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Assessing flexibility potential of a workplace Electric Vehicles charging infrastructure

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Executive Summary

Flexibility potential of a workplace charging infrastructure for Electric Vehicles (EV) is evaluated based on real employee charging data. The adopted approach centers on the perspective of a Charge Point Operator offering flexibility to a market aggregator after having determined its baseline power consumption according to different local load management strategies. The infrastructure presents maximum flexibility potential in a time band between 10 a.m. and 2-3 p.m. on working days and could provide up to 46% upward and 28% downward flexibility of the total daily energy need, depending on the baseline load management logic. Results highlight flexibility contributions of workplace charging infrastructures to the electricity system and lay groundwork for assessing EV flexibility service costs.

Keywords: Electric Vehicles, V2G, Smart Grid Integration, Energy Management, Charging business model

1 Introduction

In recent years, electric vehicles (EVs) have been increasingly adopted across Europe as a sustainable alternative to internal combustion engine vehicles. This transition comes from both the European Union's commitment to reducing greenhouse gas emissions, notably through initiatives like the "Fit for 55" package [1], but also from an increasing consumer's interest towards these sustainable and technologically advanced products. As a result, battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEV) accounted for 21 % of new car registrations in the EU in 2024, marking a significant increase from previous years [2]. However, widespread and uncontrolled EV charging proliferation poses a risk of overloading distribution networks, with potential repercussions for grid stability and security. Vehicle-Grid Integration (VGI) has emerged as a key strategy to align charging demand with network constraints and to unlock ancillary services [3]. Approaches range from time-shifted charging, to monodirectional (V1G) and bidirectional (V2G) load modulation strategies, and multiple studies have quantified their technical and economic advantages under various scenarios.
Literature works often adopt a system-level perspective, aiming to aggregate EV flexibility to exploit dynamic prices of the whole-sale market or to provide flexibility services to the grid. For example, an aggregated charging optimization aiming to minimize system "residual load" [4] —the gap between demand and renewable generation— is proposed in [5], demonstrating lower grid impact than uncontrolled charging. Londono et al. [6] point out how grid-unaware aggregate control strategies lead to higher grid impact, and therefore proposes a centralized control strategy for a high-level controller capable to optimize charging

schedule of various EV pools based on whole-sale energy prices while considering grid transformer limits. Other studies focus on large EV aggregators, proposing load management approaches to maximize overall system flexibility [7] or to maintain energy balance in the grid [8]. Finally, a nationwide scenario of transport electrification is analyzed in [9], where a huge number of sparse charging sessions are simulated and the aggregated flexibility potentials were derived, assessing various benefits in terms of reduced grid constraints violation and renewable curtailment.

However, these "top-down" approaches might overlook the multiplicity of stakeholders involved in real-world charging—each one with distinct objectives, data access, and control authority. Some actors operate at system level, such as the Balance Service Provider (BSP), others at local level, like the Charge Point Operator (CPO), which lacks visibility into market dynamics and grid conditions.

In contrast to the conventional aggregator-driven model, the present study adopts a "bottom-up" approach, in which it's the CPO, as the charging infrastructure owner, that offers its local, behind the meter flexibility to an external aggregator after having determined its charging baseline. Aiming to clarify the EV flexibility formation in a multi-actor framework, this paper introduces a novel general method to calculate the flexibility potential of any EV charging aggregate. The proposed methodology is applied to the case of a workplace charging infrastructure, whose flexibility potential is quantified and analyzed starting from experimental data.

2 EV flexibility calculation method

Extracting flexibility by EV charging presents many differences compared to a conventional power plant, which must be considered. First, significant amounts of flexibility arise from the aggregation of many geographically dispersed charging points, making flexibility evaluation a bottom-up process starting at charging infrastructure level. Second, the flexibility provision using EV charging affects many actors—end-users, Charge Point Operators (CPOs), and Balance Service Providers (BSPs)—each one with distinct roles and interests that must be mediated. Finally, the end-user energy requirement must be considered when modifying load profiles, ensuring the achievement of the desired battery State of Charge within a certain time. These aspects define a decentralized, multi-actor, and user-constrained approach to flexibility, impacting on the actual EV flexibility potential. Therefore, a precise calculation model should be introduced.

