Trust and Security of Electric Vehicle-to-Grid Systems and Hardware Supply Chains

Negin Moghadasi[1], Zachary A. Collier[2, 5], Andrew Koch[1], David L. Slutzky[1, 3], Thomas L. Polmateer[1, 5], Mark C. Manasco[4], James H. Lambert[1, 5]

[1]*Department of Engineering Systems & Environment, University of Virginia, Charlottesville, VA, USA (nm2fs@virginia.edu, atk8jf@virginia.edu, tp3qh@virginia.edu, lambert@virginia.edu)*
[2]*Department of Management, Radford University, Radford, VA, USA (zachary@collierresearchsystems.com)*
[3] *Fermata Energy, Charlottesville, VA, USA (david@fermataenergy.com)*
[4] *Commonwealth Center for Advanced Logistics Systems (CCALS), Petersburg, VA, USA (mark.manasco@ccals.com)*
[5] *NSF Center for Hardware and Embedded Systems Security & Trust (CHEST)*

Abstract

Abstract— Future electric vehicles and associated vehicle-to-grid (V2G) infrastructure, including vehicle charging stations and network communications, face a variety of cybersecurity threats. The threats include disruptions of the supply chains and operations of the embedded hardware devices of these systems. Systemic and principled approaches are needed in which the security and trust relationships among V2G systems, charger systems, and communications networks are characterized. Furthermore, there is a need for guidance in allocating resources to improve system security, resilience, and trust. Thus, this paper develops a framework to address the emergent and future conditions that are most disruptive to the security of the embedded devices of fleet electric-vehicle (EV) chargers and their networks. The innovation of this paper is to account for hybrid cybersecurity threats to the interests of system owners, operators, and users, addressing scenario-based preferences for rapidly advancing technologies. There is a demonstration with fleet electric vehicles providing logistics services, shared bidirectional chargers, and communications infrastructure.

Keywords: Enterprise Risk Management, Hardware Security, System Reliability, Systems Engineering, Internet of Things, Logistics Systems

1. INTRODUCTION

Individual consumers and owners of vehicle fleets will increasingly adopt electric vehicles (EVs) over traditional vehicles with internal combustion engines (Muthukannan et al., 2022; Barkenbus, 2020). Sales of EVs accelerated rapidly in 2020, rising by 43% to more than three million vehicles, despite the decreasing overall volume of car sales by a fifth through the coronavirus pandemic (Carrington, 2021; Shehan, 2018). Fig. 1 represents how the quantity of EVs in the USA has been steadily growing (IEA, 2020). EVs and vehicle-to-grid (V2G) technologies (Das et al., 2022; Patil and Kalkhambkar, 2021; Nguyen et al., 2021) will have roles in electricity distribution systems by contributing to the stability of the grid (Chtioui and Boukettaya, 2020; St. John, 2013; Tremblay et al., 2007). Large commercial and industrial power bills are comprised of demand charges for the highest electricity demand level during a billing period or peak demand (Banga and Sharma, 2022; Mullendore, 2017). Demand charge management (DCM) is a process designed to limit the peak power draw of a building by supplementing grid power with behind-the-meter energy storage, reducing power requirements of a typical building during times of peak demand (Andrews, 2020).

Fig. 2 is a conceptual diagram of an EV-to-Grid technologies in the context of a smart city or socio-technical system. V2G technology that can use EV batteries to provide services to the electric power grid through bidirectional chargers. V2G technology is used to increase grid stability (Almutairi et al., 2019) by applying bidirectional DC fast chargers to deploy stored electricity from EV batteries to a site. This reduces utility bills and less demand for power distribution infrastructure and even generating revenue (Sharma et al., 2022; Sweeney et al., 2017). When fleets use EVs, whether battery or electro-fuel, in conjunction with bidirectional fast chargers to participate in electric grid ancillary service markets, the portion of grid revenues received by the fleet operations ensures that the total cost of ownership (TCO) of the vehicles is competitive with the TCO of internal combustion vehicles (Fernandez et al., 2021; Debogorski, 2021; Lombardo, 2017).

The deployment of a bidirectional charging network, however, has risks as well as opportunities. For instance, in 2019, security experts identified three vulnerabilities in an electric vehicle charging station (Fiscutean, 2019). Such vulnerabilities are concerning since these charging stations are connected to the electric grid (US Government Accountability Office, 2021; Gottumukkala et al., 2019; Falk & Fries, 2012). The electric grid itself is vulnerable to attack; for example, Soltan et al. (2018) demonstrate that high-wattage devices can be used to launch an attack on the electric grid.

For V2G communications infrastructure, Saini (2020) identified several attack vectors involving the vehicle, the charging station, and exchanged information. Their distributed locations and connectivity to card readers for payment processing, make EV charging stations a target for malicious actors (Levi, 2019; Whittaker, 2019). Moreover, as cyber-physical system, the hardware security of these vehicle/charger systems and their supporting supply chains are a concern (DiMase et al., 2020, Chen et al., 2020; Hossain et al., 2020). Compromised embedded hardware within chargers has the potential for cascading effects on the vehicles connected to the chargers and the fleet.

