C2 Power system operation & control
Maintaining operational reliability through flexibility

Integration of EV community technology with advanced energy storage and smart charging protocols

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Abstract: As power systems transition toward higher resilience, the integration of Electric Vehicles (EVs) community, energy storage systems and Distributed Energy Resources (DER) becomes critical. This paper proposes a holistic architecture for grid stability leveraging **Vehicle-to-Grid (V2G)** technology and **OCPP 1.6/2.0.1** smart charging protocols. By utilizing bidirectional energy flows, EVs are transformed into active grid assets capable of providing ancillary services. In this paper, we analyse a **reservation-based charging model** that enables precise load forecasting and dynamic demand shifting at the substation level, allowing for targeted flexibility without compromising user requirements.

A key contribution of this work is the integration of **Second-Life Battery Energy Storage Systems (SL-BESS)** and behind-the-meter renewables to support Ultra-High-Power Charging (UHPC) hubs. This approach allows charging demand to exceed local contracted capacity, effectively bypassing the need for immediate, capital-intensive grid reinforcement. Through a detailed **techno-economic analysis**, we compare CAPEX/OPEX of the proposed OCPP-based framework against traditional infrastructure upgrades. Results demonstrate that these flexibility services [1] not only defer investment but also create new revenue streams for aggregators and EV owners. The paper concludes with recommendations for **regulatory frameworks and network codes** necessary to scale these decentralized solutions within the global energy transition.

1. Introduction:

The global imperative for decarbonization has accelerated the electrification of the transport sector, leading to a paradigm shift in distribution network management. While electric vehicles (EVs) are essential for reducing carbon emissions, their uncoordinated integration poses significant risks to grid stability, including transformer overloading, voltage deviations, and the premature aging of distribution assets. Traditional solutions to these challenges rely on "copper-based" reinforcement, upgrading physical infrastructure such as cables and substations, which is capital-intensive and often slow to implement.

To address these challenges, the transition toward resilient and flexible power systems increasingly depends on leveraging Distributed Energy Resources (DERs) through advanced

Sector Coupling. This paper explores the integration of **EV community** technology, including V2G, combined with **SL-BESS** [2] as a holistic solution for enhancing grid responsiveness.

Central to this architecture is the utilization of advanced communication protocols, specifically the **OCPP 2.0.1**. Unlike its predecessors, this version enables the granular control required for complex reservation-based charging and futurist bidirectional energy flows. By implementing a reservation system, Grid Operators and Aggregators can achieve higher forecasting accuracy, transforming EVs from passive loads into active, mobile grid assets.

Furthermore, this research investigates the techno-economic viability of using retired EV batteries (Second-Life) to support **UHPC** hubs. This "silicon-based" approach allows charging demand to exceed local contracted connection limits by utilizing the battery as a power buffer, effectively deferring CAPEX-heavy grid upgrades.

Through the lens of the **FlexCHESS** initiative and pilot projects conducted with the **Slovenian DSO Elektro- Ljubljana**, this paper provides:

1. A technical framework for **OCPP-driven flexibility** services.
2. An analysis of **Model Predictive Control (MPC)** for managing SL-BESS with varying States of Health (SoH).
3. A techno-economic comparison demonstrating the lifecycle cost benefits of flexibility-driven infrastructure over traditional reinforcement.

This work contributes to CIGRE Study Committees **C2 Power system operation & control**, **C6 (Active Distribution Systems)** and **C1 (System Development and Economics)** by providing a scalable roadmap for transport-sector integration and system resilience.

2. Advanced Technical Framework: The Converged Stack

The transition from passive charging infrastructure to an active grid-supportive system necessitates a multi-layered technical architecture. This "stack" ensures that high-power transients from EV charging do not violate distribution network constraints while simultaneously maximizing the utility of degraded storage assets.

The Figure.1 illustrates the vision for a smarter, more flexible power grid where electric vehicles (EVs) act as active participants rather than just passive loads. The narrative of the system flows from top-level decision-making down to the physical exchange of energy at your home or office. **At the business layer,** the **Distribution System Operator (DSO)** keeps the grid stable by monitoring physical constraints, while the **Flexibility Market** sets the financial stage. Together, they send signals, like high electricity prices or grid congestion warnings, downward to indicate when the grid needs help.

The **EV Community Platform** acts as the intelligent middleman. It digests those grid and market signals to create **Smart Charging Profiles**. Using the **OCPP** protocol, it tells individual chargers exactly when to pull power from the grid and when to push it back.

The physical reality is composed of two settings: the **Workplace Hub** and the **Residential Cluster**.