The CPO-centric approach adopted in this work considers that it's the CPO, as the owner of the charging infrastructure, which is capable of modifying EV consumption profiles by setting power setpoints to the charging stations. Flexibility provision to an external BSP aggregating many distributed resources is considered as a secondary benefit after determining the baseline charging profiles according to specific load scheduling strategies. These strategies prioritize users' charging needs while minimizing charging operating costs, either by reducing peak power withdrawal or maximizing the use of local renewable energy sources (RES) installed behind the connection point. As discussed in the following sections, adoption of different charging logics significantly affects the infrastructure's flexibility potential due to different baseline profiles determination.

The presented flexibility calculation method is based on the following assumptions:

- Charging is operated in V1G mode, meaning vehicles are not discharged.
- Charging is operated in alternate current (AC) mode via vehicle onboard charger.
- The total energy delivered in each charging session must remain unchanged when a flexibility service is activated, in order to always satisfy user energy needs.
- Each charging session can modify its baseline at most once to offer flexibility.

The general framework for calculating the flexibility potential of a single EV charging session is therefore illustrated in Figure 1. The red line represents the baseline charging profile determined by the charging strategies implemented by the CPO for load management, while the green line is maximum charging power determined by the specific onboard charger of the vehicle.

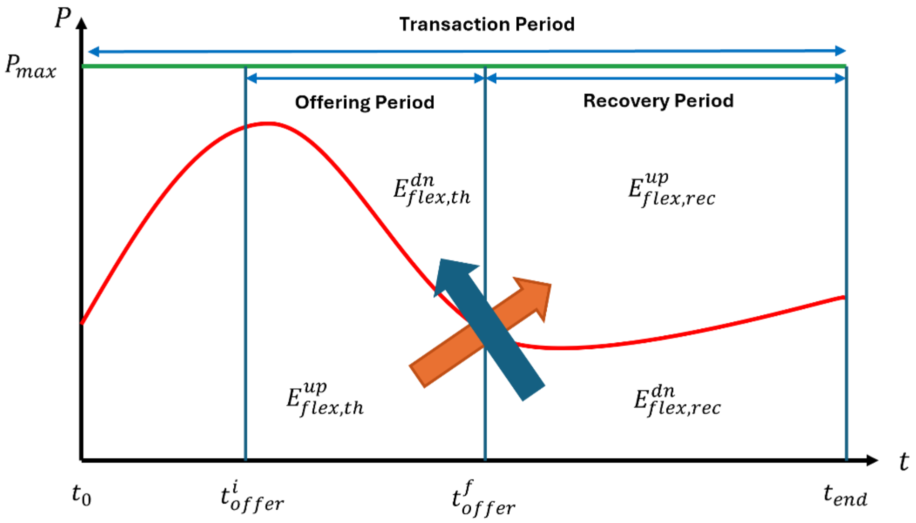

Figure 1: Flexibility calculation scheme of a single EV charge.

Three time periods are introduced for a precise definition of flexibility potential:

- **Transaction Period:** The overall duration of the charging session, starting from the vehicle's connection to the charging infrastructure (t_0) and ending with its disconnection (t_{end}).
- **Offering Period:** The time interval during which the CPO is willing to adjust charging baselines to provide flexibility services.
- **Recovery Period:** The phase in which energy modifications made during the Offering Period are compensated to ensure the total energy delivered in the session remains unchanged.

The definition of these periods, combined with the session's maximum power limit, identifies four areas within the power-time graph, each one corresponding to specific energy quantities. The meaning of these energy quantities is detailed in Table 1, using the standard generator-oriented reference system for defining upward and downward flexibility.