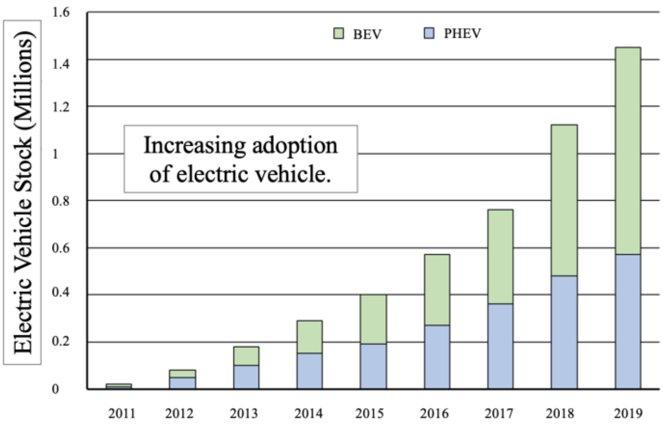

Fig. 1. EVs quantity increase in the US

With the above background, this paper will develop a modeling approach to identify the most and least disruptive scenarios for fleet EV charging network security and trust, focusing on the supply chains (Wu, et al. 2020) of embedded hardware devices. The scenarios include both the supply chains for hardware devices and the software vulnerabilities of hardware devices. The following section describes the methodology. A subsequent section demonstrates the methodology with an example of a fleet EV charging station system. The paper concludes with a summary of implications and several suggestions for future work.

2. Methods

There are various risks associated with V2G communications and electrical vehicle chargers in the mobile electric grid. To update priorities (Guo et al., 2022; Thorisson and Lambert, 2021) for risk management and design resilient systems, one must take systems view and consider the perspectives of a variety of stakeholders. Scenario identification and planning have an imperative role in structuring complex problems, supporting management with deep uncertainties, and promoting robust strategic decision making (Collier and Lambert, 2018; Montibeller & Franco, 2010). Scenario planning helps decision makers devise strategies and think about possible futures where probabilities are derived from expert opinions and are subject to cognitive bias (Hassler et al., 2019; Montibeller et al., 2006). Domain experts achieve high levels of performance on a particular task or within a given topic (Boume et al., 2014). Stakeholders are selected according to their level of expertise and education in the field and levels of interest or investment in the system (Hassler et al. 2019; Daneshvar et al. 2019). These are staff engineers and inventors of a company inventing bidirectional EV

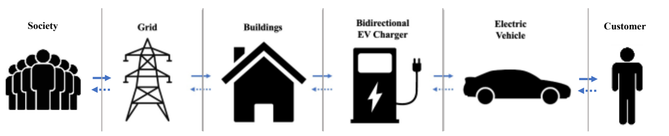

Fig. 2. Conceptual diagram of the EV to Grid technologies in the context of a socio-technical system. V2G technology that can use EV batteries to provide services to the electric power grid through bidirectional chargers.

chargers with engineering, design, economic and business background, and expertise.1 The issue of the expert bias is important here and in the rest of the field. Since expert judgments are subject to bias, several methods are used to mitigate the judgments such as simple averaging, giving importance weight to the experts, AHP, FAHP, breaking the problem into several layers and others (Kim et al. 2021; Kandemir, and Celik, 2021; Yazdi, 2020; Verzobio et al. 2021; Pandya et al. 2020). Multicriteria decision analysis (MCDA), typically coupled with scenario analysis, is a comparative decision support tool for evaluating competing alternatives involving multiple attributes of interest (Martins et al., 2019; Montibeller et al., 2006). MCDA provides the decision maker with a rationale for setting priorities considering performance indices and stakeholder perspectives (Vincke, 1992).

This section describes an elicitation of scenario-based preferences (Belton & Stewart, 2002) that aids in identifying system initiatives, criteria, and scenarios comprised of emergent and future conditions. Emergent and future conditions are events, trends, or other factors impacting decision maker priorities in future strategic planning contexts (Quenum et al., 2017; Goodwin & Wright, 2001). In the model, emergent and future conditions influence the relevance weights of individual prioritization criteria, increasing or decreasing (Hassler et al., 2019; Karvetski et al., 2010).

The first element of the model is a set of criteria. Success criteria are developed to measure the performance of investment initiatives based on the system objectives (Hassler et al., 2019). Any changes in success criteria affect expectancies of success (Ziv and Lidor, 2021) and represent the stakeholder main values. The set of success criteria is {c.01, c.02, …, c.m}. The baseline relevance of criteria is established by asking stakeholders to assess each criterion relative emphasis (low, medium, and high). These responses determine the baseline weights assigned to each of the success criteria.

Initiatives represent a set of decision-making alternatives in the form of technologies, policies, assets, projects, or other such investments (Hassler et al., 2019). Initiatives are identified by eliciting stakeholders and experts and reviewing third-party analyses to determine what hardware components, actions, assets, organizational units, policies, locations, and/or allocations of resources constitute the system. The set of initiatives is {x.01, x.02, …, x.n}.

To assess the degree to which each initiative is addressing each criterion, experts and stakeholders can be interviewed as part of the criteria-initiative (C-I) assessment. Hester et al. proposed a similar KPI[2]-criterion pairing method to criteria-initiative assessment as a key performance indicator in manufacturing organizations (Bortoluzzi et al. 2021; Hester et al. 2017).

In criteria-initiative assessment, participants are asked to what degree they agree that initiative x.i address criterion c.j, with responses such as *neutral*, *somewhat agree*, *agree*, and *strongly agree*. In the C-I assessment, neutral entries are represented by a dash (-), *somewhat agree* is represented by an unfilled circle (○), *agree* is represented by a half-filled circle (◐), and *strongly agree* is represented by a filled circle (●) in the matrix. *Increased somewhat* is introduced by Hassler et al. and is a moderate between increase and no increase or increased to some extent or degree (Hassler et al., 2019; Merriam-Webster's Collegiate Dictionary, 2022). For example, *lower economic cost* could be a criterion, and develop charger controllers could be an initiative. The relation between this criterion and initiative might be rated by an expert as *somewhat agree*. In this way, each combination of criterion c.j and initiative x.i receive a response. These linguistic responses are converted into numerical scores as described below.

