# Blockchain, AI and Smart Grids: The Three Musketeers to a Decentralized EV Charging Infrastructure

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## Abstract

The proliferation of Internet of Things (IoT) has brought an array of different services, from smart health-care, to smart transportation, all the way to smart cities. For a truly connected environment, different sectors need to collaborate. One use case of such overlap is between smart grids and Intelligent Transportation System (ITS) giving rise to Electric Vehicles and their charging infrastructure. Being such a lucrative opportunity for investors and the research community, many efforts have been made toward providing the end-user with an extraordinary Quality of Service (QoS). However, given the current protocols and deployment of the Electric Vehicle (EV) charging infrastructure, some key challenges still need to be addressed. In particular, we identify two main EV challenges: (1) vulnerable charging stations and EVs, and (2) non-optimal charging schedules. With these issues in mind, we evaluate the integration of Blockchain and AI with the EV charging infrastructure. Specifically, we discuss the current AI and Blockchain charging solutions available in the market. In addition, we propose a couple of use cases where both technologies complement each other for a secure, efficient and decentralized charging ecosystem. This article serves as starting point for stakeholders and policymakers to help identify potential directions and implementations of better charging systems for EVs.

## Introduction

When the movie "Back To The Future" was released in 1985, it boggled the viewers' minds with futuristic technologies which at that time people could hardly believe would exist. From 3D movies, tablets, and Augmented Reality to flying cars and biometric scanners, these technologies were thought of as science fiction 34 years ago. However, at a glance, it becomes evident that almost all of these technologies are realized as an intrinsic part of our daily lives. Thanks to a paradigm called IoT, sensors, actuators and Internet connectivity could be embedded within everyday "things" transforming them into smart ones [1]. This gives rise to a set of novel use cases including smart transportation, smart cities, smart health-care, etc. Considering its prominent influence, the IoT market is expected to contribute up to US$6.2 trillion in annual income by 2025 [2]. One of the rather interesting services within IoT are ITS and Smart Grids [2].

ITS encompasses a wide range of different services including self-driving cars, street surveillance and traffic monitoring. When put together, such services would form an intelligent network of cars, Road-Side Units, traffic lights, etc. to offer users a seamless driving experience [3]. In addition, in a smart grid environment, energy usage is monitored and managed through smart meters and controllers [4]. While each sector provides its unique services, new opportunities arise from their overlapping, one of which are EVs and their charging infrastructure. Although flying cars are yet to exist, there have been major advancements in vehicular technologies that rendered EVs as a lucrative opportunity for both industry and academia. To put it in perspective, according to the International Energy Agency (IEA), EVs have exceeded 5.1 million globally in 2018. Further, by 2030, it is projected that the EV stock would reach up to 250 million, cutting the demand for oil products by almost 130 tons [5]. In addition, Norway projects that by 2025 all new car sales would come from EVs. Other countries like the United Kingdom and France are proclaiming the same projections by 2040 [6]. With such a vision, a set of challenges needs to be addressed for a more robust EV ecosystem.

The high stakes set by policymakers and the high penetration rate of EVs create an urgent need for procuring a charging infrastructure to match the EV drivers' demands. As a result, many companies (such as Siemens, Shell, etc.) ventured toward manufacturing EV Charging Stations (EVCS). Further, new companies including ChargePoint and Enel are leading the EVCS market. From custom payments to membership cards, all the ways to EVCS localization, what all these companies have in common is providing the EV drivers with a beyond-satisfactory driving experience. Nevertheless, the current charging solutions lack some of the most essential properties. The two most prominent challenges facing the EV charging infrastructure is the scheduling of EV charging along with privacy and security.