Table 1: Energy quantities derived from Offering Period and Recovery Period definition.

Energy item	**Symbol**	**Description**
Theoretical upward flexibility	$E^{up}_{flex,th}$	Energy absorption reduction if charging were suspended throughout the Offering Period.
Theoretical downward flexibility	$E^{dn}_{flex,th}$	Energy absorption increase if the charging power were increased to the maximum during the throughout the Offering Period.
Recovery upward flexibility	$E^{up}_{flex,rec}$	Maximum recoverable energy by maximizing charging rate throughout the Recovery Period.
Recovery downward flexibility	$E^{dn}_{flex,rec}$	Maximum recoverable energy by suspending charging throughout the Recovery Period.

The effective upward flexibility (E^{up}_{flex}) is the maximum energy that can be postponed from the Offering Period to the Recovery Period (orange arrow, Figure 1). Conversely, the downward flexibility (E^{dn}_{flex}) represents the maximum energy that can be advanced from the Recovery Period to the Offering Period (blue arrow). Once the Offering Period is established, and consequently the Recovery Period, the upward and downward flexibility potential for a single charging transaction are determined according to Equations (1) and (2). This calculation methodology ensures that the identified flexibility potential, if offered to an external aggregator, can always be executed upon request without compromising the user's energy requirements.

$$E_{flex}^{up} = min\left[E_{flex,th}^{up}\ ;\ E_{flex,rec}^{up}\right] \quad (1)$$

$$E_{flex}^{dn} = min\left[E_{flex,th}^{dn}\ ;\ E_{flex,rec}^{dn}\right] \quad (2)$$

Another important aspect of restricting flexibility potential to a single Offering Period is the prevention of a phenomenon herein introduced as "flexibility degradation". This issue, which seems to be overlooked in literature, arises when EV flexibility is assessed over multiple intervals without considering that executing a flexibility service at one point in time reduces the available flexibility in subsequent periods due to the rebound effect [10]. Conversely, by defining flexibility relative to a specific Offering Period and its corresponding Recovery Period, the method ensures that aggregate flexibility profiles remain valid upon activation. While this additional constraint reduces the total flexibility considered compared to an instantaneous power modulation approach, it ensures that the offered flexibility remains available over time as services are executed.

3 Flexibility analysis on real workplace infrastructure

Following the definition of a rigorous methodology to calculate EV flexibility potential at transaction level, an analysis was conducted to quantify this potential using real charging data from a workplace charging infrastructure. In this case, the company offers the charging service to its employees and acts as the CPO.

3.1 Charging infrastructure description

RSE is a research center based in Milan (Italy) owning an employee-dedicated infrastructure. This facility consists of 24 charge points (22kW AC) and currently serving 19 BEV and 11 PHEV, which exhibit long dwelling times with respect to energy needs. Charging data are collected via a digital platform based on OCPP 1.6J communication protocol [11] developed on purpose to monitor charging sessions and test smart load scheduling strategies. The developed smart charging logics are all capable to dynamically schedule each session's charging profile while considering the user-specific energy constraint, thus preventing partial charge issues. The energy request to be delivered within the dwelling time is either specified by the user via a webapp application communicating with the OCCP backend software or automatically inferred from historical charging sessions using literature algorithms [12].

The system currently supports three load management strategies: 1) "Free Power", which delivers full power to meet user energy needs as quick as possible; 2) "Minimum Power", which supplies just enough constant power to fulfill mobility needs within dwelling times, thus reducing peak power component of the bill; 3) "Optimized Power", a general-purpose scheduler using a numerical MILP solver to minimize operative costs, factoring in local renewable production, peak power minimization, variable energy prices, and user needs.

Further details on developed digital infrastructure, implemented load management logics and their techno economic advantages have been presented in previous works [13] [14] [15].