Emergent and future conditions are disruptive future events, trends, and other uncertainties that can affect a project, system, schedule, and budget (Thorisson et al., 2019). Emergent and future conditions can impact the relationship between project activities and objectives and change the structure of project activities (Collier & Lambert, 2018). Emergent and future uncertainties are a significant contributor to project failure (de Meyer et al., 2002; Pich et al., 2002; Huchzermeier and Loch, 2001). Scenarios are comprised of one or more emergent and future conditions (Ogilvy & Schwartz, 2004). Let the set of scenarios be {s.01, s.02, …, s.p}.

[1] Mr. John Wheeler, Ms. Anna Bella Korbatov, and Mr. Colin Steers and other technical staff of Fermata LLC. 2021, personal communication.
[2] Key Performance Indicators

The effect of disruptive emergent and future conditions is operationalized through a change in the criteria weights. For each identified scenario, the user is asked to assess to what degree the relative importance of each criterion changes within that scenario. Responses include *decreased*, *decreased somewhat*, no change, *increased somewhat*, and *increased*. Again, these linguistic responses are converted to numerical scaling constants which adjust the weights upward or downward. The weights are re-normalized (such that they sum to 100%), resulting in scenario-specific criteria weightings.

The initiatives are prioritized with a linear additive value function (Belton and Stewart, 2002) across the baseline and identified scenarios. The value function for initiative x.i in scenario s.k is defined as:

$$V_k(x.i) = \sum_{j=1}^{m} w_{jk} v_j(x.i) \tag{1}$$

Where $v_j(x.i)$ is the partial value function of initiative x.i along with criterion c.j, which is defined through the C-I assessment. Within each scenario, the initiatives are prioritized based on their value functions. This results in k+1 rank-ordered sets of initiatives (k scenarios plus the baseline scenario). To understand the effect of emergent and future conditions on the prioritization of initiatives, disruptiveness score is defined based on the sum of squares. Specifically, the disruptiveness score for scenario s.k is calculated as:

$$D_k = \frac{\sum_i (r_{i0} - r_{ik})^2}{\sum_k D_k} \tag{2}$$

Where r_{ik} is the rank of initiative x.i under scenario s.k, and r_{i0} is the rank of the initiative x.i under the baseline scenario. The scores are normalized by dividing each score D_k by the sum of all disruptiveness scores across scenarios. The score is higher with more disruption of priorities relative to the baseline prioritization.

Fig. 3 represents the conceptual diagram of the risk assessment methodology.

3. Demonstration

This section demonstrates the above methodology on a realistic system of fleet EV chargers based on engagement with industry experts and stakeholders. As mentioned before, the stakeholders have the most investments in the system and the experts are the management team that has professional experiences in this field. The methodology demonstration is in several parts: *Criteria*, *Initiatives*, *C-I Assessment*, *Emergent Conditions* (EC), *Criteria-Scenario* (C-S) *Relevance*, and *EC Grouping*.

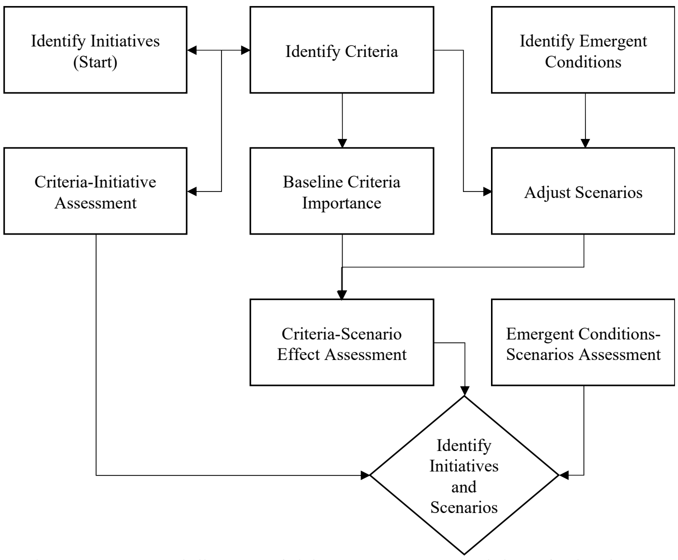

Fig. 3. Conceptual diagram of risk assessment methodology for hardware supply chains of charging infrastructure of electric vehicles.

TABLE I
SUCCESS CRITERIA TO EVALUATE THE PERFORMANCE OF BIDIRECTIONAL CHARGING NETWORKS.

Index	Criterion
c.01	Lower Economic Cost
c.02	Increase Economic Revenue
c.03	Keep Up with Market Standards
c.04	Reduce Carbon Emissions
c.05	Reduce Cyber Attack Vulnerability
c.06	Availability
c.07	Reduced Energy Consumption
c.08	Affordability
c.09	Durability
c.10	Increase Self Sufficiency
c.j	Others

Considering the perspective of the stakeholder can aid in identifying success criteria and decision alternatives (i.e., initiatives) (Collier et al., 2014). The stakeholders are:

- The EV charging station designer/owner;
- Other EV charger producers;

- Vehicle manufacturers;
- Government entities;
- Utility and grid operators;
- Plug-in electric vehicle owners.

First, success criteria are identified to represent the requirements and goals of the system. Success criteria are identified from previous studies in the literature on EV charging stations and IoT security (Andrews et al., 2020).