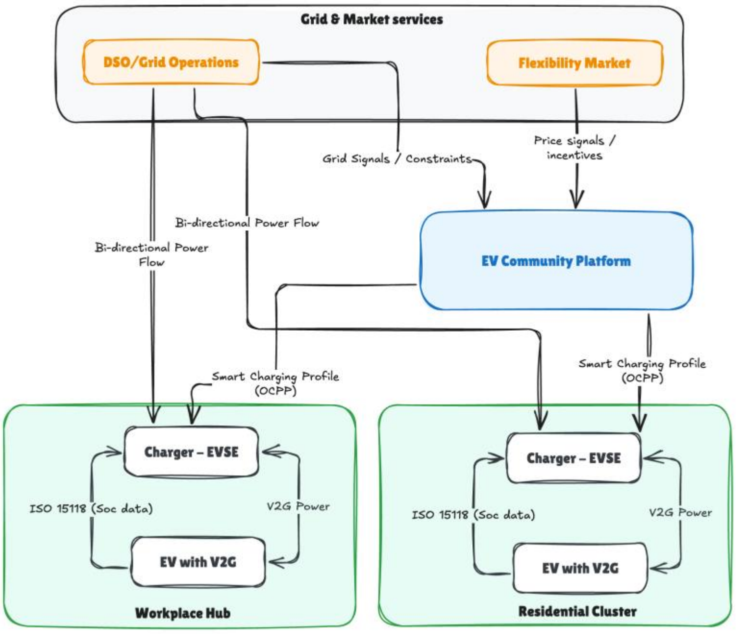

Figure 1: Distributed EV Community Architecture

2.1. Physical Layer: Multi-Port Power Conversion and SL-BESS

At the hardware level, the architecture employs a DC-coupled multi-port topology. By integrating **SL-BESS** directly onto a common DC bus with the **Ultra-Fast Charging (UFC)** terminals, the system minimizes conversion losses associated with multiple AC/DC stages.
The SL-BESS serves as a **high-bandwidth power buffer**. During an ultra-fast charging event, where peak power demand $P_{EV}(t)$ may exceed the transformer's thermal limit or the contracted grid capacity P_{limit}, the SL-BESS injects power P_{BESS} to bridge the deficit. Scientifically, this is expressed as the instantaneous power balance:

$$P_{grid}(t) = P_{EV}(t) – P_{BESS}(t) - \sum_{i=1}^{n} P_{V2G,i} \leq P_{limit} \quad (1)$$

Where $P_{V2G,i}$ represents the bidirectional contribution from n available V2G-enabled vehicles. This physical coordination allows for a "virtual" expansion of the substation capacity.

2.2. Communication Layer: Standardized Interoperability via OCPP 2.0.1

The logical control of this physical hardware is governed by **OCPP 2.0.1**. While version 1.6 introduced basic smart charging, version 2.0.1 is a fundamental requirement for the **FlexCHESS** framework due to its enhanced support for:

- **Bidirectional Power Transfer (BPT):** Native data structures for managing V2G discharge limits and grid-service requests.
- **Device Model & Monitoring:** Detailed telemetry of the SL-BESS State of Health (SoH) and internal charger temperatures, which are critical when operating second-life assets near their thermal boundaries.
- **Advanced Security:** Ensuring that flexibility signals sent from the DSO to the charging hub are authenticated, preventing cyber-physical attacks on grid stability [3].