3.2 Infrastructure flexibility calculation

The computation is performed under the assumption that the Charge Point Operator (CPO) selects a single daily Offering Period for the entire charging infrastructure. This choice reflects the utilization of a workplace infrastructure, in which all the transactions initiate and terminate within the same day. As a consequence, only charging sessions whose Transaction Period comprehends the selected Offering Period will contribute to the overall flexibility potential of the infrastructure.

The calculation process was carried out through the following steps, which are schematized in Figure 2:

1. **Selection of charging transactions:** All charging sessions occurring between May 2023 and August 2024 were extracted, each one characterized by four key parameters: EV connection time, EV disconnection time, total energy delivered, maximum charging power.
2. **Reconstruction of charging profiles:** For each transaction, the charging profile was reconstructed according to three smart charging strategies previously recalled—Free Power, Minimum Power, and Optimized Power—in order to assess the influence of different baseline charging strategies and, consequently, the varying availability of flexibility potential over time. For the Optimized Power strategy, the profiles were reconstructed under the assumption of a 30 kW photovoltaic system, which influences the EV baseline scheduling while this logic is active.
3. **Calculation of flexibility profiles:** Based on each reconstructed charging profile, the corresponding upward and downward flexibility profiles were computed as functions of the Offering Period's start time and duration. The possible start times considered were the full hours of the day, while the duration varied

between 1 and 6 hours.

4. **Aggregation of flexibility profiles:** Finally, the flexibility profiles of individual transactions were summed to obtain the overall flexibility potential of the charging infrastructure, evaluated as a function of the Offering Period's start time and duration.

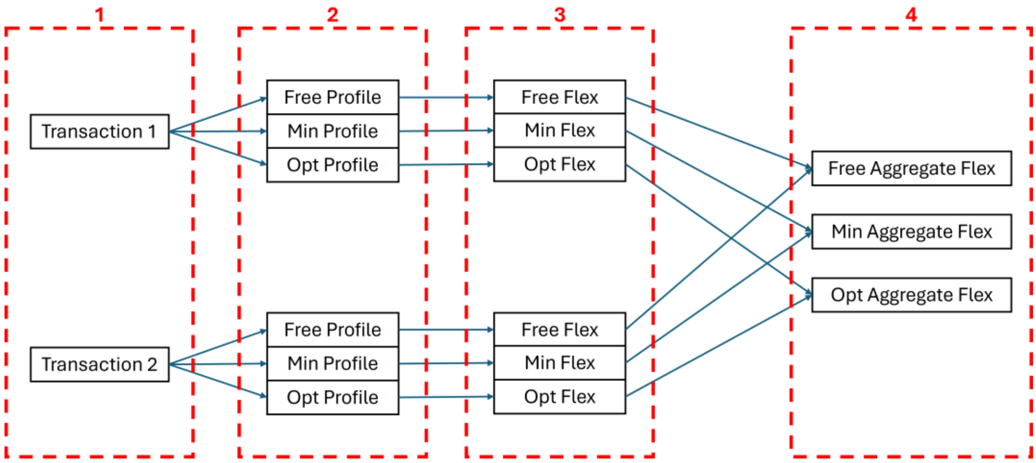

Figure 2: Aggregate flexibility profile calculation steps.

Figure 3 presents the final output for a specific baseline control logic, showing the flexibility profile of the charging infrastructure over an entire day, parameterized on the Offering Period duration. Each data point in Figure 3 represents the reconstructed flexibility potential of the overall infrastructure, assuming an Offering Period that starts at the time indicated on the x-axis, with a duration ranging from 1 to 6 hours as referenced in the graph legend. Consistent with the utilization patterns of a workplace infrastructure, the system exhibits zero flexibility in the evening and nighttime hours, when no active charging sessions are present. Conversely, a peak in flexibility is observed during the daytime, corresponding to the period when most users have recently connected their vehicles. It's possible to observe how a longer Offering Period increases, up to a certain extent, the maximum daily amount of flexibility, but reduces the number of hours in which some flexibility is present.

