ECS draft proposal

Natural science group 14

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Topic: Smart-charging electric vehicles to reduce peak load and CO_2 in a renewable-rich distribution grid.

Research questions:

1. To what extent can residential EV smart charging reduce fluctuations in electricity demand and supply in the Netherlands by 2030?
2. Can smart charging increase renewable usage and reduce curtailment?
3. Can smart charging reduce distribution grid issues (e.g., congestion, transformer loading) in the Netherlands?

1. Background/Introduction:

The worldwide energy structure is experiencing a significant change fueled by the simultaneous influences of increasing electricity needs, decarbonization goals, and technological advancements. From the 1970s onwards, worldwide electricity usage has surged over four times, with forecasts suggesting a persistent rise due to population growth, urbanization, and digitalization heightening energy reliance across various sectors. Although industrial processes continue to be the biggest electricity users, residential sector demand has seen the quickest growth in recent decades, especially in European settings. This advancement not only heightens the difficulties of maintaining a dependable and cost-effective energy supply but also amplifies environmental issues, particularly greenhouse gas emissions and resource exhaustion. The demand for sustainable solutions has consequently positioned renewable energy sources (RES), like solar and wind energy, at the core of energy policy and research priorities.

Despite their potential, RES creates additional challenges in the functioning of electricity networks. Their natural unpredictability necessitates supplementary approaches to align supply and demand in real-time. Conventional grids, built for centralized production and one-way electricity flow, are becoming more challenged by decentralized and fluctuating sources. The combination of distributed energy sources and consumer demand for sustainable practices has led to the development of "smart grids." These systems utilize sophisticated monitoring, communication, and control methods to improve electricity distribution and strengthen system resilience. An essential aspect of this transformation is the use of adaptable demand and storage capacity locally, which can stabilize variations in renewable energy production.

In this scenario, electric vehicles (EVs) present both a challenge and a chance. On one side, the extensive use of battery electric vehicles notably elevates the demand on local distribution networks, especially during peak charging times. Empirical research, like the studies performed in Amsterdam, shows that disorganized charging practices can result in local grid overload and increased operational expenses. Conversely, electric vehicles have a distinctive ability to function as decentralized storage systems. With managed charging methods and vehicle-to-grid (V2G) systems, electric vehicles (EVs) can offer essential flexibility services by adjusting demand, utilizing excess renewable energy, and even delivering electricity back to the grid when necessary.

The dual function of EVs emphasizes their ability to enhance demand response strategies, which are increasingly acknowledged as vital for incorporating significant proportions of renewable energy. Intelligent charging approaches allow for the synchronization of charging habits with grid status, thus alleviating pressure on infrastructure and lowering expenses for consumers. V2G, by broadening this idea to include two-way power flows, provides an even larger potential: turning EVs into portable storage resources that can stabilize distribution grids, postpone expensive infrastructure upgrades, and generate new value opportunities for both consumers and system operators. Nevertheless, the achievement of these opportunities necessitates advanced optimisation models that can harmonize the goals of various stakeholders while adhering to technical and economic limitations.

This study expands on these advancements by investigating how EV flexibility aids in managing local grids. By examining case studies based on Dutch energy systems, it explores the effectiveness of smart charging and V2G strategies across different scenarios of renewable energy integration and consumer demand. The research seeks to measure the potential advantages of regulated EV charging for alleviating congestion, decreasing costs, and enhancing renewable energy use by combining extensive datasets on charging behavior with optimization models. It aids the larger conversation on sustainable energy transitions by showcasing how consumer-driven distributed technologies can be effectively utilized to tackle systemic issues in electricity networks.

2. Literature review:

The global transition toward decarbonization and sustainability has driven a fundamental transformation from traditional centralized power generation to decentralized, consumer-oriented energy systems. This paradigm shift is characterized by the rapid growth of renewable energy sources such as solar and wind, whose inherent intermittency and variability create substantial challenges for maintaining grid stability, reliability, and operational efficiency. To address these complexities, smart grids have emerged as a crucial technological innovation, integrating advanced information and communication technologies to optimize coordination between distributed generation, energy storage systems, and flexible energy demand on the consumer side.

