objectives were:

1. To analyse residential energy-management requirements and represent household appliances using user-configurable HIGH, MEDIUM, and LOW priority levels based on operational importance and power demand.
2. To design an adaptive architecture that integrates monitoring, manual appliance control, priority-based load scheduling, energy-savings accounting, notifications, reporting, prepaid-unit monitoring, and tariff analysis.
3. To implement a functional mobile and backend prototype using Flutter, FastAPI, and SQLite, with interfaces that can later accept data from physical meters, sensors, embedded controllers, and switching devices.
4. To evaluate system behaviour under simulated grid, battery, appliance, and threshold conditions using mode-selection accuracy, demand reduction, action correctness, user-intent preservation, savings attribution, rate calculations, and interface consistency.
5. To assess how the integrated design can support household demand-side management, critical-load protection, backup-energy preservation, energy-use awareness, and tariff understanding.

The research questions were:

1. What residential energy-management requirements and appliance-priority factors should be represented by VoltWise 2.0?
2. How can monitoring, control, adaptive load scheduling, energy-savings measurement, prepaid monitoring, and tariff awareness be integrated within one architecture?
3. Can the prototype respond to changing battery conditions while preserving the user's latest manual appliance intention?
4. What demand-reduction and savings-attribution behaviour is observed under simulated NORMAL, SAVING, CRITICAL, and EMERGENCY conditions?
5. How effectively do the integrated functions support explainable residential demand-side management during load shedding?

Contributions of the study:
The study makes four principal contributions:
1. A user-governed priority-based load-allocation mechanism in which households, rather than the developer, determine the operational importance of connected appliances.
2. A manual-intent preservation mechanism that distinguishes the user's desired appliance state from the temporary state imposed by automated energy management.
3. A session-based energy-savings model that attributes avoided power and accumulated energy only to control actions created by VoltWise, making reported savings traceable and auditable.
4. An integrated prepaid and tariff-awareness layer that links grid-energy use, remaining units, tariff progression, proximity warnings, and the economic value of avoided consumption.

Together, these contributions position VoltWise 2.0 as an explainable residential load-allocation framework rather than a monitoring dashboard or isolated scheduling algorithm.

Scope of the study:
The study covers the design, implementation, and controlled software evaluation of VoltWise 2.0. The implemented scope includes grid and battery status, current household demand, daily grid energy, appliance registration and manual control, user-defined priority management, configurable battery thresholds, four operating modes, preservation of manual intention, notifications, reports, usage history, session-based savings, prepaid monitoring, and tariff analytics. Grid, battery, appliance, energy, and rate inputs were simulated. Certified mains wiring, calibrated metering, physical relays or contactors, cybersecurity penetration testing, and long-duration household trials are outside the present software validation phase.

Literature Review:-

Smart home energy management and demand flexibility
SHEMSs combine measurement, communication, decision logic, storage, and user interfaces to observe and influence residential electricity use [1], [2]. Typical functions include real-time monitoring, appliance scheduling, demand forecasting, renewable-energy coordination, battery management, tariff response, and feedback to occupants. Research has demonstrated that coordinated scheduling can reduce peak demand and cost, especially when household loads are aligned with photovoltaic generation or demand-response signals [4], [5]. Lower-complexity decision models further show that useful coordination can be achieved without computationally intensive optimisation [3]. Demand flexibility provides the conceptual bridge between these approaches and household load shedding. It describes the ability to alter the timing or amount of electricity use in response to supply, price, or system conditions [8]. During a grid outage, the relevant signal is not a price period but the declining state of a finite backup resource. The household therefore requires a policy that progressively restricts deferrable demand while protecting the services it considers critical.

Residential resilience and critical-load protection:-
Resilience-oriented energy management extends beyond cost minimisation by prioritising the continuity of selected services. Gaikwad et al. [6] show that coordinating storage resources with critical loads can improve service continuity and reduce the battery capacity required to sustain essential demand. This perspective is particularly relevant in load-shedding-prone environments, where households may experience repeated transitions between utility and backup operation. A practical system must therefore recognise that the importance of an appliance is contextual: one household may prioritise refrigeration, while another may prioritise communication, lighting, medical equipment, or security. VoltWise adopts user-defined priorities to represent this contextual variation. The system does not classify an appliance solely from its type. Instead, HIGH, MEDIUM, and LOW levels are assigned by the household and become inputs to the decision engine. This design preserves household authority while enabling consistent and repeatable load allocation.