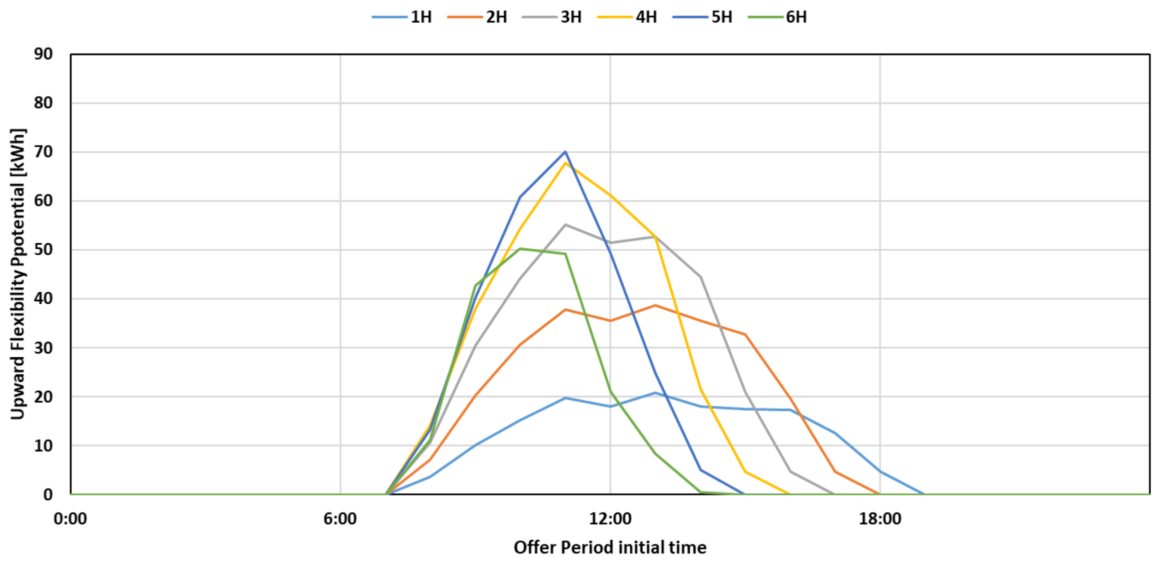

Figure 3: Aggregate flexibility profile of a single day parametrized on Offering Period duration. Graph referred to "Minimum Power" logic case.

Based on this observed daily pattern, an analysis was conducted to determine the Offering Period during which the RSE infrastructure exhibits, on average, the highest flexibility potential. For each of the three baseline charging strategies considered, the average flexibility potential of the infrastructure was computed by grouping results according to the start time and duration of possible Offering Periods. The maximum identified value corresponds to the *optimal Offering Period*, during which the infrastructure provides, on average, the highest flexibility given a fixed baseline load management strategy (Figure 4).