Table I shows the list of success criteria used to identify scenarios in the system. Also, the list of criteria is produced to measure the appeal of the various initiatives concluded from different sources. In this project, ten main success criteria are identified. These criteria are augmented for specific goals and missions. The criteria categories that introduce this list comprise energy efficiency, reducing carbon emissions, energy reliability, energy availability, reducing cyber-attacks (Iaiani et al., 2021), affordability, enhancing trust and security, enhancing information privacy, keeping up with market supply and demand, reducing environmental risks and integrating renewables. More studies may lead to more criteria. *c.01. Lower Economic Cost, c.02. Increase Economic Revenue, c.06. Availability, c.07. Reducing Energy Consumption, and c.09. Durability* are examples for success of bidirectional charging. Success criteria can be adjusted and expanded as deemed necessary in future iterations.

Initiatives are projects or activities that are impactful to the success of the system. The initiatives vary in terms of their resource requirements and programmatic impacts. Initiatives are identified from a literature review to determine what actions are available to protect and mitigate the risk to the system. Next, a list of the potential initiatives is compiled.

Table II introduces twenty main initiatives that address one or more of the criteria used to evaluate the success criteria. Initiatives could be assets, projects, policies, rules, funds, suborganizations, or classes of technology (Hassler et al., 2019). The perspectives and opinions of stakeholders, reviewers, experts, and managers of the project are used in assessment of initiatives. A key interest is to find how the rankings of initiatives change across scenarios relative to a baseline scenario. *X.01. Simulation for Market Variability* and *x.011. Analysis of Long-Term Wear on Batteries* are examples of the initiatives.

TABLE II

INITIATIVES ADDRESS ONE OR MORE OF THE SUCCESS CRITERIA FOR HARDWARE SUPPLY CHAINS OF CHARGING INFRASTRUCTURE OF ELECTRIC VEHICLES.

Index	Initiative
x.01	Simulation For Market Variability
x.02	Regional Resource Planning
x.03	Standards Of Encryption
x.04	Develop Charge Controllers
x.05	Understanding Load Cycles
x.06	Identify At-Risk Components
x.07	Test At-Risk Components
x.08	Develop Tools for Showing Benefits of Bidirectional Charging
x.09	Analysis Of Time-Of-Use Rates
x.10	Build Out to Rural Networks
x.11	Analysis Of Long-Term Wear on Batteries
x.12	Understanding Effects of Battery Use on The Environment
x.13	Cost-Effective Resource Allocation to Portfolios of Security Measures for Embedded Devices in A Large-Scale System
x.14	Trusted Enterprise Communications and Cyber-Physical Integration of Advanced Fleet Electrical Vehicle Chargers in A Mobile Electric Grid
x.15	Secure Processor Design By RISC-V Framework
x.16	Current Sensing Based On-Chip Analog Trojan Detection Circuit Compatible with Chip Design and Validation Flow
x.17	Stochasticity, Polymorphism and Non-Volatility: Three Pillars of Security and Trust Intrinsic to Emerging Technologies
x.18	Design Obfuscation and Performance Locking Solutions for Analog/RF Ics
x.19	Connectionless RFID Based Secure Supply Chain Management
x.20	Leveraging Hardware Isolation for Secure Execution of Safety-Critical Applications in Distributed Embedded Systems
x.i	Others

The next step is to perform the criteria-initiative assessment, which visually compares criteria to initiatives and provides a score that signifies the degree to which an initiative addresses a criterion. This score is used to rank the effectiveness of each initiative. The assessments are decided based on engagement with experts.

Table III shows the impact of ten success criteria on twenty initiatives that are introduced before. A dashed line indicates the initiative has *no impact* on the success criteria, an empty circle indicates a *low impact*, a half-filled circle indicates *medium impact*, and a filled in circle indicates that the initiative has *high impact* to a success criterion. The corresponding numerical scores of 0, 0.3, 0.7, and 1 were assigned to the graphical responses. *No impact* means that an initiative has no relevance to the criterion. For instance, *c.01. Lower Economic Cost* has a high impact on *x.13. Cost-Effective Resource Allocation to Portfolios of Security Measures for Embedded Devices in A Large-Scale System*. Also, *c.01. Lower Economic Cost* does not affect *x.12. Understanding Effects of Battery Use on The Environment*. However, *c.01. Lower Economic Cost* has a medium impact on *x.05. Understanding Load Cycles, x.06. Identify At-Risk Components* and *x.07. Test At-Risk Components*.

TABLE III

THE CRITERIA-INITIATIVE ASSESSMENT SHOWS HOW WELL EACH INITIATIVE ADDRESSES THE SUCCESS CRITERIA OF BIDIRECTIONAL CHARGING SYSTEM.

STRONGLY AGREE IS REPRESENTED BY A FILLED CIRCLE (●), *AGREE* IS REPRESENTED BY A HALF-FILLED CIRCLE (◐), *SOMEWHAT AGREE* IS REPRESENTED BY AN UNFILLED CIRCLE (○), AND *NEUTRAL* IS REPRESENTED BY A DASH (-).