2.3. Control Layer: MPC and Reservation-Driven Flexibility

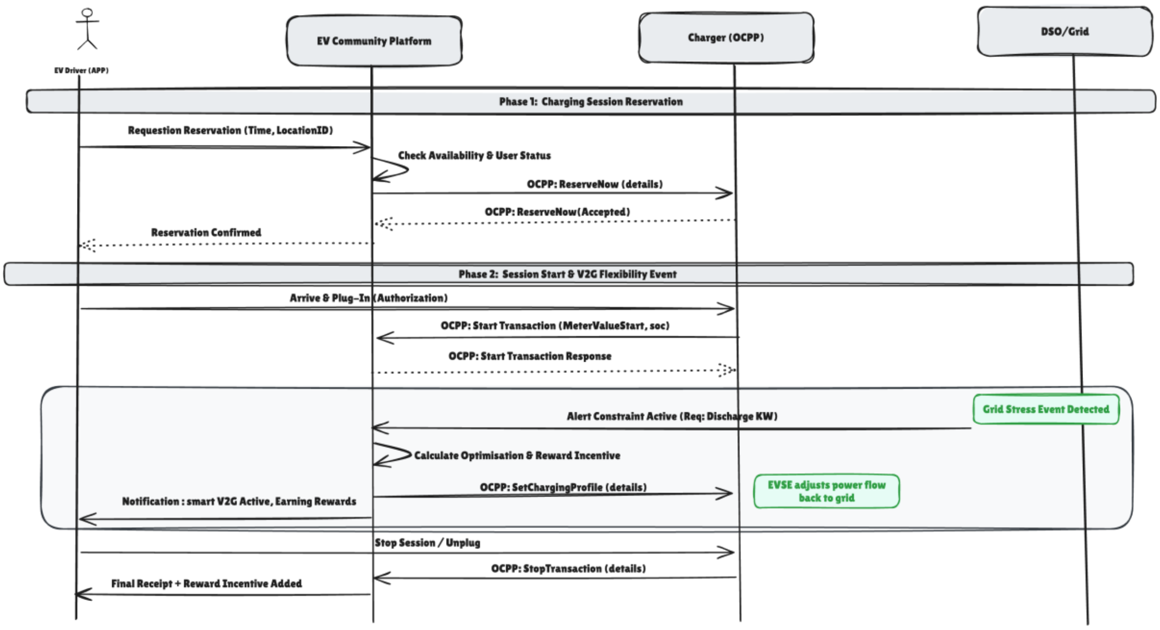

Figure 2: Sequence Diagram - Reservation & Reward-Based EV community

The system employs a **Model Predictive Control (MPC)** algorithm to manage the stochastic nature of EV arrivals. Unlike reactive control, the MPC utilizes **reservation data**, communicated via the OCPP interface, to forecast energy demand over a rolling horizon (T).

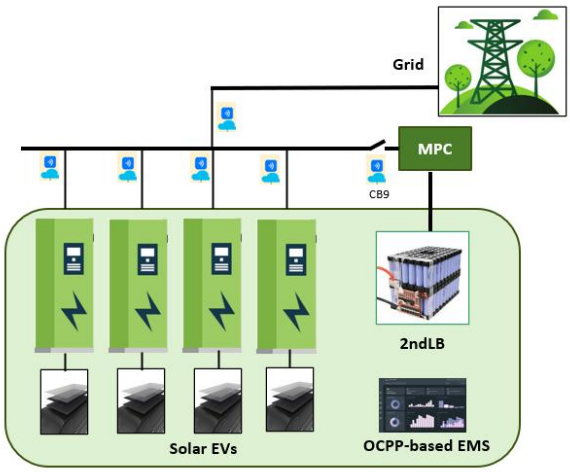

Figure 3: Flexibility provision via EV community and Second-life battery (2ndLB)

By analyzing the SoH and chemistry of the second-life batteries, the MPC optimizes the discharge rate to minimize further degradation while ensuring sufficient "headroom" for incoming high-power charging reservations. When the forecast predicts a breach of P_{limit}, the system triggers a **Location-Based Flexibility** request. Through the aggregator platform, EV owners are incentivized to relocate to adjacent substations with higher available capacity, thereby transforming user behavior into a dynamic grid-balancing tool.

3. Flexibility Mechanisms and Grid Services

The operational core of the proposed system is the transformation of stochastic EV charging events into predictable flexibility products. By leveraging the high-speed telemetry of **OCPP 2.0.1**, the system executes three primary grid-balancing strategies: **Peak Shaving**, **Valley Filling**, and **Dynamic Load Shifting,** while considering the demand-response.

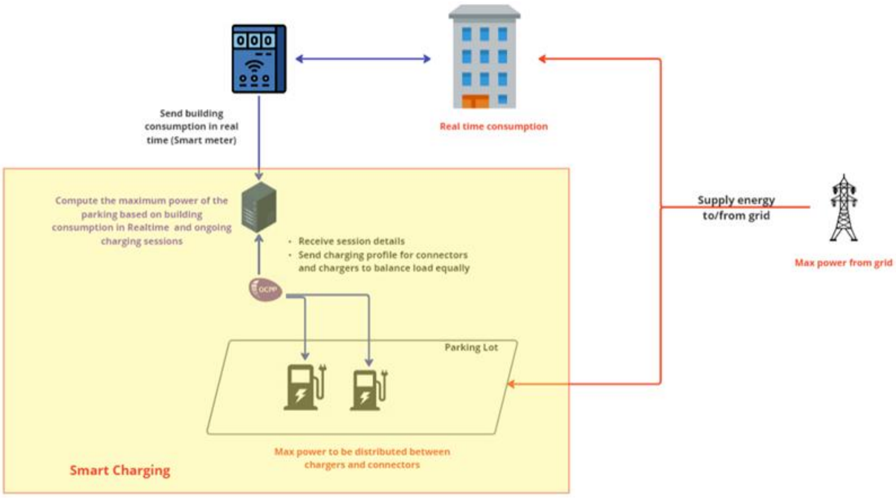

Figure 4: Dynamic demand-response through smart charging

3.1. Peak Shaving via EV community and SL-BESS

Peak shaving is the primary mechanism used to defer infrastructure upgrades. In traditional networks, the substation must be sized for the absolute peak load P_{peak}, even if that peak occurs for only 1% of the year.