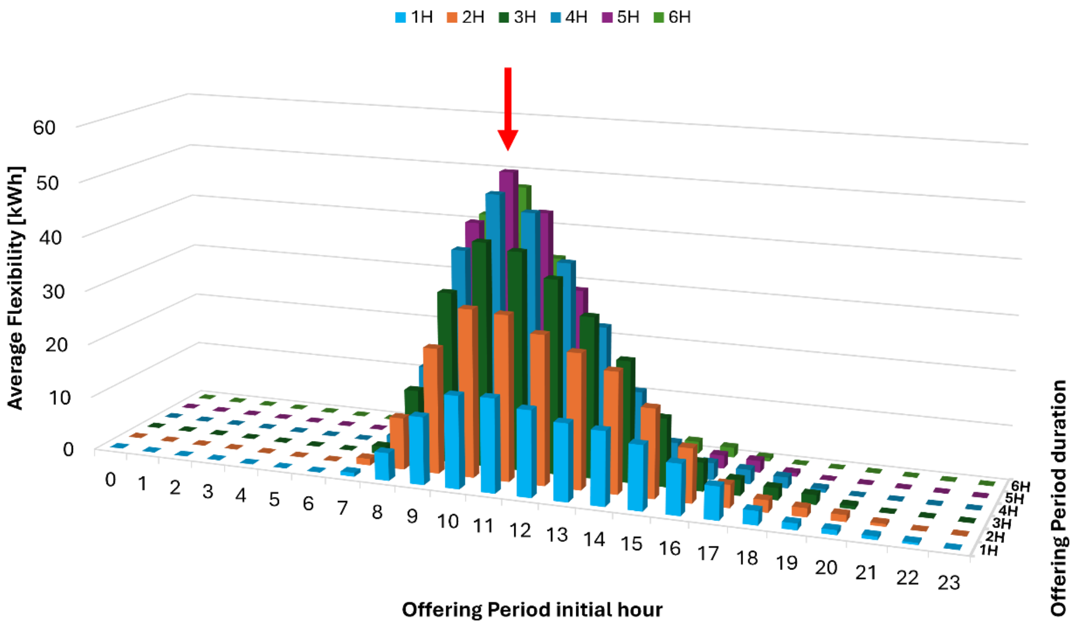

Figure 4: Infrastructure average upward flexibility varying the initial hour and duration of the Offering Period. The red arrow identifies the optimal Offering Period.

4 Results analysis

The average infrastructure flexibility potentials in the identified optimal Offering Periods are reported in Table 2 (upward) and Table 3Table 3 (downward). Regardless of the baseline charging logic, maximum flexibility always occurs from 10 a.m., when most employees have arrived within two hours, and the majority of transactions are still far from being completed.

The “Free Power” logic presents high amounts of upward flexibility, but zero downward, as it always charges at maximum power. Also, a shorter optimal Offer Period than the other two logics is due to rapid charge completion. The “Minimum Power” and “Optimized Power”, conversely, exhibit more balanced flexibility between upward and downward potential. Because of their slower charging patterns, they are also characterized by a longer optimal Offering Period of five hours, lasting until 3 p.m. As shown in the rightmost column of both tables, the upward flexibility potential of the considered infrastructure ranges between 37% and 46% of the daily energy provision, while the downward flexibility, when available, reaches nearly 29%.

Table 2: Optimal Offering Period and average upward flexibility potential.

Baseline Logic	Period Offer	Mean Flexibility	% Energy need
Free Power	10:00-14:00	65 kWh	46.3%
Minimum Power	10:00-15:00	52 kWh	37.0%
Optimized Power	10:00-15:00	57 kWh	40.6%

Table 3: Optimal Offering Period and average downward flexibility potential.

Baseline Logic	Period Offer	Mean Flexibility	% Energy need
Free Power	-	0 kWh	0%
Minimum Power	10:00-15:00	40 kWh	28.6%
Optimized Power	10:00-15:00	40 kWh	28.9%

The values presented in Table 2 and Table 3 represent the overall average flexibility potential, without accounting for variability across different months of the year or days of the week. Assessing such variability is particularly important because the flexibility margins should be offered in advance to the electricity system for scheduling purposes. Offering the average daily flexibility potential entails significant risks of overestimation or underestimation of the actually available flexibility when activation is requested. Overestimation can lead to resource unreliability, while underestimation results in missed flexibility provision opportunities. Consequently, analyzing the temporal variability of infrastructure flexibility potential is essential to identify possible patterns for a more accurate characterization of the system.
Based on the experimental dataset under consideration, Figure 5 and Figure 6 report the average upward flexibility potential of the three charging logics grouped by month and by day of the week, respectively. Flexibility potential is significantly lower in August and nearly absent on Saturdays and Sundays, reflecting the infrastructure's primary function as a workplace charging facility.