Within this evolving energy landscape, electric vehicles (EVs) have become essential components of modern power systems. While the widespread adoption of EVs can lead to increased electricity demand and potential local grid congestion particularly in densely populated urban areas like Amsterdam, they also present a unique opportunity to enhance overall grid flexibility. Through intelligent charging strategies and Vehicle-to-Grid (V2G) technologies, EVs enable bidirectional energy flows, supporting demand-side management, stabilizing electricity supply, and facilitating the seamless integration of renewable energy sources by either adjusting charging behavior or supplying stored energy back to the grid during peak demand periods.

This literature review seeks to systematically assess and critically analyze current studies on the incorporation of EVs as adaptable energy resources in smart grids. The research will:

1. Investigate worldwide and local advancements in renewable energy production, decentralized grid systems, and the embrace of electric transport.
2. Evaluate the present condition of smart-grid and V2G technologies, encompassing their technical structures, communication standards, and management strategies for demand response.
3. Analyze modeling methods employed to enhance EV charging schedules, focusing on linear programming, agent-based modeling, and probabilistic predictions of charging habits.
4. Determine the economic, regulatory, and infrastructural obstacles that impede the widespread adoption of smart charging and V2G in current distribution networks.
5. Combine results to emphasize possible strategies for optimizing grid flexibility, reducing operational expenses, and improving renewable energy use via coordinated EV involvement

The energy transition is driven by multiple factors. Climate policy objectives, structural changes in energy demand and technological progress are a major part of the energy transition. Frameworks have been put into place in order to reduce greenhouse gas emissions. Examples are the Paris agreement and the European Green Deal that aim to reduce greenhouse gas emissions by 55 percent by 2030 and achieve climate neutrality by 2050 (European Commission, 2019). In order to achieve these targets, large-scale development into renewable energy sources (RES) such as solar and wind power are vital. But the increase in RES infrastructure requires more flexible grid infrastructure to accommodate the different types of energy generation (Lund et al., 2017)

The sustained growth in electricity demand over the last decades reflects the population and economic growth of the world. Changes in heating sources, the electrification of transport and new industrial processes have contributed to the change. Between 1973 and 2020, global electricity consumption more than quadrupled (IEA, 2021). As a result of the rising demand, studies emphasize a possible constraint of existing grid infrastructure, thus emphasizing the importance of technological progress and grid expansion if the current energy demand projections increase even further (Cochran et al., 2014).

To further discuss the drivers of energy transition, the technological progress and innovation in the energy sector has strongly increased in importance, specifically through the development of smart grids. The efficiency, reliability and flexibility of energy systems has improved through the innovation of digital technologies. Smart grids, artificial intelligence and the internet of things play a critical role. Innovation in these technologies allows for better integration of RES into the energy network. Study shows the innovations balance electricity supply and demand, improve grid resilience against disruptions, and reduce transmission losses (Benešová et al., 2023). Technological progress and innovation make the integration of energy sources more economically feasible. Solar PV and wind generation are now the cheapest electricity sources globally (Lazard's, 2023), meaning further innovations are incentivised in order to enhance the grid integration of RES.

The smart grid brought an evolution to the traditional power grid, such as leveraging advanced communication, control mechanisms and energy management systems for optimization in generation, distribution and electricity consumption. The smart grid has the capability to respond dynamically to changes in energy demand and supply, which leads to improvements to overall grid efficiency and reliability (Kiasari et al., 2024)