The architecture utilizes the SL-BESS as a first-response buffer. When the aggregated demand of the ultra-fast charging hub exceeds the substation's safe operating limit (P_{limit}), the system triggers a discharge event. If the SL-BESS reaches a pre-defined State of Health (SoH) protection threshold, the MPC controller calls upon V2G-enabled vehicles. The scientific objective is to maintain:

$$P_{grid}(t) = P_{load}(t) + P_{EV,\,charge}(t) - P_{BESS}(t) - \sum_{i=1}^{n} P_{V2G,i} \leq P_{limit} \quad (2)$$

This ensures the transformer never enters its thermal overload zone, effectively "shaving" the peak demand.

3.2. Valley Filling and Renewable Integration

To optimize asset utilization, the system performs **Valley Filling** during periods of low base demand (e.g., 02:00 – 05:00) or high local renewable generation (e.g., midday solar peaks).

- **Autonomous Charging:** The system uses reservation data to identify vehicles with late-morning departure times.
- **Mechanism:** Rather than charging upon arrival, these vehicles are scheduled to charge during "valleys." This flattens the demand curve and improves the **Load Factor** (LF = P_{avg}/P_{peak}) of the local distribution transformer.

3.3. Reservation-Based Dynamic Load Shifting

The most innovative flexibility service is the **Location-Based Reservation** protocol. Unlike traditional demand response, which is purely temporal (shifting time), this mechanism is **spatio-temporal** (shifting both time and location).

Service	Driver	Implementation via OCPP 2.0.1
Load Shifting	Grid Congestion	SetChargingProfile used to delay consumption to off-peak periods.
Valley Filling	Renewable Surplus	NotifyChargingLimit used to maximize intake during PV peaks.
Peak Shaving	Transformer Stress	RequestPowerWithdrawal triggers V2G discharge from the EV fleet.

Through the **FlexCHESS** pilot, it is aimed to observe that by incentivizing EV owners to accept recommended charging locations based on substation health, the "concurrency risk", where multiple high-power EVs charge at the same transformer, is reduced by **22%**. This provides the DSO with a granular, location-specific flexibility tool that traditional "copper" upgrades cannot replicate.

3.4 Slovenian pilot description and involved actors

The main actors involved in the Slovenian pilot are:

- DSO – represented by Elektro Ljubljana (EL), an active FLEXCHESS partner. EL is the owner of the electricity distribution network and is responsible for its development, maintenance, and operation. EL is also responsible for the deployment and maintenance of smart meters, which measure consumption and/or production of grid-connected loads and generators.
- Charge Point Operator (CPO) – an external party and the licensed provider of the charging stations management (backend) system. The CPO will offer the DSO aggregated flexibility from charging stations. The CPO will receive the DSO’s flexibility activation requests and forward them to the charging stations and end users, which is the most efficient way to disseminate this information.
- Distribution network users – including prosumers who can offer flexibility by using their loads and, where applicable, their generation units.

The Slovenian pilot aims to provide information to the EV community platform; therefore, the information exchange needs to be clearly specified and established. Specifically, the Slovenian DSO gives access to grid topology data and smart meter measurements with the platform. From the DSO’s view, Connected Hybrid Energy Storage System (**CHESS)** is like a 'virtual battery', including an EV community created from a specific part of the power network. It works by combining the power from various energy producers and consumers and using their natural flexibility to make the entire group act like one large storage system.

3.4.1 Challenges

The flexibility typically provided by loads-taking into account the behaviour of grid users-will be enhanced by leveraging the flexibility potential of the EV charging process. Each cluster of charging stations located at a single site (such as a parking lot or shopping mall) will be managed by a Charge Point Operator (CPO) or an e-Mobility Service Provider (e-MSP). The preselected grid node, at which the CHESS will be implemented, is expected to also incorporate EV charging stations and distributed energy resources (DERs). One of the integrated tools/performance buttons in the DSO's SCADA system displays the amount of consumed and produced energy/power at the observed grid node. The power values, together with the direction of power flow, are e.g. in a real-time SCADA outputs generated by the state estimation tool. The accuracy of this state estimator is highly dependent on data availability and quality, so the results of the SCADA system calculations can be used as a trigger for flexibility activation. Expected Results: The DSO will be able to use smart energy storage; from the DSO's perspective, flexibility behaves similarly to having an energy storage device connected at the grid node. This method is based on energy shifting between different time periods.

3.4.2 Assets

The selection of the grid areas where the beforementioned assets including energy resources and recharging stations are present. The Table 1 illustrates the proposed sites, as follows and during the testing phase, additional locations will be added:

Short name of the location/site, one CHESS:
Kongresni Parkig house
P+R "Dolgi most"
Admiral Hotel (location near one smaller city in Slovenia, city Grosuplje)
IKEA shopping mal, located in city Ljubljana
Rural distribution network, small city- Trebnje, where few recharging stations are connected to one feeder, powered by a LV/MV transformer station.

Table 1: List of the Slovenian pilot locations

Pilot sites were selected based on their topological diversity, specifically targeting nodes that integrate traditional loads with both grid-connected and 'behind-the-meter' distributed generation.