User control, explainability, and intention preservation:-

Occupant acceptance is a recurring challenge in automated energy systems. A controller may be technically correct yet undesirable if it acts without explanation or reverses a deliberate user choice. Many scheduling studies model appliance availability, operating windows, or comfort constraints, but they do not explicitly distinguish the current physical state of an appliance from the user's latest manual intention [3]-[5]. This distinction becomes important during recovery. If automation temporarily disconnects an appliance, restoration may be appropriate when conditions improve; if the user deliberately switched it off, automatic restoration is inappropriate. VoltWise therefore records actual status, user-desired status, and the last control source as separate state variables. Each action can be traced to the battery value, configured threshold, appliance priority, user intention, and control source. The resulting decisions are deterministic and auditable, which strengthens both technical verification and user understanding.

Energy-savings attribution and tariff awareness:
Energy-savings reporting often combines several concepts that should remain distinct. Power reduction is an instantaneous quantity expressed in watts, whereas avoided energy accumulates over time and is expressed in kilowatt-hours. A system may also overstate savings by counting appliances that were already off before automation acted. Session-based accounting addresses both problems by opening a record when the controller disconnects a load and closing it when that load is restored or manually reactivated. Tariff and prepaid information add an economic dimension. A prepaid balance answers how much purchased energy remains; tariff progression explains how cumulative grid use affects the applicable rate and the next threshold. These indicators are meaningful only when grid and battery energy are separated. Battery-supplied consumption should remain visible as household demand, but it should not be added to utility-energy or tariff calculations.

Research gap:
Representative research establishes strong foundations in monitoring, optimisation, demand response, and resilience, but the mechanisms required for recurrent household load shedding are commonly treated as separate concerns. Broad SHEMS surveys identify monitoring, scheduling, communication, security, and user participation as central themes [1], [2]. Optimisation studies coordinate appliances with photovoltaic output, prices, and demand-response programmes [4], [5], while resilience studies link storage to critical loads [6]. The literature provides less explicit treatment of persistent manual intention, session-level savings attribution, and integrated prepaid and tariff interpretation within a load-shedding-focused mobile artefact.

Table 1. Comparison of representative approaches and VoltWise 2.0

Capability	Representative existing approaches	VoltWise 2.0
Real-time monitoring	Common in SHEMS platforms	Integrated grid, battery, demand, appliance, and energy views
Scheduling objective	Price, PV utilisation, peak reduction, or resilience	Progressive outage-priority modes
Household priority control	Often model-defined or constraint-based	User-configurable HIGH, MEDIUM, and LOW priorities
Manual-intent preservation	Rarely explicit	Persistent desired state and control-source tracking
Savings accounting	Aggregate reduction or optimisation outcome	Session-attributed watts and kilowatt-hours
Load-shedding focus	Limited or partial	Primary operating context
Tariff and prepaid analytics	Often separate or limited	Integrated with grid-only energy accounting
Decision explanation	Varies by method	Deterministic, traceable reasons for each action

The gap identified in Table 1 is not the absence of individual monitoring or scheduling techniques. It is the absence of a coherent, user-governed framework that integrates priority allocation, intention preservation, attributable savings, and rate awareness for recurrent load shedding. VoltWise 2.0 addresses this integration gap through a lightweight architecture designed for later connection to residential hardware.

Methodology:-

Research design

The study adopted Design Science Research Methodology because its central output is a technological artefact developed to address a practical energy-management problem [14]. The process comprised problem identification, definition of objectives, design and development, demonstration, evaluation, and communication. Agile prototyping was used within these stages to refine the data model, REST endpoints, mobile screens, scheduling rules, notifications, savings sessions, rate logic, and test scenarios. The artefact was evaluated through controlled simulation because physical household meters and switching equipment were not part of the current implementation phase.

System architecture and implementation:

The artefact consists of a Flutter Android application, a FastAPI backend, and an SQLite database. The mobile layer provides dashboard, appliance, automation, report, notification, setting, usage-history, and rate interfaces. The backend validates requests, maintains system state, applies operating rules, records savings sessions, calculates energy and tariff indicators, and returns explainable responses. SQLite stores grid, battery, appliance, setting, reading, notification, and energy-saving entities. Figure 1 summarises the architecture and its future physical boundary.