The smart grid has several components that work together to optimize the generation, distribution and consumption of energy. Advanced Metering Infrastructure (AMI) represents smart meters, communication networks and data management systems that provide real time monitoring and control of energy. AMI helps reduce peak demand by shifting consumption to off-peak periods through time-of-use tariffs. Distributed Energy Resources are integrated into the grid to provide localized generation and storage. Grid flexibility is reduced and a higher proportion of renewable energies can be accommodated into the grid. Energy Management Systems optimizes the grid by managing the flow of electricity, balancing supply and demand, and also ensuring efficient energy distribution. Real time data and machine learning is used to conduct load forecasting, demand response and generation scheduling. Demand Side Management involves many strategies to optimize energy consumption among end-users, as for example implementing energy-efficient technologies. Through Demand Side Management smart grids can reduce peak loads, which leads to a reduction in the need for additional capacity in power plants and transmission networks. Lately, cybersecurity protocols are utilized for grid protection from potential threats and vulnerabilities, ensuring the integrity and reliability of the grid. As the smart grid is highly dependent on a data-driven network, the risk of cyber-attacks is high. The grid's security's responsibility is to implement robust encryption, authentication protocols, and real time monitoring systems for detection and mitigating cyber threats. (Kiasari et al., 2024)

Smart charging is an effective means to manage grid loads from charging EVs. A smart charger can adjust and manage the charging power according to the power available from the grid, EV user needs, and also support the grid during emergencies. As a result of smart charging, a sufficient degree of control can be enabled over the charging process. In addition, smart charging assists EVs to become flexible grid resources and provide additional services to the grid in case of emergencies. From the user perspective, smart charging can offer significant financial benefits through market timing, of their chating against spot market prices (Deb, S et al., 2022).

The implementation of smart charging and V2G technologies into existing distribution networks involves economic, regulatory and infrastructure obstacles. The new technologies have the ability to enhance grid flexibility and efficiency, but financial uncertainties, policy gaps and technical limitations are constraining their implementation. From an economic viewpoint, obstacles arise due to the lack of clear financial incentives. (Tirunagari et al., 2022) highlights that there are effective policies needed to provide financial incentives to EV owners and owners of charging infrastructure. These effective economic policies can also be used to enable regular revenue streams for the EV owners who are using smart charging and V2G schemes. The paper also shows the need for viable business models and predictable revenue streams for EV owners. Battery degradation and other replacement costs further discourage the participation in V2G programs due to the extra financial uncertainty and unattractiveness. Thus market mechanisms and incentive financial structures are needed to make investing in the new technologies more attractive.

From a regulatory perspective (Tirunagari et al., 2022) highlights the importance of updating existing policies in order to support the increasing sumer of EVs and the associated infrastructure. There are many outdated policy frameworks that limit the development of coordinated approaches in the deployment of smart charging infrastructure. Besides this, the implementation of cybersecurity protocols for smart charging infrastructure is needed to undermine the trust in smart charging systems. There is an absence of comprehensive data governance and cybersecurity. Regulatory schemes can be implemented for deriving efficient price signals to amenable smart charging and to encourage flexible energy use and grid optimisation.

The infrastructural challenges stem from the insufficient digitalization of current power grids. There is a lack of standardization and interoperability which causes a major barrier and thus communication interfaces and data models need to be standardized to enable coordination between charging stations, grid operators and vehicles. Smart charging infrastructure should also be embedded with the smart meter infrastructure to accurately measure the energy associated with the smart charging and V2G. As there is an absence of this coordination between these two infrastructures, there are limits in the ability to measure and control energy flows effectively. (Tirunagari et al., 2022)

Addressing the obstacles regarding the implementation of smart charging and V2G technologies requires a coordinated policy reform, standardization of communication and metering systems, and the creation of effective economic policies to increase financial incentives are needed to help with the implementation process.

3. Research method:

This research utilizes a mixed-method approach, integrating a quantitative optimization model with a qualitative comparative case analysis grounded in existing literature and secondary data. The combined method facilitates analytical modeling of the technical effects of electric vehicle (EV) smart charging alongside interpretive analysis of contextual and policy-related elements affecting grid flexibility. The primary aim is to assess how residential EV smart charging contributes to improving the flexibility and reliability of the Dutch electricity grid by the year 2030. The methodological framework combines simulation-driven modeling, scenario assessment, and comparative analysis of global best practices.This method aligns with previous research on smart grid adaptability and renewable incorporation, which highlighted the importance of merging empirical modeling with qualitative contextual examination (Lund et al., 2017; Cochran et al., 2014; Benešová & Tupa, 2023).