The criterion c.xx is address by this initiative	c.01 - Lower Economic Cost	c.02 - Increase Economic Revenue	c.03 - Keep Up with Market Standards	c.04 - Reduce Carbon Emissions	c.05 - Reduce Cyber Attack Vulnerability	c.06 - Availability	c.07 - Reduced Energy Consumption	c.08 - Affordability	c.09 - Durability	c.10 - Increase Self Suffiency	c.i - Other
x.01	-	○	◐	-	-	◐	-	-	-	-	
x.02	○	◐	●	-	-	●	◐	◐	-	○	
x.03	-	○	◐	-	●	-	-	-	○	◐	
x.04	○	-	●	-	-	-	◐	○	-	-	
x.05	◐	●	◐	○	-	○	◐	○	-	○	
x.06	◐	◐	○	-	◐	○	-	-	◐	◐	
x.07	◐	◐	○	-	●	-	○	-	◐	◐	
x.08	-	○	-	-	-	◐	-	-	-	-	
x.09	○	○	○	-	-	◐	●	◐	-	-	
x.10	○	●	○	◐	-	●	○	○	-	-	
x.11	○	◐	◐	-	-	○	-	○	●	◐	
x.12	-	-	○	○	-	-	○	-	-	-	
x.13	●	○	○	-	◐	-	-	-	-	-	
x.14	-	○	○	-	◐	-	-	-	-	●	
x.15	-	-	◐	○	●	-	-	-	-	◐	
x.16	-	○	◐	-	●	-	-	-	-	◐	
x.17	○	◐	◐	○	○	-	-	-	-	-	
x.18	-	○	○	-	○	-	-	-	-	-	
x.19	-	-	○	-	●	-	-	-	○	-	
x.20	-	-	-	-	●	○	-	-	-	◐	

TABLE IV
EMERGENT CONDITIONS USED TO CREATE SETS OF SCENARIOS FOR RISK ANALYSIS OF HARDWARE SUPPLY CHAINS OF ELECTRIC VEHICLE CHARGING INFRASTRUCTURE.

Index	Emergent Condition
e.01	New Fuel Economy Standards
e.02	Reduced Battery Costs
e.03	Enhanced Electric Vehicle Efficiency
e.04	Cyber Security Attack
e.05	Material Supply Shortage
e.06	Increased Power Grid Reliability
e.07	Increased Electricity Usage
e.08	Increased Renewable Energy Generation
e.09	Increased Electricity Prices
e.10	Cyber Security Practices Become Outdated
e.11	Implementation Goes Over Budget
e.12	Implementation Takes Longer Than Expected
e.13	Government Policy Changes
e.14	Shortage Of Production Materials
e.15	New/Increased Number of Suppliers
e.16	Increased Renewable Energy Dependence
e.17	Counterfeit Product in Supply Chain
e.18	Change In Worldwide Energy Stance
e.19	Development Of Newer, More Advanced Hardware Security
e.20	Development Of More Powerful Chargers
e.21	Increased EV Purchase Subsidies
e.22	Versatility Of Charging Locations
e.23	Denial Of Service
e.24	Attacks On IoT Service
e.25	Ransomware
e.26	Unauthorized Access Attacks
e.27	Data Collection: Phishing, Spamming, Spoofing
e.28	User Authentication Issues
e.29	Poorly Encrypted Data/No Data Encryption
e.30	Limiting Employee Access to Hardware
e.31	Pilot Testing of Services to Ensure Security Functionality
e.32	Auditability/Ease of Monitoring System Activity
e.33	Development Of More Advanced Blockchain Storage/Distributed Data Storage
e.34	Physical Disruption of Charging Networks
e.35	Denial Of Service Attacks
e.36	Reliable And Resilient Power Grid
e.37	Charging Infrastructure Capacity
e.i	Others

TABLE V
RELEVANCE BETWEEN SCENARIOS AND EMERGENT CONDITIONS IN BIDIRECTIONAL CHARGING HARDWARE SUPPLY CHAINS.

	s.01	*s.02*	*s.03*	*s.04*	*s.05*	*s.06*	*s.07*	*s.08*	*s.09*	*s.i*
e.01	✓	✓		✓					✓	
e.02	✓	✓	✓							
e.03	✓	✓			✓			✓		
e.04					✓		✓	✓		
e.05	✓				✓				✓	
e.06	✓	✓	✓		✓					
e.07		✓	✓	✓						
e.08	✓	✓	✓	✓					✓	
e.09			✓			✓		✓		
e.10					✓			✓	✓	
e.11					✓	✓				
e.12						✓	✓	✓		
e.13		✓		✓		✓			✓	
e.14								✓	✓	
e.15		✓	✓		✓					
e.16			✓	✓					✓	
e.17						✓	✓			
e.18			✓	✓		✓			✓	
e.19					✓					
e.20					✓					
e.21									✓	
e.22		✓								
e.23		✓								✓
e.24										✓
e.25										✓
e.26		✓								✓
e.27										✓
e.28		✓								✓
e.29		✓								✓
e.30	✓									✓
e.31					✓					✓
e.32										✓
e.33					✓					
e.34		✓								✓
e.35		✓								✓
e.36					✓					
e.37	✓	✓			✓					

Emergent conditions are next identified. Emergent conditions are trends or events that disrupt the relative importance of the success criteria, and thus the rankings of the initiatives for the bidirectional charger system. Through a literature review and stakeholder interviews, emergent conditions were identified. The emergent conditions primarily focused on the changes in government policy, societal behaviors, the markets, and technology and innovations. Table IV represents the list of emergent conditions used to create sets of scenarios for the risk analysis. Emergent conditions are used to create sets of scenarios for bi-directional chargers risk analysis. The thirty-seven main emergent and future conditions are described in this table. This list can get expanded by further findings and studies. The emergent conditions are also selected based on stakeholder and expert values and scores. Therefore, the stakeholder and expert opinion and perspective bias on scoring impact how initiatives are evaluated and ultimately affects the result of the study. These emergent conditions put the system in danger by disrupting the initiatives prioritization. The general emergent and future categories used in this study are technological, environmental, economic, demographical, political, and regulatory. Several of the emergent and future conditions used In this study are *e.01. New Fuel-Economy Standards, e.04. Cyber Security Attack, e.07. Increase Electricity Usage, e.13. Government Policy Changes, e.17. Counterfeit Product in Supply Chain* and more. Some of these emergent conditions can be predicted.