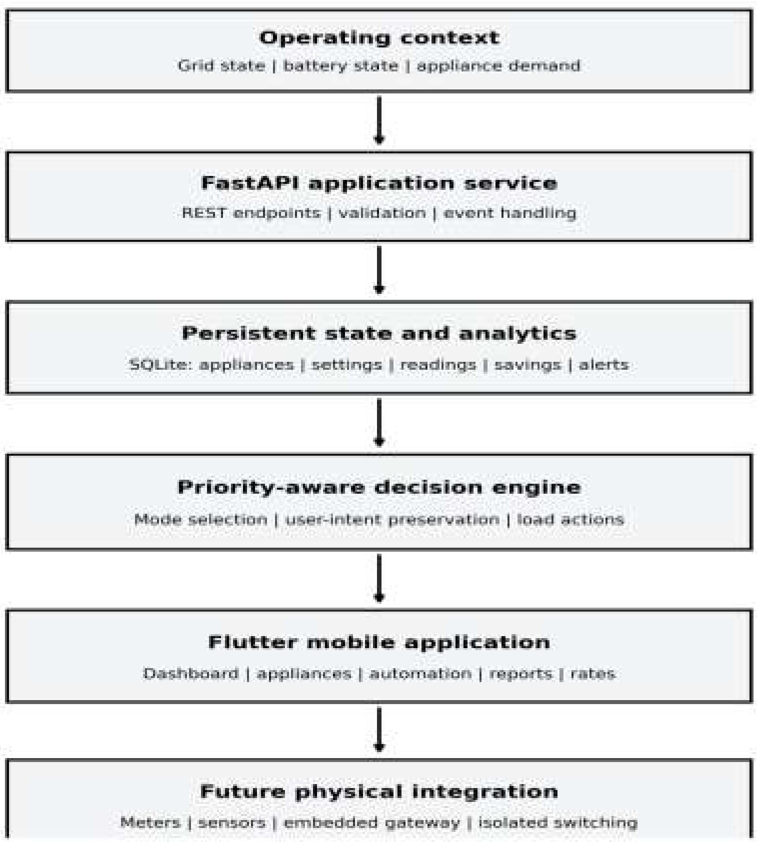

Figure 1. Integrated VoltWise 2.0 software architecture and future physical-integration boundary.

The architecture separates presentation, application logic, and persistent state. This separation enables the same decision engine to support a simulated environment today and sensor-driven operation later. It also ensures that one action can be reflected consistently across modules: a load-control event changes appliance demand, updates the dashboard, opens or closes a savings session, and generates a notification or explanation.

Appliance and user-intent state model:

Each appliance is represented by an identifier, name, rated power, priority, actual status, automation-enabled flag, user-desired status, and last control source. The actual status records whether the appliance is presently on or off. The desired status records what the user wants, while the control-source field distinguishes user action from system action. When VoltWise temporarily disconnects a load, the desired state remains unchanged. Restoration is permitted only if conditions improve and the desired state is still true. This design prevents the recovery process from reactivating appliances that the user intentionally left off.

Priority-based decision engine

The decision engine uses grid availability, battery state of charge b, and configurable thresholds Tn, Ts, and Tc, where Tn > Ts > Tc. Grid availability permits normal user-desired operation. During battery operation, the selected mode is defined as follows:

$$M(b) = NORMAL,\ b \geq Tn;\ SAVING,\ Ts \leq b < Tn;\ CRITICAL,\ Tc \leq b < Ts;\ EMERGENCY,\ b < Tc \quad (1)$$

NORMAL permits all priorities that the user still wants on. SAVING disconnects LOW-priority loads. CRITICAL disconnects LOW- and MEDIUM-priority loads. EMERGENCY permits only HIGH-priority loads whose desired status remains true. Priorities are assigned by the household rather than fixed by the developer, allowing the same appliance type to be treated differently in different homes. Each action is accompanied by a reason describing the battery state, selected mode, affected priority, and appliance change.