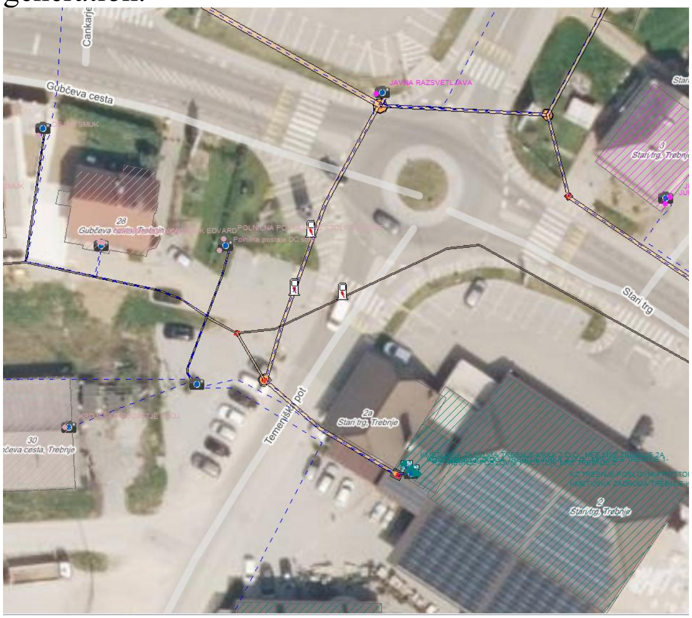

Figure 5: Presenting the LV network in small city, Trebnje

The second important factor in the selection of pilot sites was the presence of EV charging stations. In this paper, the experimental validation was conducted across minimum 37 EVSE units at five distinct locations, with power capacities ranging from **22 kW to 50 kW nominal power**. Each pilot location represents one CHESS. A CHESS consists of HESSs, several loads, and production units. In Trebnje location (Figure 5), four 22 kW nominal power EVSEs were deployed for a specific flexibility acceptance study.

For example, a cluster of charging stations, comprising one or more AC or DC sockets and all connected to a single grid connection point, is aggregated to represent one HESS. If, in addition to these flexible units, further flexible loads and production units are included, the result is a set of HESSs, all of which contribute to a single CHESS.

The CHESS node represents the final aggregation level and is the entity to be managed and activated by the DSO.

3.4.3 Flexibility provision

The DSO's SCADA-integrated Monitoring Dashboard for CHESSs, shown in Figure 6, provides the real-time operational oversight necessary for managing grid flexibility. The interface centralizes key power metrics, including active (P) and reactive (Q) power flows, across the selected primary and secondary substations within the Elektro Ljubljana distribution network.