Emergent condition grouping serves to combine emergent and future conditions to create scenarios. Grouping emergent conditions can aid in visualizing what conditions are similar and have similar outcomes.

One or more emergent conditions are combined to create a scenario, allowing for analysis of concurrent threats. Granular emergent conditions are also easier to identify in the real world and prove to be easier to prepare for and research than trying to mitigate the effects of a change in a broadly defined potential scenario like changes in public support.

Table V describes how scenarios are assembled as emergent and future conditions combinations. The aim is ultimately to find the most and least disruptive scenarios. Scenarios reflect the most uncertainties in the system life cycle identified by stakeholder and decision maker points of view. The assessment has been inspired by different objectives and perspectives.

As described above, scenarios have been selected by combining one or more emergent and future conditions. For instance, scenario *s.01. Private Support* comprises of emergent conditions *e.01. New Fuel Economy Standards, e.02. Reduced Battery Costs, e.03. Enhanced Electric Vehicle Efficiency, e.05. Material Supply Shortage, e.06. Increased Power Grid Reliability, e.08. Increased Renewable Energy Generation, e.30. Limiting Employee Access to Hardware,* and *e.37. Charging Infrastructure Capacity.*

Table VI shows the list of developed scenarios. There are nine main scenarios to ascertain the robustness of the prioritization of initiatives for the system of chargers. For example, *s.01. Private Support, s.06. Funding Decreases*, and *s.07. Changing in Government Policy* are some of the scenarios in bi-directional charging.

Next, the method finds weights across the success criteria in the baseline scenario. Each success criterion is assigned an assessment of low, medium, or high relevance to the listed success criteria. These assessments are translated into numerical values of 1, 2, and 4, respectively, which are then used to derive baseline weights.

Table VII represents the baseline relevance of success criteria for the charger system and represents an assessment of each criterion for the stakeholder of the system. This is the first part of the *Criteria-Scenario Relevance* analysis. These relevant options are decided based on discussions with industry experts and previous literature (Hassler et al., 2019).

After creating the baseline weights, the *Criteria-Scenario Relevance* is analyzed, exploring how each scenario influences the relevance of each success criterion.

Table VIII represents the Criteria-Scenario relevance shows how each scenario updates importance across the success criteria. This assessment elicits the change in the importance of each criterion under each scenario, with the question, "under scenario s.k, is criterion c.j more or less important in comparison to the other criteria than in the baseline scenario, if so, what is the extent of the change?" In response, the answers can be *Decreases*, *Decreases Somewhat*, *Neutral*, *Increases Somewhat*, and *Increases*. A scaling constant, α, was defined that adjusts the baseline criterion weight up or down, based on the reply, where α = {1/8, 1/6, 1, 6, 8}, respectively (see Karvetski et al., 2009 for a decision theoretic interpretation of the value of α). For example, the criterion

TABLE VI
SCENARIO DEVELOPED FROM EMERGENT CONDITIONS FOR BI-DIRECTIONAL CHARGERS.

Index	Scenarios
s.01	Private Support
s.02	Public Support
s.03	Electricity Market
s.04	Green Movement
s.05	Technology Innovation
s.06	Funding Decreases
s.07	Change Of Vendor
s.08	Obsolete Technology
s.09	Change In Government Policy
s.i	Others

TABLE VII
BASELINE RELEVANCE FROM THE PERSPECTIVE OF THE CHARGER MANUFACTURE.

Index	-	Relevance among the other criteria
c.01 - Lower Economic Cost has	high	relevance
c.02 - Increase Economic Revenue has	high	relevance
c.03 - Keep Up with Market Standards has	high	relevance
c.04 - Reduce Carbon Emissions has	high	relevance
c.05 - Reduce Cyber Attack Vulnerability has	high	relevance
c.06 - Availability has	high	relevance
c.07 - Reduced Energy Consumption has	high	relevance
c.08 - Affordability has	high	relevance
c.09 - Durability has	high	relevance
c.10 - Increase Self Sufficiency has	high	relevance

TABLE VIII
THE CRITERIA-SCENARIO RELEVANCE SHOWS HOW WELL EACH SCENARIO FITS THE SUCCESS CRITERION IN HARDWARE SUPPLY CHAINS OF CHARGING INFRASTRUCTURE OF ELECTRIC VEHICLES.