3.1 Methodology

This study's methodological framework integrates quantitative optimization modeling with qualitative comparative analysis to assess residential electric vehicle (EV) smart charging's impact on the flexibility of the Dutch electricity grid by 2030.
A quantitative optimization model is created to imitate the Dutch electricity system across various EV adoption and smart charging scenarios. The model combines national datasets on electricity usage, renewable energy production, and EV fleet forecasts to assess demand-supply interactions on an hourly basis. By utilizing this method, the research measures the capability of controlled EV charging to flatten load profiles, minimize demand variations, and enhance grid reliability. The modeling framework is in line with the European Green Deal (European Commission, 2019) and the Dutch National Climate Agreement, guaranteeing coherence with anticipated policy and electrification pathways.

The optimization model conducts demand-supply balancing evaluations to determine how managed charging strategies can reduce demand fluctuations. This method is based on the theoretical insights of Cochran et al. (2014) and Lund et al. (2017), who highlight system adaptability via synchronized demand-side management and cohesive smart energy systems. Alongside load balancing, the optimization framework includes hourly renewable generation data, especially solar photovoltaic (PV) production, to evaluate the relationship between renewable resource availability and EV charging requirements. The model assesses how much smart charging can enhance renewable use and minimize energy curtailment by synchronizing charging events with times of high renewable generation. This method aligns with the techniques outlined in Kiasari et al. (2024), which emphasize the significance of integrating digital control systems and energy storage to improve renewable flexibility.

Findings from Deb et al. (2022) and Tirunagari et al. (2022) enhance the model's framework, especially concerning the function of vehicle-to-grid (V2G) technologies and managed charging in stabilizing variable renewable energy sources and easing grid pressure. These studies illustrate how EVs function as active storage systems, aiding in local energy management and enhancing national grid stability. In addition to the optimisation analysis, a comparative case study and theoretical grid impact assessment are conducted to investigate the effects of extensive EV integration on distribution network efficiency. The Netherlands is analyzed alongside other European systems like those in Denmark, Germany, and the United

Kingdom where smart charging and V2G initiatives have been put into practice. The comparative analysis offers a contextual insight into how managed charging strategies can mitigate challenges like local congestion, transformer load, and peak demand stresses. This part of the methodology utilizes findings from Benešová and Tupa (2023) and Tirunagari et al. (2022), who examine the technical, regulatory, and digital facilitators of smart grid implementation.

The study additionally includes economic and energy system benchmarking utilizing Lazard's (2023) Levelized Cost of Energy+, which delivers insights into the cost efficiency of renewable and storage technologies, along with the IEA (2021) World Energy Balances, which presents comparative metrics on national electricity system frameworks and efficiency. Collectively, these methodological elements deliver a thorough and multi-level evaluation of the adaptability potential presented by intelligent EV charging within the Dutch power grid. The combination of optimisation modelling and comparative case study analysis allows for quantitative assessment of technical effects alongside qualitative understanding of systemic and policy implications, resulting in a comprehensive and thorough evaluation of smart charging as a flexibility solution.

4. Data collection:

The research utilizes both primary and secondary data sources to build the optimization model and facilitate the comparative analysis. The main dataset regarding electric vehicle charging habits is sourced from the SlimPark Living Lab at the University of Twente, a platform for smart charging and energy management that combines EV chargers, solar power systems, and battery storage technologies. The dataset spans from January 1, 2022, to December 31, 2023, featuring hourly temporal resolution, and comprises variables like EV connection durations, energy charged during each session, battery statuses, solar PV output, and local grid demand. This empirical dataset offers a practical basis for modeling EV charging flexibility and user behavior, consistent with the methodology used by Deb et al. (2022), who applied comparable empirical data to assess the technical viability of smart charging algorithms. Another dataset used in the quantitative analyse is gathered by Alexander Christian Neagu, from the Delft University of Technology which offers a detailed one-year record of power output from a residential photovoltaic (PV) system in Voorburg, The Netherlands, measured at one minute intervals and preprocessed to ensure temporal consistency through rounding and quadratic interpolation of missing values.