Demand, savings, and cost calculations:

Current household demand is calculated from the rated power of active appliances:

$$Pactive(t) = \Sigma\, si(t)Pi \quad (2)$$

where Pi is the rated power of appliance i and si(t) is 1 when the appliance is active and 0 otherwise. Instantaneous demand removed is calculated only for appliances whose off state was created by VoltWise. A saving session begins when the system disconnects an appliance and ends when the appliance is restored or manually switched on. Accumulated avoided energy is:

$$Esaved = \Sigma[Pi \times \Delta ti] / 3{,}600{,}000 \ \ kWh \quad (3)$$

where Δti is the attributable session duration in seconds. This method prevents a manually disabled appliance from being counted as an automated saving and avoids treating watts as kilowatt-hours. The daily summary aggregates total avoided energy, battery-related savings, grid-related savings, control actions, appliances managed, and the highest-contributing appliance.

The monetary value of accumulated avoided grid energy is calculated using the applicable configured rate r:

$$Csaved = Esaved{,}grid \times r \quad (4)$$

The cost estimate is intentionally linked only to grid-related savings. Battery-related savings represent preserved backup energy and potential runtime benefit rather than direct avoidance of utility charges at the time of the outage.

Grid-energy, prepaid, and tariff analytics:

Grid-energy accounting is conditional on grid availability. Current Usage remains visible during an outage because it describes total active demand, but new utility energy is not accumulated while the battery supplies the household. For cumulative monthly grid energy Eg,m, the tariff service identifies the configured band, current rate, estimated cost, and the remaining energy before the next threshold:

$$Hnext = Ucurrent - Eg{,}m \quad (5)$$

where Ucurrent is the upper boundary of the active tariff band. A warning is generated when Hnext falls below a configured proximity value. The prepaid component records remaining units and estimates days of supply from an assumed or recent daily-consumption rate. Because electricity schedules can change, rates, thresholds, and warning distances are stored as configurable data rather than being permanently embedded in the application [13].

Evaluation design, reference strategies, and metrics

Controlled test cases were constructed because the prototype is deterministic and physical household measurements were not yet available. Each case defined grid state, battery percentage, configured thresholds, appliance states, appliance priorities, expected operating mode, expected control actions, expected savings attribution, and expected dashboard response. The representative user-permitted baseline comprised a 150 W refrigerator, a 15 W router, and a 60 W lighting load, producing 225 W. A 120 W television was registered but deliberately left off by the user to test manual-intent preservation.

Table 2. Representative evaluation configuration

Component	Rated power	Priority	User-desired state	Purpose in evaluation
Refrigerator	150 W	MEDIUM	ON	Tests progressive removal of a substantial non-HIGH load
Wi-Fi router	15 W	HIGH	ON	Represents protected communication service
Lighting	60 W	LOW	ON	Tests early removal in SAVING mode
Television	120 W	MEDIUM	OFF	Tests preservation of a deliberate manual choice

Initial thresholds were 50%, 20%, and 10%. A second configuration of 90%, 45%, and 15% tested whether threshold values were dynamic rather than hard-coded. Two reference strategies were used to prevent the benefits from being presented in isolation. The manual/no-intervention baseline retained all user-permitted loads at every battery state. A basic single-threshold controller disconnected LOW-priority loads only after the battery fell below 20% and did not escalate further. VoltWise applied progressive priority restrictions across SAVING, CRITICAL, and EMERGENCY states.

Evaluation metrics included mode-selection accuracy, active demand, demand removed, percentage reduction, reference-strategy improvement, preservation of manual intent, correctness of savings attribution, consistency of grid-only energy accounting, tariff-band selection, estimated cost, proximity-to-next-band reporting, and agreement between backend state and the mobile interface. Quantitative results were analysed descriptively because the study used deterministic scenarios rather than a random household sample.

Results and Discussion:-

Functional correctness and mode transitions

At 75% battery charge, the initial thresholds selected NORMAL mode and maintained the 225 W user-permitted baseline. At 49%, SAVING mode disconnected the 60 W LOW-priority lighting load, leaving 165 W and producing a 26.7% reduction. At 19%, CRITICAL mode removed the 150 W MEDIUM-priority refrigerator in addition to the lighting load, leaving only the 15 W HIGH-priority router. At 9%, EMERGENCY mode maintained the same protected communication load. The two lowest battery states therefore kept 210 W disconnected, equivalent to 93.3% of the baseline.