	s.01 - Private Support	s.02 - Public Support	s.03 - Electricity Market	s.04 - Green Movement	s.05 - Technology Innovation	s.06 - Funding Decreases	s.07 - Change of Vendor	s.08 - Obsolete Technology	s.09 - Change In Government Policy	s.10 - Other
c.01 - Lower Economic Cost	-	-	Decreases Somewhat	-	-	-	-	-	Increases Somewhat	
c.02 - Increase Economic Revenue	Increases Somewhat	Increases	-	-	-	Decreases	-	Decreases Somewhat	Increases Somewhat	
c.03 - Keep Up with Market Standards	Increases Somewhat	Increases Somewhat	-	-	Increases Somewhat	-	-	Decreases Somewhat	Increases Somewhat	
c.04 - Reduce Carbon Emissions	-	Increases	-	Increases	-	Decreases Somewhat	-	Decreases Somewhat	Increases Somewhat	
c.05 - Reduce Cyber Attack Vulnerability	Increases Somewhat	-	-	-	-	-	Increases Somewhat	-	-	
c.06 - Availability	-	Decreases Somewhat	Increases	-	-	Decreases	Increases Somewhat	-	Increases Somewhat	
c.07 - Reduced Energy Consumption	-	Decreases	Decreases Somewhat	Decreases	Increases	Decreases Somewhat	Increases Somewhat	-	Decreases Somewhat	
c.08 - Affordability	Increases Somewhat	-	Decreases Somewhat	Decreases Somewhat	Increases	Decreases Somewhat	Increases	Decreases Somewhat	-	
c.09 - Durability	-	Decreases Somewhat	-	-	Increases	-	Increases Somewhat	Decreases Somewhat	-	
c.10 - Increase Self Suffiency	-	-	-	-	Increases	-	Increases Somewhat	Decreases Somewhat	-	

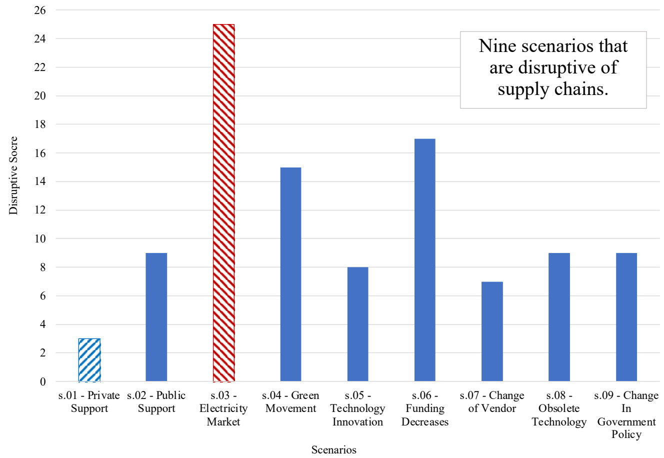

Fig. 4. Disruptive score of potential scenarios is based on which have the least mitigated emergent conditions by the applicable Initiatives.

TABLE IX
SCENARIOS ORDERED FROM MOST TO LEAST DISRUPTIVE, WITH RESPECT TO RANKINGS OF THE INITIATIVES FOR ELECTRICAL VEHICLE CHARGING SYSTEMS.

Disruption	Scenarios
Most	*s.03* – Electricity Market
-	*s.06* – Funding Decreases
-	*s.04* – Green Movement
-	*s.02* – Public Support
-	*s.09* – Change in Government Policy
-	*s.08* – Obsolete Technology
-	*s.05* – Technology Innovation
-	*s.07* – Change of Vendor
Least	*s.01* – Private Support

c.01. Lower Economic Cost decreases somewhat under scenario *s.03, Electricity Market*, and increases somewhat under scenario *s.09. Change in Government Policy* relative to the baseline scenario relevance.

In Fig. 4 each scenario is given a disruptiveness score, where the higher the score, the more of an issue the scenario might be for the system. Scenarios *s.03. Electricity Market*, *s.06. Funding Decreases*, and *s.04. Green Movement* respectively have the most significant impact on the EV system. Also, scenarios *s.05. Technology Innovation*, *s.07. Change Of Vendor*, and *s.01. Private Support* have the least disruptive impact on the system.

Table IX represents the summary of the normalized disruptiveness scores. This table shows that electricity market is the most disruptive and private support is the least disruptive scenarios to the electrical vehicle charging systems. Public support and green movement are also scenarios that need more attention. Investors could attract public support to green movement in various ways, such as equipping the public with the proper knowledge, leveraging the leaders, drawing the people with economic and product quality rewards, and others (Fischoff, 2020). These results will be updated month by month and require the stakeholders and managers to take action to enhance and improve the system.

Fig. 5 shows the variation in the prioritization of initiatives across scenarios. The bar indicates the range of ranking of each initiative subject to disruptions by scenarios. The blue dotted and red diagonal stripes extensions highlight the possible upper and lower range of each initiative from the baseline rank of each initiative, whereas the black bar shows the baseline ranking of each initiative. The blue dotted bars are not shown if the initiatives get the highest ranking. The red diagonal stripes bars are not shown if the initiatives get the lowest ranking among other available initiatives. This graph shows that there is no blue dotted bar in initiative *x.07. Test At-Risk Components* as the highest-ranking initiative and no red diagonal stripes bar in initiative *x.12. Understanding Effects of Battery Use on The Environment* as the lowest ranking initiative. If the baseline rank is towards the middle of the bar, it means that the initiative is not ranked consistently among any of the scenarios. If the baseline rank is toward the left edge of the bar and the baseline receives the highest rank, it indicates that the initiatives only decrease in rank under different scenarios. On the other hand, if the baseline rank is toward the right side of the bar and received the lowest rank, it means that the initiative improves in rank under different scenarios (Hassler et al., 2019). For instance, initiative *x.07. Test At-Risk Components* ranks as the highest initiative without variation across the scenarios and it indicates resilience of the initiative. Initiative *x.12. Understanding Effects of Battery Use on The Environment* has the lowest baseline rank and shows resilience to the low ranks and sensitivity to various scenarios. All the initiatives have the potential to be the most important initiative depending on how scenarios play out in the real world. Table X shows that initiatives *x.07. Test At-Risk Components, x.02. Regional Resource Planning,* and *x.06. Identify At- Risk Components* have the highest baseline rankings.