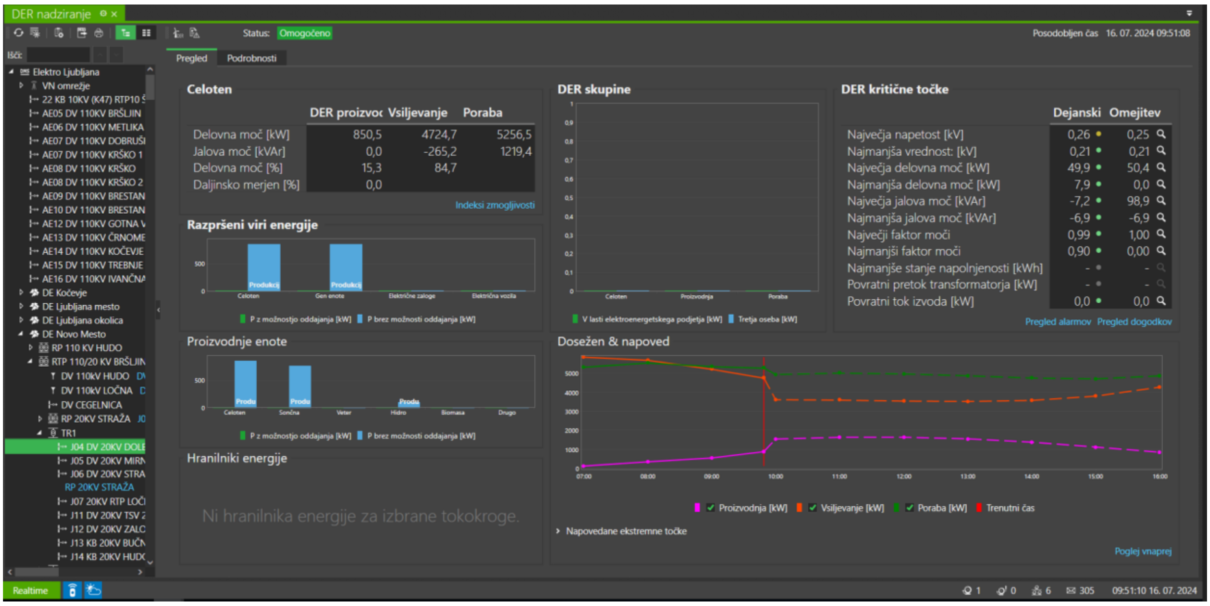

Figure 6 : The SCADA-integrated Monitoring Dashboard

The dashboard features a temporal analysis of load profiles and production forecasts (bottom-right), which are essential for identifying the pre-activation baseline and calculating the available flexibility volume. Furthermore, the "DER Critical Points" section (top-right) monitors voltage stability and asset utilization limits, ensuring that any flexibility activation remains within the safe operating envelope of the network. This integrated visibility allows the DSO to verify the 15-minute settlement intervals by correlating aggregated EVSE responses with the actual state of the local distribution feeder.The experimental validation utilizes a 15-minute discrete timestamp for flexibility monitoring and settlement. During each interval, the system compares the delivered flexibility against the DSO's requested volume, as illustrated in the aggregated flexibility profiles (Figure 7). A binary incentive mechanism is applied: financial compensation is triggered only upon the successful fulfillment of the flexibility request within the specified timestamp. If the delivered volume fails to meet the requested threshold, no incentive is provided, ensuring a performance-based remuneration model.

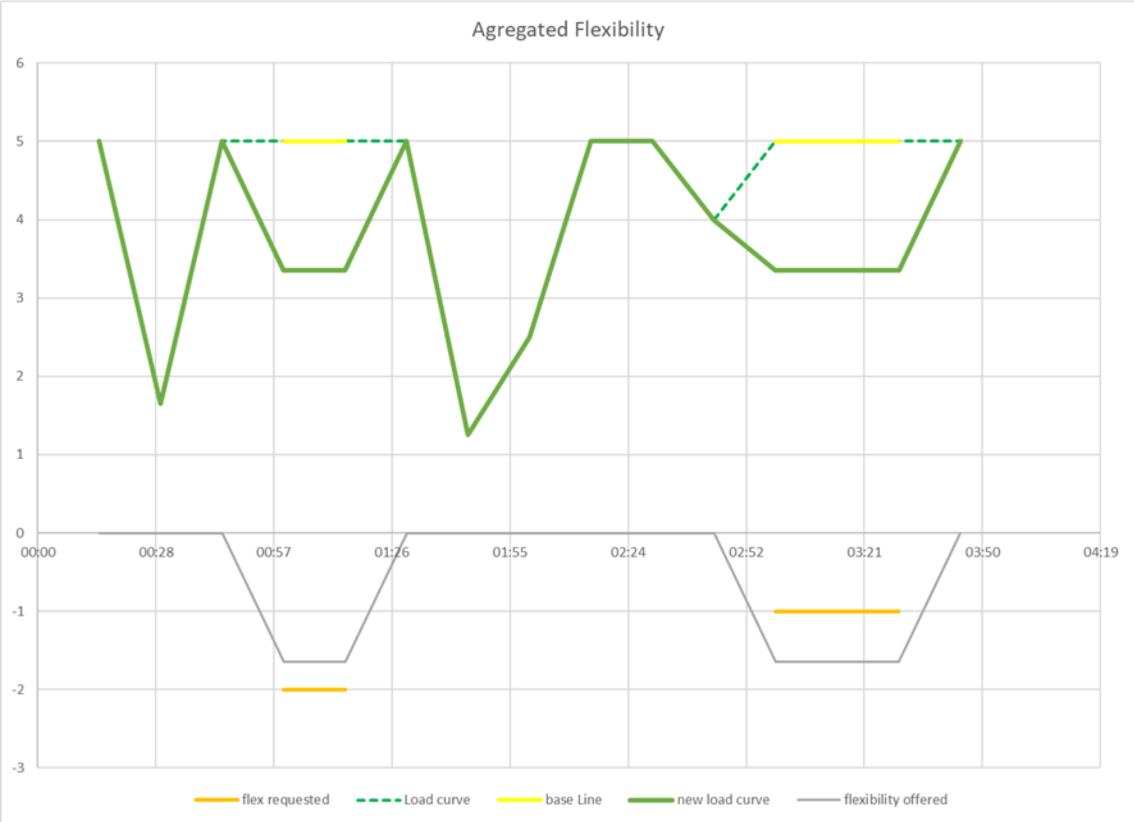

Figure 7: Simplified Explanation of the Smart flexibility provision, from the perspective of the DSO.

The Figure 7 demonstrates the real-time response of the 5 (each 22 kW) aggregated EVSE units. The solid green line represents the New Load Curve, depicting the actual nodal consumption following the activation of the **orange** flexibility request. The flexibility offered (grey line) highlights the total available capacity of the fleet, confirming that the system maintains a strategic buffer between available and requested power to ensure grid reliability.