The scheduling of EVs represents a dilemma whether to satisfy the EV driver by providing fast and reliable chargers at every possible location or minimize the number of chargers to avoid disturbances on the power grid. With that in mind, many research efforts have focused on leveraging different technologies and techniques such as Artificial Intelligence (AI), and Optimization, etc. to provide improved charging schemes while satisfying both the power grid and EV drivers. On the other side of the spectrum, security and privacy are the long-lasting enemy of the IoT paradigm. Being part of the IoT environment, it has been shown in different research contributions that EVCSs are vulnerable to an array of cyber-threats including Denial-of-Service (DoS) and Remote Code Execution (RCE). Such vulnerabilities may not only lead to energy and users' private data theft, but also to threatening the charging infrastructure as a whole, all of which would impact the adoption of EVs [7]. Accordingly, there have been major research efforts to mitigate such vulnerabilities by proposing lightweight security protocols and leveraging technologies such as Blockchain and AI.

While different technologies could be leveraged to mitigate the aforementioned challenges, we focus in this article on Blockchain and AI. Blockchain is a secure distributed and decentralized ledger of transactions, allowing different entities to perform transactions between different entities in a trust-less, decentralized and secure environment through the use of Hashing, Consensus mechanisms and Smart Contracts. On the other hand, AI has excelled in determining unrecognized patterns and making decisions accordingly. With the aforementioned discussion, our main contributions are:

- Providing a wide-eye view of the current deployment and protocols of EV charging and identifying the key challenges

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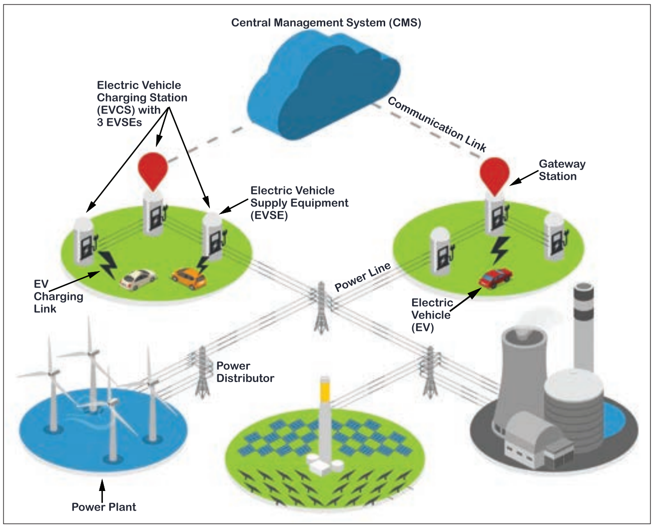


FIGURE 1. Electric vehicle infrastructure and protocols.

being faced with the EV infrastructure, specifically regarding scheduling and security.

- Evaluating the role of AI and Blockchain in solving such challenges. Specifically, we survey the different solutions from both the industry and academic sectors that leverage these two technologies separately opening the door to further identifying gaps and unsolved issues.
- Evaluating how the two technologies could be exploited in a complementary fashion to provide a more robust charging ecosystem.

The remainder of the article is organized as follows. We discuss the current deployment and protocols of the EV charging infrastructure, as well as the challenges being faced. We then discuss how AI and Blockchain could be used to solve these challenges. Further, we evaluate how both technologies can be used jointly to deliver the best charging service to the end-user. We finally discuss possible research directions and conclude the article.

## EV Charging: Deployments, Protocols and Challenges

The EV charging infrastructure is composed of multiple entities communicating via a set of different protocols. Figure 1 shows an abstraction of the current deployment of the EV charging infrastructure and its constituents are:

- **Energy Supplier:** The Energy Supplier could be any entity that is able to supply sufficient energy to operate the charging stations.
- **Electric Vehicle Charging Station:** With the energy supplied from the power grid, the EVCS is the medium at which EVs drivers can charge their vehicles. The EVCS itself is comprised of the Electric Vehicles Supply Equipments (EVSE) which are the actual physical devices that EVs connect to via connectors/plugs. Typically, EVSEs come in three different types depending on their power rating: Level 1, 2 and 3, with Level 3 being the most powerful [8]. In addition, EVSEs could be public or private depending on their access methods. Further, depending on the deployment, a set of EVSEs are usually connected to the gateway station via a Local Area Network (LAN). The gateway station then connects the Central Management System (CMS) via a Wide Area Network (WAN).
- **Central Management System:** The CMS is software responsible for managing the charging stations in terms of scheduling EVs, logging transactions, creating a database of authorized users, etc.
- **Electric Vehicles:** EVs are the end users that receive the power through their physical connection to the EVSE.