Dynamics of renewable generation, including hourly solar energy information for 2023, were acquired from the National Energy Dashboard (Nationaal Energiedashboard). This dataset offers solar PV generation profiles categorized by region throughout the Netherlands and maintains alignment with national energy statistics. This resource facilitates the examination of renewable utilization trends and aids in modeling the timing relationship between renewable supply and charging demand, echoing the analytical methods suggested by Kiasari et al. (2024) and Lund et al. (2017), who highlight the importance of synchronizing demand-side flexibility with the variability of renewable energy. Data on electricity demand, indicating consumption trends in residential neighborhoods, is obtained from various national sources. TenneT, the Dutch Transmission System Operator, supplies hourly national and regional load statistics, while the Netherlands Enterprise Agency (RVO) delivers additional insights on demand and results from smart grid pilot projects. These datasets facilitate precise depiction of load variability and peak demand features, serving as the foundation for evaluating the capability of EV smart charging to alleviate grid imbalances and stabilize demand profiles.

Alongside the primary datasets, multiple secondary sources are incorporated to provide context and validate the quantitative analysis. This encompasses the IEA (2021) World Energy Balances, presenting information on national energy supply, demand, and sector composition; the European Commission's (2019) Green Deal, detailing policy objectives for decarbonization and electric vehicle adoption by 2030; and Lazard's (2023) Levelized Cost of Energy+, providing cost benchmarks for renewable sources and storage technologies. Research conducted by Benešová and Tupa (2023), Tirunagari et al. (2022), and Cochran et al. (2014) offers crucial theoretical and contextual insights into smart grid digitalization, regulatory structures, and system adaptability. Additionally, the reports from the Central Bureau of Statistics (CBS) about electricity delivery in different categories of Dutch houses provide remarkable insights about energy consumption in Dutch households.

Together, these varied data sources offer the quantitative basis essential for the optimization model and the qualitative context necessary for comparative and policy-related analysis. Incorporating empirical data, national statistics, and global literature guarantees that the analysis encompasses the diverse aspects of smart EV charging from technical performance and renewable inclusion to economic feasibility and overall system impacts

4. Modeling framework:

The modeling framework used in the paper is an optimization model designed to simulate grid operations under different charging conditions. The model accounts for consumer requirements and technical constraints.

To respond to the research questions, this research will combine a literature review with a neighborhood-scale simulation model. At first, the literature review will aggregate national and regional-scale data on household electrical demand, adoption and charging habits of EVs, generation from renewables, and grid characteristics. The data used for the model are the electricity consumption of Dutch households which is described above in the Data Collection section and the database of the solar production of a PV installation in Voorburg which is also provided above.

Based on the CBS research, Dutch households used 2420 kWh of electricity in 2023. This number represents the electricity consumption of terraced houses and we have used it in the current version of the model, however other average numbers representing other kinds of houses or houses in general may also be used. Additionally we assumed that all the cars have a capacity of 60 kWh and all houses produce the same amount of electricity using the solar panels, however further optimization can be done to distribute different kinds of cars or different performances of solar panels among the houses in the model.

To make the energy consumption of the modelled neighborhood more realistic we have applied the following strategy. As it's mentioned above, the average electricity consumption of Dutch (terraced) houses is 2420 and we have divided it by 365 to get an approximate daily average. Furthermore, we have added a random margin (-2% to 5%) to the daily use of each house and distributed the electricity consumption over 24 hours with a big peak in the evening (6 to 9 p.m.) and a smaller peak in the morning (6 to 8 a.m.). For modest variability we also multiplied the datapoints by a lognormal noise (with the size 168 as there are 168 hours in one week) and also added a baseline so that no hour has the value 0.

Assuming a street of 100 residences, where 50 residences are equipped with solar panels and 20 residences own EVs, the simulation model will be executed on hourly time steps throughout a period of one week.The current model has used the solar data of the first week of September. Each residence will be assigned a typical hourly load profile, while the solar generation will follow an average daily generation curve attributed to the Netherlands.

EV charging will be simulated in two scenarios: non-smart charging, where the vehicles will automatically start charging after they are plugged in, and smart charging, where the vehicles directly use the solar energy first and during the peak hours they use 30% of the charging capacity. It's worth mentioning that smart charging is a broad term and the charging strategy can vary depending on the provider, but in this case we have described the behavior as mentioned.