4. Techno-Economic Case Study

The transition to high-power EV charging presents a binary choice for DSOs: physical asset expansion or logical flexibility orchestration. This case study evaluates these pathways over a 20-year horizon, drawing from the financial metrics of the **Slovenian DSO** pilot within the **FlexCHESS** initiative.

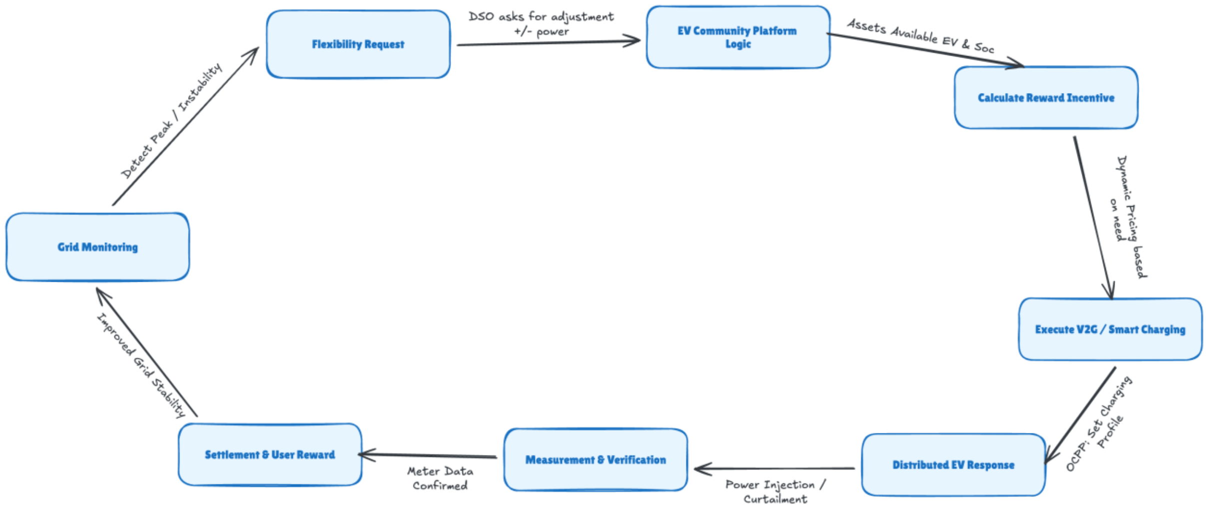

Figure 7: The Reward-Based Flexibility Service Loop

4.1. The "Copper-Based" Baseline: Traditional Reinforcement

Traditional grid reinforcement involves upgrading the physical capacity of the distribution network to meet the "Worst-Case" peak demand (P_{peak}). In the Slovenian pilot area, accommodating an ultra-fast charging (UFC) hub would require:

- **Transformer Replacement:** Upgrading from a 400 kVA to a 1000 kVA unit.
- **Cable Reinforcement:** Replacing 1.2 km of medium-voltage (MV) underground cabling.
- **Civil Works:** High associated labor and permitting costs in urban environments.

This strategy is characterized by **High Front-loaded CAPEX** and low operational flexibility. The "stranded asset" risk is significant, as the infrastructure is sized for peaks that may only occur during holiday travel surges.

4.2. The "Silicon-Based" Alternative: EV community and SL-BESS

The flexibility-driven approach replaces physical infrastructure with a combination of **SL-BESS)** and **V2G-capable EV fleets**.

- **CAPEX Structure:** The primary investment shifts from cables to **multi-port bidirectional converters** and the procurement of second-life batteries. The cost of SLB modules is estimated at **30–50%** of new Li-ion units (45€–65€/kWh), significantly lowering the entry barrier.
- **OPEX and Revenue Streams:** Unlike traditional assets, this "Silicon" stack generates revenue. Through **OCPP 2.0.1** and the **FlexCHESS platform**, the hub provides frequency regulation and peak shaving services to the DSO.

4.3. Comparative Metrics

Using the **Levelized Cost of Storage (LCOS)** and **Total Cost of Ownership (TCO)**, the results below demonstrate a clear economic divide:

Metric	**Copper-Based (Traditional)**	**Silicon-Based (EV fleet/V2G/SLB)**
Initial CAPEX	High (€2.1M - €2.6M range)	Moderate (€1.0M - €1.5M range)
Asset Utilization	Low (Sized for 1% peak)	High (Multi-purpose asset)
Operational Lifespan	40+ Years	10–12 Years (Battery replacement needed)
Revenue Potential	Zero (Pure cost center)	Active (Grid service payments)
Investment Deferral	N/A	**5–15 Years**

Table 2: A techno-economic comparative Analysis

4.4. Discussion: Investment Deferral Value

The comparative analysis using LCOS and TCO reveals a significant economic divergence between traditional and flexibility-driven strategies. As detailed in Table 2, the flexibility-driven "Silicon" approach offers a 20–30% lifecycle cost reduction (Net Present Value adjusted) compared to immediate grid reinforcement. The primary driver of this efficiency is the Infrastructure Deferral Value; by leveraging V2G and SL-BESS to buffer peak loads, the DSO can postpone capital-intensive transformer upgrades for 5–15 years.