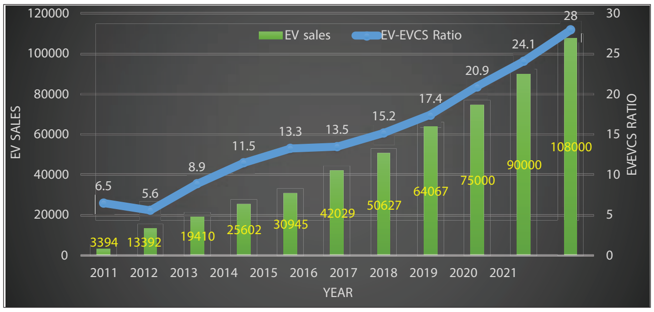


FIGURE 2. US EVs to EVCS ratio.

In terms of communication protocols, there is a myriad set of protocols being used within the EV charging ecosystem. For instance, Open Charge Point Protocol (OCPP) is an open source communication protocol between the EVCS and the CMS. It manages the registration of EVCS as well as remotely controlling their operations. Moreover, different companies such as Schneider Electric, Siemens, etc. utilize their own proprietary communication protocols between the EVCS and the CMS. Also, the power flow from the EVSEs to the EVs is managed by a set of communication protocols. The most prominent ones are: ISO-15118, IEC61851, SAE-J2293 and chAdeMO [7].

Besides the infrastructure and protocols, the EV market has been evolving over the past decade and accordingly the business of its charging ecosystem is booming. Figure 3 contextualizes the sales of EVs and their ratio to EVCSs over the past 10 years in the U.S. As can be seen from Fig. 2, the number of EVs has been increasing in almost a linear rate every year. However, the number of deployed EVCSs is not increasing at the same rate causing an increasing gap between EVs to EVCSs.

With the aforementioned discussion on EV charging deployments and protocols, we identify two main challenges facing the charging ecosystem:

### Security and Privacy

Security and privacy are always a major concern when a new service comes into existence. The EV charging infrastructure is no exception. By observing closely the current charging infrastructure, two major concerns become evident. The first concern is having multiple protocols. This variety imposes vulnerabilities to the system as each one of these protocols brings about its own unique set of vulnerabilities. For instance, OCPP was found vulnerable to Man-In-The-Middle Attacks (MITM) [9]. Thus, having a set of protocols used with the current charging ecosystem renders the overall system insecure. This, in return, leads to the second challenge which is having multiple entry points to the system. Each of the entities and protocols within the charging infrastructure could be exploited and compromised. For instance, many EVCSs by major operators were found to be vulnerable to RCE, and Buffer Overflow attacks [7]. Thus, an adversary could exploit the most vulnerable entities to compromise the more critical ones (Power Grid). These scenarios can render huge leverage to an adversary giving him/her the capability of stealing users' critical data, energy theft, and causing a DoS attack. To exacerbate the situation, given that these EVCSs have high power ratings, compromising them and synchronously tampering the schedules can cause disturbances to the grid due to a sudden increase in load [8].

### Optimal Charging Schedules

The second most critical challenge facing the EV charging ecosystem is the lack of optimal scheduling schemes. According to CleanTechnica, 40 percent of 3000 EV drivers believe that EVCSs are somewhat conveniently located for their needs. Further, almost half of these drivers found that the current infrastructure is somewhat adequate for long-distance trips. By correlating these statistics with Fig. 2, this trend of mediocre

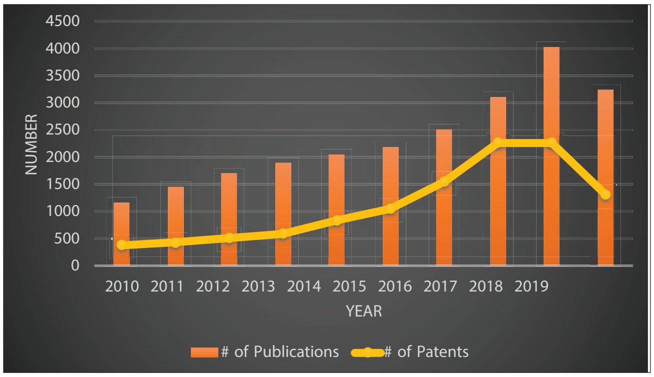

FIGURE 3. The Use of AI within the EV charging environment in terms of publications and patents over the past decade.