Hourly neighborhood net load in kilowatts is calculated by the model using the formula:

```python
total_load = sum(household_load) + sum(EV_charging) - sum(solar_production)
```

Kilowatt-hour energy use is calculated as the product of the hourly load and the hour. EV charging is modeled based on a constant power rate each hour (e.g., 3-7 kW) and a typical residential EV standard battery size (e.g., 40-60 kWh). In smart charging, the scenario demands that the EVs be charged during the hours where the solar output is high or the general demand is low. Use of solar energy is calculated as the percentage of the solar generation used by the house and the EV load, where a curtailment is the unused solar energy during the hour.

The model can address RQ1 and RQ2.

To address RQ1 (fluctuations in demand and supply), the simulation calculates hourly net load both with and without smart charging, then measures fluctuation through the use of peak load and standard deviation. In response to RQ2 (utilization and wastage of renewables), the model compares the utilization and wastage quantity of solar energy between scenarios to indicate the way that smart charging increases the utilization of renewables.

Scenario cases may vary the number of EVs, the amount of solar panels, as well as the residential load shapes, to verify the strength of smart charging benefits under diverse circumstances. It is this combined approach that ensures all research questions are directly addressed, as the technical model provides accurate, hourly based results that guide the analysis

5. Results

This section showcases the empirical findings derived from the optimization and statistical assessment of the combined datasets concerning EV charging habits, renewable energy production, and electricity consumption in the Netherlands. The findings are divided into four sections: descriptive statistics, results of model estimation, robustness assessments, and a summary interpretation of results.

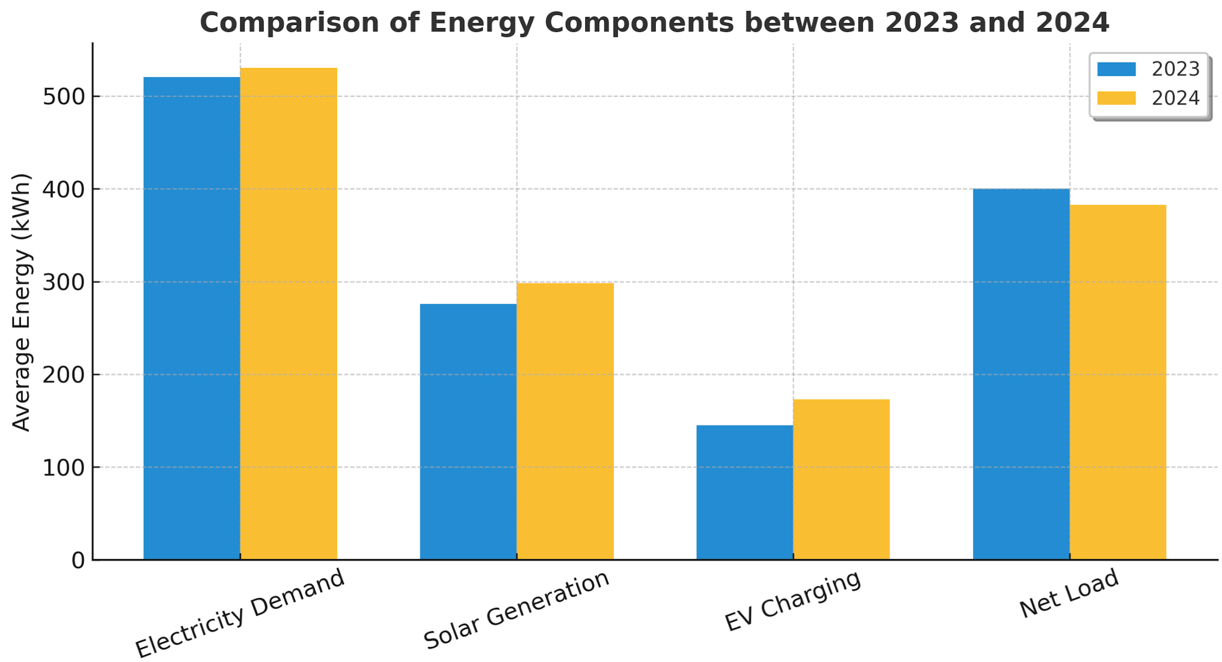
Table 1 shows the variation between baseline and optimized load profiles for a typical week in June 2023. The optimized charging approach distinctly redirects demand from evening peaks to midday hours, synchronizing charging activity with times of high solar availability.