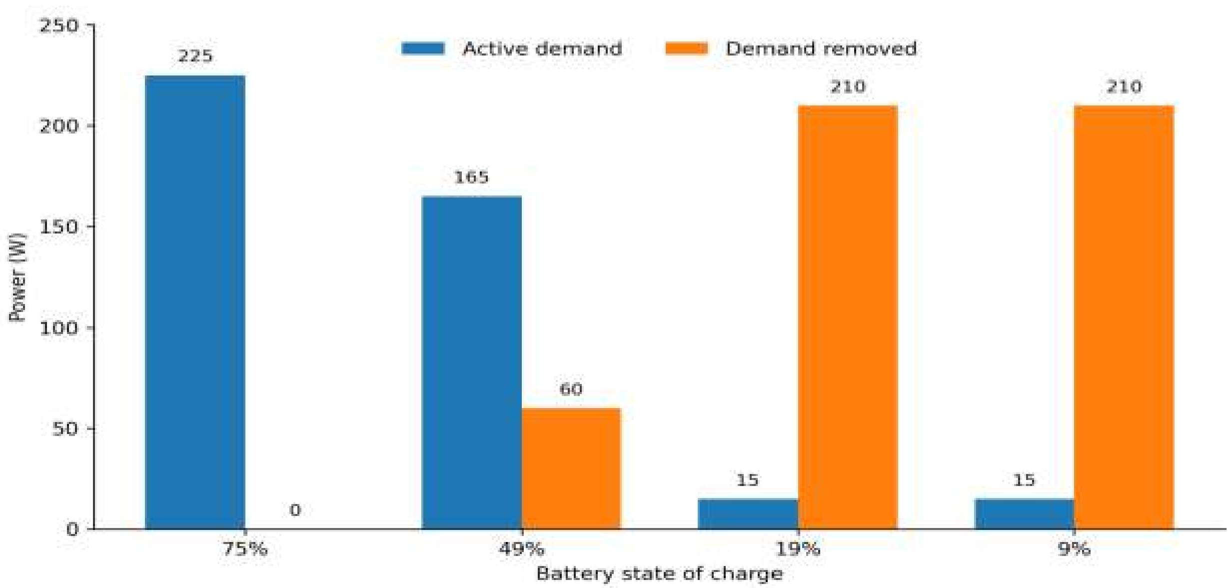

Figure 2. Active demand and demand removed under simulated battery conditions.

The results confirm that VoltWise did not wait for the battery to become critically low before acting. The SAVING stage reduced demand while 49% capacity remained, creating an earlier conservation response than the single-threshold comparator. Progressive escalation then protected only the HIGH-priority communication load as conditions became severe.

Comparison with manual and single-threshold strategies

Table 3. Active-load comparison across reference strategies

Battery state	Manual/no intervention	Single-threshold control	VoltWise 2.0
75%	225 W	225 W	225 W
49%	225 W	225 W	165 W
19%	225 W	165 W	15 W
9%	225 W	165 W	15 W