satisfaction is likely to remain as the gap between the EV and EVCSs is increasing over time. Although there have been major research efforts targeting the problem of EVCS placement and EV charging, as well as developments in battery technologies allowing EVs to travel longer distances per charge, the major challenge resides in trading-off customer satisfaction in terms of waiting time and reliability, and minimizing load fluctuation on the power grid.

There have been major research efforts that tackle the aforementioned problems by introducing lightweight secure charging protocols, proposing improvements on existing protocols or restructuring the infrastructure for a secure charging ecosystem. On the other hand, different optimization techniques and game theoretic approaches were proposed to solve the scheduling and placement problem. In what follows we evaluate the use of AI and Blockchain technologies to tackle such challenges.

## AI: Towards Intelligent EV Charging

Artificial Intelligence has been around for a couple of years and it has proven its applicability and efficiency in solving complex problems in different fields. The edge of AI is its capability to detect complex patterns and provide forecasts accordingly. Within the context of EV charging, AI could be the solution toward devising optimal charging schemes. As a result, many research contributions from patents, publications, books, etc. have explored the role of AI in the EV charging ecosystem. We scrapped Google Scholar to collect data on publications and patents on the use of AI within the EV charging environment and demonstrated the results in Fig. 3.

As demonstrated in Fig. 3, over the past decade, there has been an increase of almost 500 publications per year. More interestingly, the number of patents has also been increasing over the past decades. By closely observing the publications, the role of AI in the EV charging ecosystem becomes more evident. To contextualize this role, consider a scenario where a large number of EV drivers need to charge their vehicles during peak times. If the charging of those EVs starts at the same time during peak hours, there would be a surge in load on the power grid. Thus, a dilemma exists as to how to satisfy these EV drivers without causing a huge load increase on the grid. This could be solved using optimization or game theory. However, in order to solve this scheduling problem, the EV drivers' charging behavior should be considered. This is where AI comes into play. By exploiting meta-data on EV drivers' driving habits, charging behaviors, trips, etc., an AI agent could not only predict the charging behavior of EV drivers, but also the EVs' load profile on the power grid over time. This becomes very handy to the grid operator to manage the schedules of the EV drivers based on the forecasts from the AI agents. Further, AI could further be exploited to orchestrate the locations of EVCSs to be deployed. By collecting readily available data on a population living in a specific area, as well as historical data of EV drivers, an AI agent could predict the percentage of the population that is more likely to purchase EVs along with the potential load profile. Thus, from the grid operator perspective, these predictions could be leveraged to plan the locations of EVCSs to be deployed. Thus, the role of AI could be summarized in:

1. *Load profile prediction to optimally deploy EVCS.*
2. *EV drivers' behavior forecast for better scheduling schemes.*

On the industry side, the role of AI still serves the same purpose, and as such, there have been a few companies and startups that leveraged AI to improve the EV charging infrastructure. For instance, Oracle acquired Opower Inc. in 2016 gaining access to billions of data points on households' energy usage from 60 million customers across 100 utilities. Leveraging Oracle's deep learning framework, this rich dataset is used to forecast EV loads and inform power utilities so they would manage their power generation accordingly to accommodate for the load. Another interesting use case of AI is by a startup called GBatteries that demonstrated their patent in CES 2019. The company uses AI to speed up the charging process by collecting health indicators from the EV battery. These indicators are then analyzed and a decision is made determining whether the battery could be charged using the maximum power. The tradeoff here is that charging at the maximum power leads to faster charging; however, it comes at the expense of depleting the battery. Thus, by leveraging AI, a decision on the power level to be delivered to the EV battery is made.