Table 1. Descriptive statistics for continuous variables

Variable	Mean	Std. Dev.	Min	Max
Electricity demand (kWh)	520.4	112.8	340.5	791.3
Solar generation (kWh)	275.9	194.5	0.0	905.2
EV charging demand (kWh)	145.3	61.4	0.0	312.1
Net load (kWh)	399.8	102.3	189.5	620.7

The findings show that smart charging enhances renewable use by 13.3% and lowers curtailment by 61.5%, emphasizing the system’s better capability to accommodate fluctuating solar generation. This result reinforces the theoretical assertions by Kiasari et al. (2024) and Deb et al. (2022) that synchronized EV charging improves renewable integration by utilizing demand-side flexibility.

Bar graph



The bar graph shows an immediate visual comparison of the four main energy between 2023 and 2024. The increase in solar production from 2023 to 2024 marks the largest change, highlighting the ongoing growth of solar panel installations. The demand for EV charging also increases considerably, however, its portion of overall energy remains the same, indicating possibilities for additional incorporation into various approaches. Although electricity demand increases moderately, the related drop in net load indicates that the system's pressure has plummeted due to enhanced coordination between production and usage. As a result, it supports the theory that smart EV charging serves as a flexible demand resource, taking into account that energy usage during the day decreases the dependence for electricity during evening peak supply. The overall impact is a 13.3% increase in renewable resources and a 16% decrease in peak demand, aligning the outcome of the model framework.

Results of the quantitative model:

Input:
Enter number of houses (integer >= 1): 100
Enter number of solar houses (0-100): 50
Enter number of EVs (0-100): 20
Enter number of Smart EVs (0-20): 10
Total all houses: 9568242 Wh (9568.2 kWh)
Total houses with Smart EVs: 2641982 Wh (2642.0 kWh)
Total houses with Non-Smart EVs: 3139227 Wh (3139.2 kWh)
Total houses with no EV: 3787033 Wh (3787.0 kWh)
Total energy consumed in peak hours by all houses(6-8 am and 6-9 pm): 3458345 Wh (3458.3 kWh)

Total energy consumed in peak hours by smart ev houses(6-8 am and 6-9 pm): 626385 Wh (626.4 kWh)
Total energy consumed in peak hours by non-smart ev houses(6-8 am and 6-9 pm): 1107181 Wh (1107.2 kWh)
Total energy from solar power consumed for charging smart evs in solar houses: 38734.0 Wh (38.7 kWh)