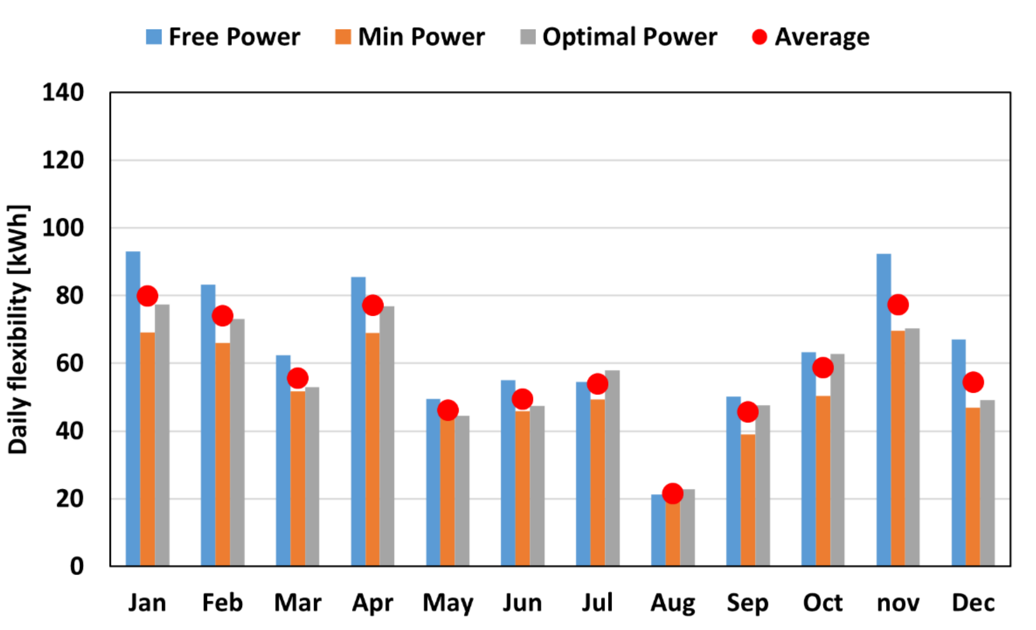

Figure 5: Average daily infrastructure upward flexibility grouped by month.

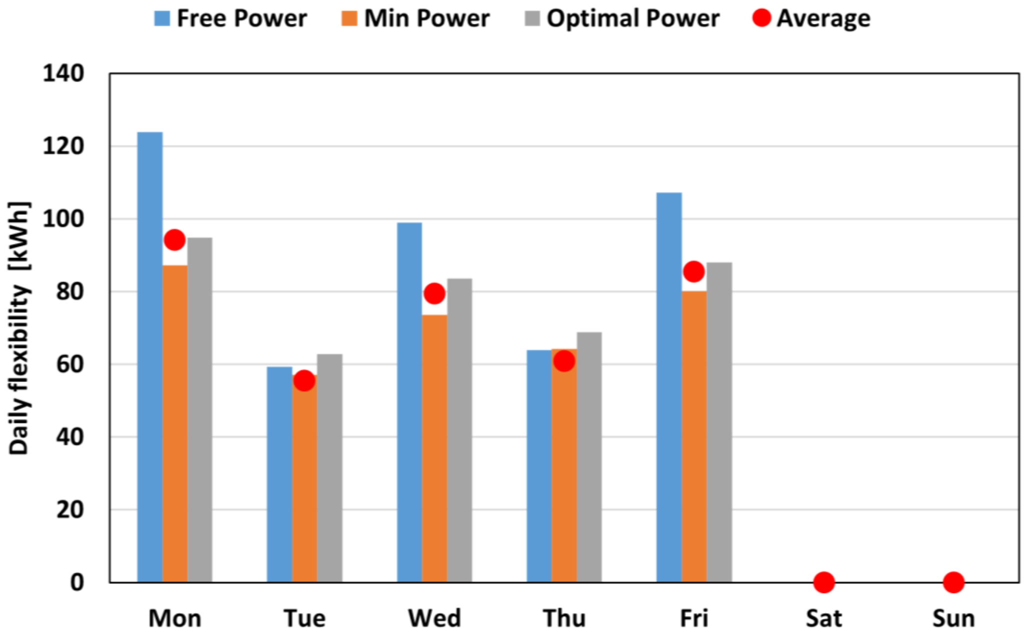

Figure 6: Average daily infrastructure upward flexibility grouped by weekday.