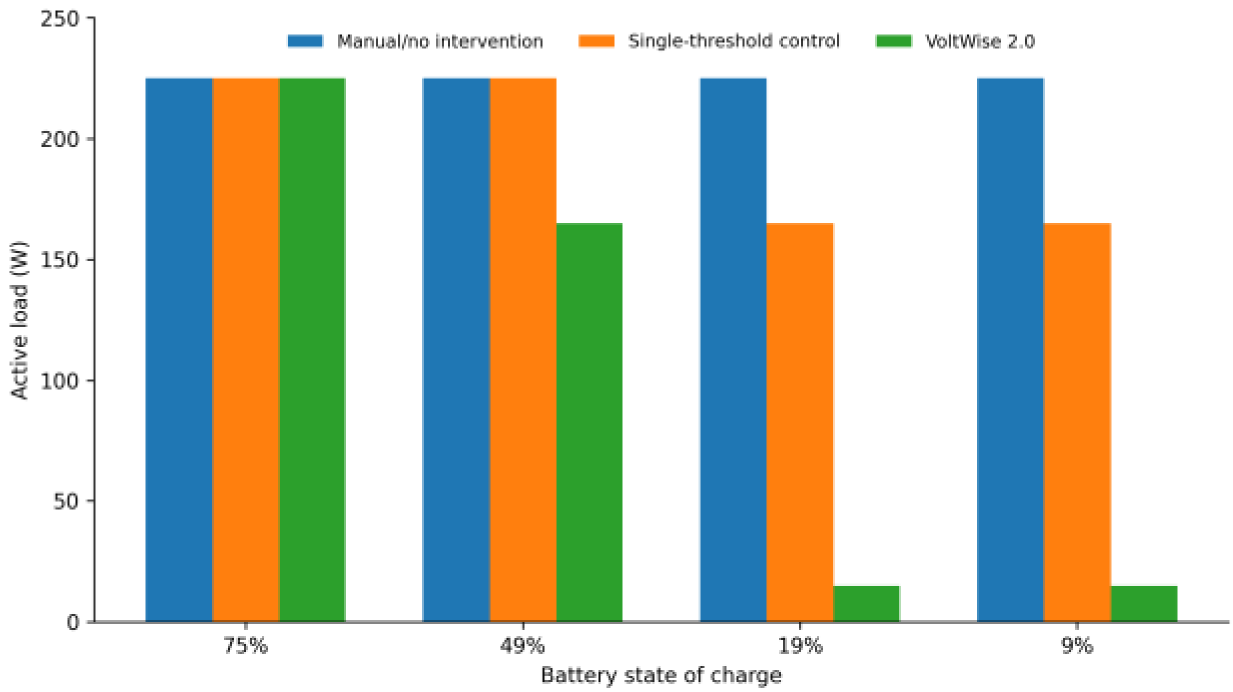

Figure 3. Comparative active load for manual, single-threshold, and VoltWise strategies.

At 49%, both reference strategies retained 225 W, whereas VoltWise reduced demand to 165 W. This represented a 26.7% reduction relative to both comparators. At 19% and 9%, manual operation continued to carry 225 W and the single-threshold controller carried 165 W, while VoltWise retained 15 W. VoltWise therefore achieved a 93.3% reduction relative to manual operation and a 90.9% reduction relative to the single-threshold controller at the two lowest battery states. The comparative advantage arose from progressive priority escalation rather than threshold detection alone.

Under an idealised fixed energy relationship, the residual-load ratio provides an indication of potential load-supported duration. Reducing demand from 225 W to 165 W produces a duration factor of approximately 1.36, while reducing demand to 15 W produces a factor of 15.0 relative to the baseline. These ratios do not replace field battery testing because actual runtime also depends on inverter efficiency, battery chemistry, discharge limits, start-up current, and state-of-charge accuracy. They nevertheless demonstrate the practical significance of the reduction: the available backup reserve is concentrated on the household's selected critical service rather than being shared across deferrable loads.

Dynamic settings, explainability, and user-intent preservation:
When thresholds were changed to 90%, 45%, and 15%, a 50% battery input selected SAVING mode rather than NORMAL. This confirmed that the engine read its boundaries from persisted settings. The resulting messages explained why lower-priority appliances were restricted. Because the rules are deterministic, the observed action can be traced to a specific battery value, threshold, appliance priority, desired state, and control source. The television remained off after the battery recovered because its user-desired status was false. This result is important because a system that automatically restores every appliance would reverse an explicit household choice and could introduce avoidable demand immediately after recovery. VoltWise distinguished a temporary system-created off state from a user-created off state and restored only appliances that the user still wanted on.

Session-based energy-savings attribution:
At 9%, VoltWise reported an instantaneous 210 W reduction from the refrigerator and lighting loads. The manually disabled 120 W television was excluded because the system had not created its off state. The dashboard therefore did not claim a saving that resulted from the user's earlier choice. Saving sessions supported kilowatt-hour accumulation over time, separation of grid and battery savings, counting of control actions and managed appliances, and identification of the leading contributor.

The session model also resolves a common semantic error. A 210 W reduction describes an instantaneous difference between baseline and active demand; it becomes 0.210 kWh only if maintained for one hour. By recording duration, VoltWise can report both quantities correctly. This is valuable during long outages because a series of short interventions may preserve less energy than one sustained disconnection even when the same rated appliance is involved.