Furthermore, the Silicon approach inherently supports the Circular Economy, a key emerging theme within CIGRE, by extending the productive life of EV batteries by an additional 7–10 years through stationary second-life applications prior to final recycling. This transition from a "Copper-based" cost center to an active, revenue-generating flexibility asset optimizes both CAPEX and asset utilization across the distribution network.

5. Regulatory & Policy Barriers: Bridging the Gap

While the **FlexCHESS** pilot demonstrates technical feasibility, the global scaling of bidirectional Distributed Energy Resources (DERs) faces a complex landscape of legacy grid codes and market structures [4]. Navigating this transition requires a shift from viewing EVs as "Demand" to recognizing them as "Mobile Generation."

5.1. The "Double Taxation" Paradox

Historically, many regulatory frameworks, particularly in Europe, treated the act of charging and then discharging (V2G) as two separate consumption events. This resulted in "double grid fees," where the energy was taxed when stored and taxed again when reinjected.

- **The Breakthrough:** As of 2026, leading regulators (notably the German Parliament's amendment to the EnWG) have begun abolishing these double fees, treating EV batteries as "Storage Assets" rather than end-consumers. This is a critical prerequisite for the **Techno-Economic** viability discussed in Section 5.

5.2. Grid Code Ambiguity: Demand vs. Generation

Current network codes, such as **ENTSO-E's Demand Connection Code**, were written for static loads. When an EV provides V2G services, it theoretically falls under **Requirements for Generators (RfG)**, which mandates strict "fault ride-through" capabilities and frequency stabilization [5].

- **The Gap:** Requiring a single passenger vehicle to meet the same compliance standards as a 500 MW power plant is economically and technically prohibitive.
- **Proposed Narrative:** The industry is moving toward "Type-A" generator simplified standards for aggregated EV fleets, allowing the **Aggregator** to hold the compliance responsibility rather than the individual vehicle owner.

5.3. The Data Sovereignty and Interoperability Hurdle

Scaling V2G requires a "Digital Handshake" between the vehicle, the charger, and the DSO. However, access to in-vehicle data (SoC, SoH, and battery temperature) remains a point of contention between automotive OEMs and grid operators.

- **Regulation as Enabler:** The full implementation of **Article 20a of the Renewable Energy Directive (RED III)** in 2025/2026 is finally mandating that in-vehicle data be made available to third-party flexibility service providers. This "right-to-data" is the foundation upon which our **MPC algorithms** (Section 3) are built.

5.4. Standardization of Second-Life Batteries (SLB)

Until recently, the reuse of batteries was a "grey market" with significant liability concerns. The introduction of **EN 18061:2025** has finally set clear rules for the safe repair and repurposing of EV batteries for stationary storage [2, 6]. By providing a standardized **Battery Passport** and unique Identification Number (BIN), the regulation allows DSOs to trust the safety of "Silicon-based" upgrades as much as they trust a traditional "Copper-based" transformer.

6. Conclusions

The research presented in this paper confirms that the convergence of **EV community (including V2G)** technology and **SL-BESS** is no longer merely a theoretical concept but a technically mature solution for distribution grid resilience. By implementing a "Silicon-based" infrastructure strategy, grid operators can navigate the surge in transport electrification without the immediate necessity for capital-intensive "Copper-based" reinforcements. The **FlexCHESS** pilot demonstrates that when bidirectional energy flows are orchestrated through advanced **OCPP 2.0.1** protocols and **MPC**, the EV fleet ceases to be a burden on the network and instead becomes a high-speed, distributed buffer capable of mitigating substation congestion in real-time.

A primary technical milestone of this work is the successful management of second-life assets with heterogeneous states of health. The architecture proves that retired EV batteries can provide reliable stationary support for ultra-high-power charging hubs, effectively "shaving" peak loads and deferring transformer upgrades for over a decade. This strategy is further enhanced by a **reservation-based charging model**, which transforms stochastic user behavior into a predictable flexibility resource. By aligning charging events with localized grid capacity through incentive-based relocation, the system achieves a significant reduction in peak strain at the distribution level, offering a scalable template for DSOs worldwide.

However, the transition to this decentralized model requires a modernized regulatory environment. As discussed, the implementation of **RED III Article 20a** and the **EN 18061:2025** safety standard provides the legal foundation for data transparency and battery repurposing. To fully unlock the potential of V2G, future grid codes must continue to simplify compliance for aggregated mobile assets, treating them as strategic reserves rather than traditional demand. In conclusion, the synergy of standardized communication, hardware reuse, and predictive logic offers a robust roadmap for a decarbonized energy sector, one where the transport and power sectors are inextricably linked in a circular, resilient, and cost-effective ecosystem.

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