To determine whether variability is greater across months or days of the week, the standard deviations of the average flexibility potentials were calculated, following the groupings in Figure 5 and Figure 6. Outliers from August and weekends were excluded, as it can be assumed that the infrastructure does not provide significant flexibility to the system during these periods.

The analysis revealed that variability is greater across different days of the week than across different months of the year. Therefore, any ex-ante estimation method for the RSE infrastructure's flexibility should give more weight to the day of the week rather than the month of the year. Additionally, it is expected that monthly variability will further decrease as the dataset expands over multiple years, due to the diminishing influence of individual-year holidays or company-specific closures dictated by the calendar. High weekday variability is instead due to the employees taking advantage of the workplace charge for their weekend mobility needs, concentrating charging sessions on Monday and Friday.

5 Conclusions

This study quantifies the flexibility potential of a real workplace charging infrastructure, considering real users behavior and the effect of different charging scheduling strategies. Flexibility provision is assumed to be managed by the Charge Point Operator (CPO), which may consider flexibility provision to an external BSP as a secondary benefit after satisfying end-user charging needs and minimizing its operating costs via smart charging strategies. By defining clear constraints and priorities, and the roles and responsibilities of the involved business actors, a structured approach to estimate flexibility potential of EV charging was presented.

The proposed methodology has been used to calculate the flexibility potential of a real workplace charging infrastructure, taking advantage of historical data collected. Results indicate that the highest flexibility potential occurs during the central hours of the day, between 10 a.m. and 3 p.m., reflecting user behavior shaped by standard office hours. Quick charging baseline strategies offer higher upward flexibility potential, but for a shorter time span during the day, while slower strategies enable a more balanced and sustained provision of both upward and downward flexibility throughout the day. Flexibility potential variation resulted to be more influenced by intra-week dynamics rather than intra-month, suggesting a relatively stable flexibility contribute throughout the year from workplace infrastructures. However, dynamics dictated by specific business features such as remote working policies, infrastructure sizing compared to employees needs or charging cost could differ between different workplace infrastructures. Nevertheless, these specific characteristics may significantly influence flexibility potential across different workplace contexts. The findings provide valuable insight into the role that widespread adoption of workplace charging infrastructure could play in supporting grid flexibility, with potential contributions ranging from 28% to 46% of daily energy demand.

As a final remark, the presented analysis calculated flexibility relative to a multi-hour optimal Offering Period, meaning the total amount of energy that can be anticipated or delayed at infrastructure level with respect to the baseline. This calculation helped identify when and how much flexibility the infrastructure can provide. However, it is important to note that flexibility is not evenly distributed within the optimal Offering Period. Future work should analyze the hourly and quarter-hourly distribution of flexibility within these periods, extracting actual flexibility profiles of interest to system operators. Further research will also address the economic dimension, focusing on the CPO's profitability in activating flexibility while accounting for baseline modifications.

Acknowledgments

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Presenter Biography

Piersilvio Marcolin graduated in Energy Engineering at Politecnico di Milano (2020). In its professional career he managed R&D projects on flexible energy systems integrated with energy markets, acquiring broad-spectrum knowledge on optimal sizing and operation via ICT technologies. He is now a researcher at Ricerca sul Sistema Energetico (RSE) S.p.a., focusing on e-mobility, Vehicle-Grid-Integration (VGI) and Smart Grids.