Economic value of avoided energy
The session model allows avoided grid energy to be translated into a monetary estimate using the active tariff. For a representative saving of 0.5 kWh per day, VoltWise would avoid 15 kWh per month and 182.5 kWh per year. At K0.54/kWh, this corresponds to approximately K8.10 per month and K98.55 per year. At K1.28/kWh, the same energy corresponds to approximately K19.20 per month and K233.60 per year. The benefit may be larger when reduced consumption delays movement into a higher tariff band.

Table 4. Illustrative monetary value of 0.5 kWh daily avoided grid energy

Tariff rate	Monthly avoided energy	Estimated monthly saving	Estimated annual saving
K0.54/kWh	15 kWh	K8.10	K98.55
K1.28/kWh	15 kWh	K19.20	K233.60

These values are illustrative outputs of the implemented accounting logic rather than field-measured household savings. Their importance lies in connecting a traceable control action to accumulated energy and then to household cost. Battery-related savings are reported separately because their immediate benefit is preserved backup capacity and potential service continuity rather than a direct utility-charge reduction during the outage.

Prepaid and tariff analytics:
The rate service mapped monthly grid-energy inputs to configured bands and returned the current rate, estimated cost, distance to the next threshold, and a proximity warning. An 80 kWh case selected the first band and produced K43.20 at K0.54/kWh. A 150 kWh case selected the second band and produced K192.00 at K1.28/kWh. At 92 kWh, the service reported 8 kWh remaining before the next band and generated a warning. These cases verified that cumulative grid consumption was translated into actionable cost information.

Table 5. Tariff analytics validation cases

Monthly grid energy	Selected band/rate	Estimated cost	Distance to next band	System response
80 kWh	R1 / K0.54 per kWh	K43.20	20 kWh	Normal status
92 kWh	R1 / K0.54 per kWh	K49.68	8 kWh	Proximity warning
150 kWh	R2 / K1.28 per kWh	K192.00	50 kWh	R2 status

The prepaid component complemented tariff analysis by presenting remaining units, consumption status, and an estimated duration based on recent or assumed daily use. The indicators answer different questions: prepaid balance shows how much purchased energy remains, while tariff progression shows how cumulative grid consumption affects the current cost position. Linking both to appliance demand and attributable savings gives the household a practical basis for adjusting consumption before units are exhausted or a higher tariff band is reached.

Integrated system behaviour and practical implications:

The Flutter application retrieved appliance, dashboard, setting, notification, saving, report, and rate data from the FastAPI backend. Changes to battery level, grid state, appliance priority, thresholds, and manual status were reflected consistently across the relevant interfaces. Persistent state allowed one module's decision to become another module's evidence: a control action changed appliance demand, opened a saving session, updated the dashboard, and generated an explanation or notification. The practical value of VoltWise lies in this chain of evidence. A user can see the current household condition, define what matters, observe the action taken, understand why it occurred, and later review the resulting energy and cost implications. This transparency is especially important during load shedding, where households must balance service continuity against finite backup capacity. The system does not remove household authority; it operationalizes that authority through stored priorities and intentions.

Validity, limitations, and deployment pathway:-

The controlled evaluation provides repeatable evidence of software correctness, comparative policy behaviour, and consistency across monitoring, control, savings, and tariff analytics. Internal validity was strengthened by deterministic input conditions and explicit expected outputs. Construct validity was supported by separating instantaneous power, accumulated energy, grid consumption, battery-related savings, and monetary estimates. The comparison with manual and single-threshold strategies reduced the risk of presenting benefits in isolation. The principal limitation is the absence of physical household measurements. The results validate decision logic and accounting behaviour but do not yet establish switching reliability, realised battery-runtime improvement, inverter losses, start-up-current effects, or user acceptance under live conditions. The evaluation also used a small, purposive appliance set. The next stage should connect calibrated meters, battery and inverter telemetry, smart plugs or isolated relays, and a broader range of household loads. Repeated outage profiles and structured usability assessment should then measure actual energy savings, runtime extension, response time, switching accuracy, and user understanding.