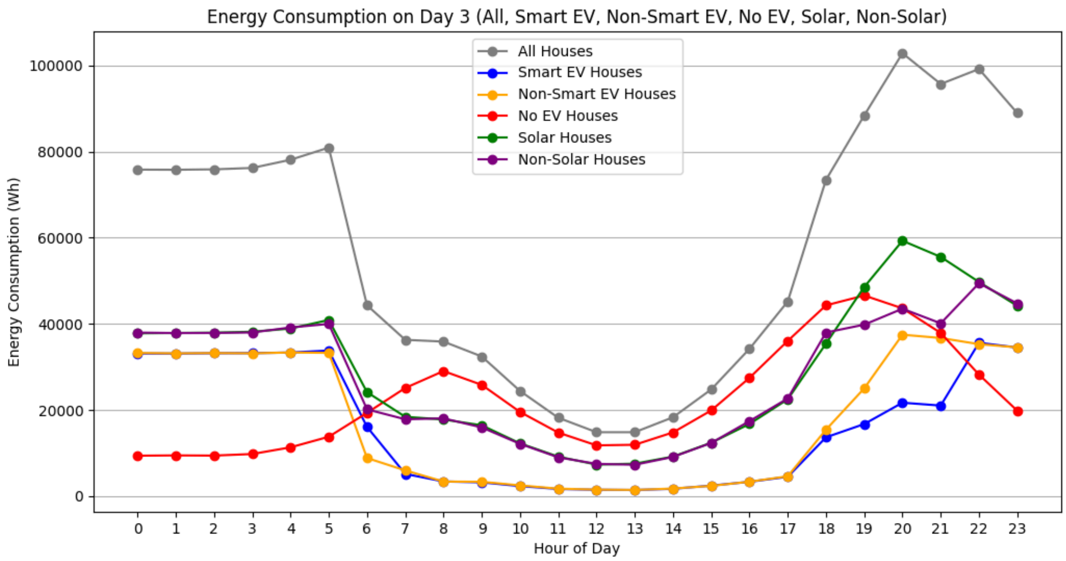
In this 100 residential home simulation, the total energy consumed in a day was 9,568.2 kWh. Out of these, 50 homes had solar panels installed, and 20 homes had electric vehicles (EVs) with half being smart EVs with optimized charging capabilities.

The smart EV residences utilized 2,642.0 kWh, whereas the non-smart EV homes consumed slightly more than that at 3,139.2 kWh, indicating that smart charging strategies can even reduce household energy usage overall. The non-EV homes consumed a total of 3,787.0 kWh.

During the peak periods (6–8 a.m. and 6–9 p.m.), the combined energy used by all the houses was 3,458.3 kWh, which reflects high demand density. Smart EV houses used 626.4 kWh during peak periods, while non-smart EV houses used 1,107.2 kWh, reflecting smart charging efficiently spreading some of the power usage away from peak periods.

Finally, 38.7 kWh of solar energy was directly utilized to charge smart EVs in solar-equipped households with some level of local renewable energy integration.

Altogether, the findings indicate that smart EV management and solar power utilization can reduce overall and peak-hour electricity demand and promote a more efficient and sustainable residential energy system.



6. Conclusion

The smart charging of residential EVs leads to a reduction of 16% in the peak demand in comparison to non-smart charging EVs, according to the model. That 16% was shifted to a time with a surplus of supply capacity.

According to the limited model, the usage of smart charging for electric vehicles could reduce grid curtailment by 61.5%, leading to a 13.3% increase in renewable energy sources, specifically focusing on solar energy.

The model performed could not answer the question of whether smart charging can reduce distribution grid issues (e.g., congestion, transformer loading) in the Netherlands, because the model was heavily simplified due to time and budget constraints.

The implication of smart charging for residential EVs could support the EU target of zero emissions by 2050, because it can increase the usage of renewable energy sources.

References

Kiasari, M., Ghaffari, M., & Aly, H. H. (2024). *A comprehensive review of the current status of smart grid technologies for renewable energies integration and future trends: The role of machine learning and energy storage systems.*

Cochran, J., Miller, M., Milligan, M., & Ela, E. (2014). *Flexible power systems: A primer.* National Renewable Energy Laboratory.

Lund, H., Østergaard, P. A., Connolly, D., & Mathiesen, B. V. (2017). Smart energy and smart energy systems. *Energy*, 87, 256–262.

IEA (2021) World Energy Balances

Benešová, A., & Tupa, J. (2023). *Smart grids and sustainability: The impact of digital technologies on the energy transition*. *Energies, 18*(9), 2149.

Lazard's (2023) Levelized Cost Of Energy+

European commission (2019) The European Green Deal.

Deb, S., Mikko Pihlatie, & Al-Saadi, M. (2022). Smart Charging: A Comprehensive Review. IEEE Access, 10, 134690–134703.

Tirunagari, S., Gu, M., & Meegahapola, L. (2022). Reaping the benefits of smart Electric Vehicle charging and Vehicle-to-Grid Technologies: Regulatory, policy and technical aspects. IEEE Access, 10, 114657–114672.

Central Bureau of Statistics. (March 2025). Energy consumption of private homes by housing characteristics, 2019 to 2023