In short, the power of AI revolves around detecting complex patterns and providing decisions/forecasts that could be mainly used by the power utility to better manage their power generation, or by EV drivers to speed up their charging.

## Blockchain: For Secure Decentralized EV Charging

Blockchain is a disruptive technology that allows entities to perform transactions in a

1. *Distributed environment: all transaction history is distributed among all nodes in the network.*
2. *Decentralized environment: no central entity controlling the transactions.*
3. *Secure environment: through the use of Public Key Infrastructure (PKI).*

The basis of Blockchain is to allow different nodes/entities to communicate together in a trustless environment without the need to rely on a central entity to overlook these transactions. With such, the applicability of Blockchain could be extended from simply a distributed ledger, to include trading of digitized assets (energy, money, etc.). The first application of Blockchain dates back to 2008 when Satoshi Nakamoto introduced the Bitcoin network as a way to transfer monetary value between different sources without the need for a bank. Later, Ethereum was born allowing the Blockchain technology to reach its true potential by allowing the creation of Decentralized App (dApps for short). With Ethereum, the concept of smart contracts was introduced, which are pieces of software residing on the Blockchain network and automatically invoked when specific clauses are met. With smart contracts, Blockchain provides an edge in creating decentralized economies for trading virtually any asset. An abstraction of a Blockchain network consists of three main layers:

- **Network Layer:** The network layer represents the communication protocol between the nodes in the network. Usually, the Blockchain network operates using Peer-to-Peer (P2P) protocols.
- **Consensus Layer:** The consensus layer is responsible for ensuring the validity of the data being shared in the Blockchain network. That is, when a transaction is issued and broadcast over the network, how to make sure that it is a valid transaction. For that, different consensus algorithms have been proposed with Proof of Work (PoW) and Proof of Stake (PoS) being the most famous mechanisms used. For scalability, specific nodes in the network known as min-

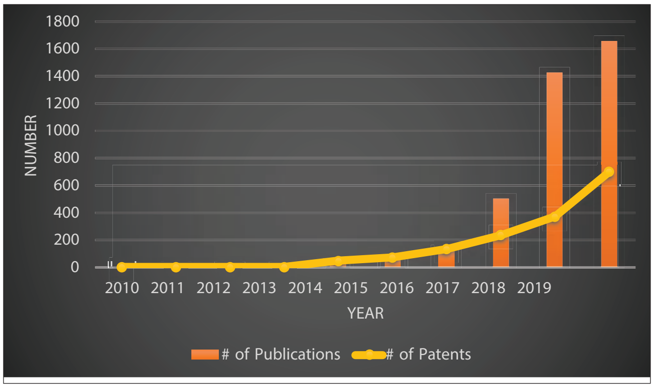

FIGURE 4. The Use of Blockchain within the EV charging environment in terms of publications and patents over the past decade.

ers/validators are responsible for performing the consensus algorithms. Further, depending on the implementation of the network, these validators/miners could be awarded with cryptocurrency for their contribution.

- **Transaction Layer:** The transaction layer is the last layer in the stack and is responsible for handling data being transacted in the network. Stated simply, it defines smart contracts and makes sure that they are properly invoked.

With such abstraction, Blockchain networks could be:

- **Public/Permissionless:** anyone can join the network and participate in the consensus/validation process.
- **Private/Permissioned:** only a set of authorized nodes can not only perform the validation process but also decide who joins the network, manages the network in terms of updates, etc.

Each implementation of the Blockchain network has its pros and cons. For instance, public Blockchain networks are the closest form of a decentralized, trustless environment that relies on its nodes to sustain itself. However, this comes at the expense of speed due to a large number of participating nodes. In contrast, private Blockchain networks are more scalable and faster networks; however, they give more control to the authorized nodes.

Within the context of EV charging, Blockchain networks could be the answer to the security and privacy problems facing the current infrastructure. Accordingly, there have been efforts from both the research and industry sectors to utilize Blockchain networks with EV charging. Similar to AI, we contextualize these efforts in Fig. 4.