Conclusion:-

VoltWise 2.0 demonstrates that recurrent household load shedding can be addressed as a transparent and user-governed energy-allocation problem. The system unifies progressive priority control, manual-intent preservation, attributable savings sessions, prepaid monitoring, and tariff interpretation within a single mobile and backend architecture. Controlled evaluation showed that VoltWise reduced the 225 W user-permitted load to 165 W at 49% battery charge and to 15 W at 19% and 9%. Against the manual/no-intervention baseline, these outcomes represented reductions of 26.7% and 93.3%, respectively. Against the single-threshold controller, VoltWise achieved a further 90.9% reduction at the two lowest battery states. The system simultaneously protected a 15 W high-priority communication service, preserved the user's deliberate decision to keep the television off, excluded user-created off states from savings, and maintained separate grid and backup accounting.

The savings and tariff modules converted control events into auditable household value. A representative 0.5 kWh daily grid-energy saving corresponds to 15 kWh per month and an estimated K8.10-K19.20 monthly benefit across the two evaluated rates, with additional value possible when consumption remains below a higher tariff threshold. This connection among appliance action, accumulated energy, prepaid units, tariff progression, and cost distinguishes VoltWise from systems that report states or instantaneous demand without an attributable economic interpretation. VoltWise demonstrates that transparent, user-governed energy allocation can support residential resilience during load shedding while providing auditable savings and cost-awareness mechanisms. Users define what matters, the system adapts demand as available energy changes, and every action remains traceable to a priority, threshold, intention, and measurable outcome. The architecture therefore provides a strong foundation for physical deployment and broader empirical evaluation in load-shedding-prone households.

Declarations:

Funding: This research received no external funding.

Conflict of interest: The authors declare no conflict of interest.

Ethical considerations: The study evaluated a software prototype using simulated household-energy data and did not involve human participants, personal data, or live household electrical installations.

Data availability: The test conditions and representative results used in the evaluation are described in this manuscript. Additional implementation data may be made available by the corresponding author subject to institutional and submission requirements.

References:-

[1] A. Raza, J. Li, Y. Ghadi, M. Adnan, and M. Ali, "Smart home energy management systems: Research challenges and survey," Alexandria Engineering Journal, vol. 92, pp. 117-170, 2024. https://doi.org/10.1016/j.aej.2024.02.033
[2] J. Leitão, P. Gil, B. Ribeiro, and A. Cardoso, "A survey on home energy management," IEEE Access, vol. 8, pp. 5699-5722, 2020. https://doi.org/10.1109/ACCESS.2019.2963502
[3] M. Salgado, M. Negrete-Pincetic, A. Lorca, and D. Olivares, "A low-complexity decision model for home energy management systems," Applied Energy, vol. 294, Art. no. 116985, 2021. https://doi.org/10.1016/j.apenergy.2021.116985
[4] L.-G. Hua et al., "Smart home load scheduling system with solar photovoltaic generation and demand response in the smart grid," Frontiers in Energy Research, vol. 12, Art. no. 1322047, 2024. https://doi.org/10.3389/fenrg.2024.1322047
[5] C. H. Antunes, M. J. Alves, and I. Soares, "A comprehensive and modular set of appliance operation MILP models for demand response optimization," Applied Energy, vol. 322, Art. no. 119142, 2022. https://doi.org/10.1016/j.apenergy.2022.119142
[6] N. Gaikwad, N. S. Raman, and P. Barooah, "Smart home energy management system for power system resiliency," arXiv:2003.05570, 2020. https://arxiv.org/abs/2003.05570
[7] International Energy Agency, Energy Efficiency 2024. Paris, France: IEA, 2024. https://www.iea.org/reports/energy-efficiency-2024
[8] International Energy Agency, The Value of Demand Flexibility: Benefits Beyond Balancing. Paris, France: IEA, 2025. https://www.iea.org/reports/the-value-of-demand-flexibility
[9] Government of the Republic of Zambia, National Energy Compact for Zambia, Mission 300, 2025. https://www.worldbank.org/en/programs/mission-300
[10] Google, "Flutter documentation." https://docs.flutter.dev/
[11] FastAPI Project, "FastAPI documentation." https://fastapi.tiangolo.com/
[12] SQLite Consortium, "About SQLite." https://www.sqlite.org/about.html
[13] Energy Regulation Board, "Electricity tariff decisions and publications." https://www.erb.org.zm/
[14] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, "A design science research methodology for information systems research," Journal of Management Information Systems, vol. 24, no. 3, pp. 45-77, 2007. https://doi.org/10.2753/MIS0742-1222240302.