As shown in Fig. 4, the number of publications and patents for Blockchain-enabled EV charging networks started to see the light in 2014 followed by a huge increase by 2018 and 2019. To put these efforts in perspective, the early contributions were about digitizing energy by proposing P2P energy trading systems. Later, publications moved toward a Blockchain-enabled EV charging ecosystem that would allow the integration between smart grids and EVCSs to serve EV drivers. For instance, some research efforts focused on creating a Blockchain network to securely manage the energy trading between local communities generating energy and EVCSs. This scenario becomes advantageous as it would eliminate intermediaries (lower costs), and prevent malicious entities from misusing the system. Other work focused on creating a network of Blockchain networks composed of all entities participating in the charging infrastructure [10–12].

On the industry side, the major role of Blockchain in the EV environment is to enable secure energy trading by allowing homeowners to sell their energy (making their EVCSs open to the public) to other EV drivers in a decentralized environment. Within this P2P energy trading context, different companies have taken initiatives to build Blockchain-enabled EV charging networks. For instance, Oxygen Initiative has extended already existing EV charging protocols (ISO-15118) and proposed a Blockchain network that enables either the utilities or any EVCS to offer pricing and grid conditions for EVs. Thus, in a sense, their network acts as an auction house for the EVs allowing them to choose the best available options as well as giving them incentives if they choose to delay their charging to later times. The company believes that its system could further be extended to include the functionality of EV drivers selling energy back to the grid. Further, a company called Charg offers an Uber-like service, through the Ethereum network, for energy trading by allowing anyone to lease their EVCSs to EV drivers in what they have called the Internet of Energy (IoE).

Thus, the key role of Blockchain resides in aiding EV drivers and home owners to trade energy securely with no intermediaries. This functionality could be easily extended to include EV drivers selling energy to the power grid as a way of peak shaving. Hence, Blockchain serves as an incentive for EV adoption as it would benefit both homeowners (making their EVCSs public) and EV drivers (selling energy to the grid).

## The Best of Both Worlds: Blockchain and AI

Based on the aforementioned discussion, AI plays a key role in managing the schedules of EVs and orchestrating their deployments through load profiles' forecast and charging behavior predictions. However, an AI-enabled charging system still relies on a central entity (power utility) to manage the transfer of energy. This scenario becomes particularly problematic when the security is taken into consideration. For instance, malicious entities can compromise EVCSs and either cause disturbances to the power grid or simply steal energy or users' critical data. On the other hand, Blockchain aims at providing a secure, trustless, decentralized and distributed energy trading system. With such, this system could render intermediaries and central entities obsolete reducing unnecessary operational costs. Further, the Blockchain charging network could serve as an auction house where different energy suppliers (utility, private EVCS owners, etc.) could broadcast their availabilities and prices over the network based on the grid and EVs conditions. However, the deployments of smart contracts in Blockchain lacks the flexibility to adapt to the dynamic charging behavior of EV drivers and grid conditions. Thus, for a fully-fledged EV charging system, AI and Blockchain should complement each other.

One such scenario on the collaboration of AI and Blockchain is the work done in [13]. The authors proposed a Blockchain-enabled EV charging system where:

1. EV drivers could charge their EVs from either the power grid, private EVCS owner, or local communities.
2. Drivers can discharge their EVs back to the grid to help reduce the load on the power grid.

The authors then considered the optimization of the charging/discharging schedules through an adaptive algorithm to account for the change in EV charging demands.

Another scenario for the collaboration of AI and Blockchain is in [14] where the authors focused on the scalability of the Blockchain network itself rather than the schedules of EVs. In particular, the authors, based on EV data, leveraged deep learning to maximize the transactional throughput while ensuring the decentralization, latency and security of the system. This is particularly interesting as the proposed system is capable of changing its working mechanisms (block size, block dynamics, etc.) according to the dynamic changes in the environment.

On the industry side, a team in the Odyssey Hackathon, the Porsche Digital Lab, proposed a Blockchain-enabled charging environment backed with AI. The motive was similar to the aforementioned discussion, which involves reducing load on the grid, increasing user satisfaction and ensuring security. As a result, the team proposed an energy trading economy that allows local communities to lease their EVCSs, and EV drivers to sell back their energy. Further, the team introduced an AI agent to manage the schedules of EVs by predicting prices, availabilities and driving patterns.

## Research Directions

Aside from existing work, the collaboration between AI and Blockchain goes beyond merely creating an open trading ecosystem for digitized assets. The true value for such collaboration prevails when considering the challenges they mitigate. In terms of security, Blockchain, indeed, provides a secure and immutable record of transactions through PKI and consensus algorithms. In fact, by decentralizing and distributing the infrastructure, Blockchain mitigates one of the root causes of having a vulnerable charging ecosystem, i.e., multiple entry points. In particular, with a decentralized system, the role of CMS and power grid as managing entities would be rendered obsolete and would merely act as facilitators, reducing the threat landscape. Moreover, AI has held its ground in providing forecasts as well as detecting anomalies. Therefore, integrating AI with Blockchain paves the way for creating self-sustaining, self-correcting ecosystems. To put it in perspective, AI can be integrated within each layer of the Blockchain network providing different functionality at each layer. At the network layer, AI can be used as an added security layer to predict anomalies in the network and take action accordingly (isolating malicious nodes for instance). Further, at the consensus layer, AI can be used as a scalability measure to predict the system dynamics (network size, data frequency, etc.) and accordingly adjust the consensus mechanisms (block size, block generation time, etc.). Finally, AI can be used in the transaction layer to both detect anomalies and forecast the system dynamics, all of which would be used to adjust the smart contracts for better EV scheduling mechanisms. In principle, the integration of AI and Blockchain serves as the niche for a self-correcting EV charging ecosystem.

While the research shows promising theoretical results, there is a need for further explorations. Specifically, the scalability and reliability of Blockchain within the EV charging networks need to be properly evaluated given the penetration rate of EVs. This can be further extended to develop new consensus algorithms that reduce the overhead in the network while considering the trade-offs in terms of security. Moreover, given the transparency in Blockchain transactions (all transactions are available and accessible), research directions in Zero-Knowledge Proofs (ZKP) and Homomorphic encryption are needed to solve this privacy issue. In addition, the use of federated learning within the Blockchain network is a rather interesting research direction that would aid in providing a fully-decentralized network with distributed AI nodes. Another way of decentralization is to abstract the EV charging network as a Multi-Agent System (MAS) with some agents responsible for data collection, AI calculations, block validation, etc. Thus, each agent can perform independently its allocated task. Further, much of the work that integrated AI and Blockchain was on the theoretical side. However, there is much-needed real-world experimentations of such proposed systems to properly evaluate their performance. In addition, some research has been done on how to leverage AI to detect new vulnerabilities, thus it would be interesting to explore the resilience of Blockchain and AI charging networks against demand-side IoT attacks (where an adversary compromises high wattage devices to cause disturbances to the grid), as well as new ones. A more interesting research direction is how to extend existing protocols (such as OCPP) to exploit both technologies for better security and energy management.

## Conclusion

In this article, we investigated the current deployments, protocols and infrastructure of the EV charging ecosystem. We identified two key challenges: the trade-off between user satisfaction and grid operations, and security and privacy. For that, we evaluated, through collecting data on recent trends from research and industry, the use of AI to manage the schedules of EVs and help provision EVCSs. Similarly, we evaluated the role of Blockchain in securing the EV charging ecosystem and providing a trustless trading system that allows EVs, private EVCS owners and power utilities to trade energy. It was shown that Blockchain can:

- Help manage peak shaving by giving incentives to EV drivers to sell energy to the grid.
- Increase the satisfaction of EV drivers by allowing the selling of energy from private EVCS owners and local communities, as well as lowering the costs by excluding intermediaries.

While both on their own target some key challenges, a more robust charging ecosystem requires the integration of AI and Blockchain. For that, we evaluated different use cases on how AI and Blockchain could be leveraged together to improve the charging ecosystem.

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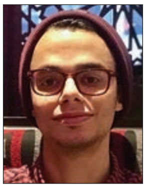
### Biographies



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