4. Discussion

The following details of the study are important to consider.

First, there is a need to understand how the power grid will handle the increased stress of powering all the buildings and infrastructure in an area along with new fleet electric vehicle and charger networks. These systems exhibit uncertainties of reliability, cost, and schedules, and it is critical to consider disruptive scenarios and emergent conditions that influence markets, organizations, and the environment (Thorisson et al., 2018).

Second, identifying the most and least disruptive scenarios is valuable for the stakeholder in complex systems. The results of such analyses may impact managerial and stakeholder decision making concerning where to focus risk management investments. The most disruptive scenarios are identified and tracked month to month. For instance, some scenarios have the most disruption on the system, such as *government funding decreases*. The funds will help enhance and improve the charging network across the nation. Therefore, decreasing the fund and losing government support will harm the EV bidirectional chargers supply chain (Noblet, 2021).

Third, fluctuations in supply and demand lead to a significant impact on the system. The National Renewable Energy Laboratory (NREL) indicated that

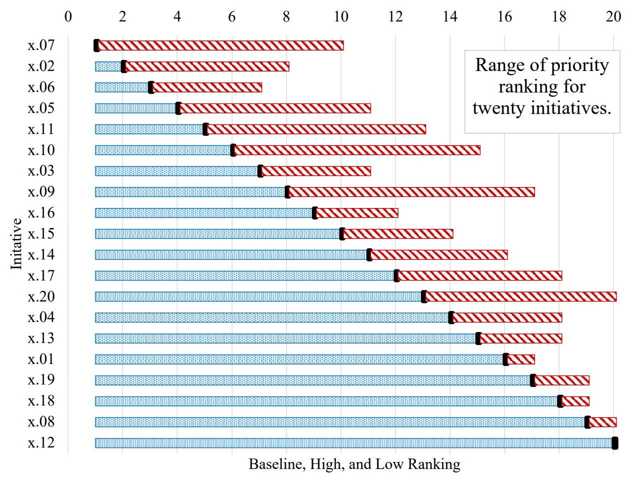

Fig. 5. Distributions of initiative influence rankings are based on which emergent conditions that could arise more often or never occur.

TABLE X
INITIATIVE INFLUENCE RANKINGS ARE BASED ON WHICH EMERGENT CONDITIONS THAT COULD ARISE MORE OFTEN OR NEVER OCCUR. RESILIENCE RANKING FOR TOP FIVE INITIATIVES IN ELECTRICAL VEHICLE CHARGING SYSTEMS. THIS TABLE DESCRIBES THE RISK TO THE EV CHARGING ENTERPRISE.

Rank	Initiative
1	*x.07* – Test At-Risk Components
2	*x.02* – Regional Resource Planning
3	*x.06* – Identify At-Risk Components
4	*x.05* – Understand Load Cycles
5	*x.11* – Analysis of Long-Term Wear on Batteries

"bidirectional vehicle charging posed the greatest risk to the operational demonstration of the microgrid." Therefore, testing the at-risk components plays a significant role in reducing the risk to the microgrid. Moreover, changes in government policy will significantly impact the system supply chains, e.g., state-administered grants for deploying EV charging stations across the nation (Noblet, 2021). Increasing and improving the nationwide stations will mitigate the fluctuations in supply and demand and ultimately the bidirectional vehicle charging risk to the microgrid.

Fourth, the prioritization of initiatives and identification of disruptive scenarios are not meant to be the ultimate findings and do not substitute for a quantitative risk analysis study. Rather, Karvetski and Lambert (2012) suggests:

- More modeling resources are needed to understand the precursors of threats represented by the scenarios, and to update the implications of those threats for the prioritization of the initiatives.
- A subset of robust and resilient initiatives is warranting further attention of system owners/operators.

Fifth, theoretical foundations of the current effort that combines scenario-based preferences and risk analysis, also, the approach of the compatibility of the guidelines and how the risk scenarios influence the priorities of the program, are found in Thorisson and Lambert (2021); Almutairi et al. (2019 & 2018); Hassler et al. (2019). Next, the alignment of the framework and ISO risk management and principals are defined as follows. The ISO definition of risk is the effect of uncertainty on objectives that describes a set of guidelines intended to streamline risk management for the organization. (Peterson, 2019; Aven, 2010). The *risk* in the current manuscript is an influence of scenarios to priorities (Thorisson and Lambert, 2021). Aven (2010) addresses the complementarity among the definitions of *risk*.

5. Conclusions

This study has identified the most disruptive scenarios to the development and operations of future EV charging systems. The approach is a multi-perspective scenario-based preference analysis. Two key vulnerabilities are supply chain disruptions for hardware devices and the hardware devices that have software vulnerabilities. Accordingly, a framework was developed to address emergent conditions and scenarios that are most and least disruptive to the security of the embedded devices of fleet electric-vehicle (EV) chargers and their networks.

Several limitations of the present study are as follows. As a scenario-based methodology, this study found the least and most disruptive scenarios only with respect to the particular scenarios identified, based on the sources and data available during the study. Limited access to more data and documents and stakeholder engagement in the study are other limitations to mention. Other factors that could impact the results of this study are the biases of the stakeholders and experts during the interviews. Stakeholders have varied motivations across the interviews. An investigation to identify what scenarios are most disruptive could avoid the "game" or manipulation of the analysis result. A key aim has been to identify where further investigation was required and not only to identify different inputs of the stakeholders. Instead of aggregating stakeholder inputs, the approach preserves the influences of individual stakeholders. There are benefits to this method, such as prioritizing initiatives with different stakeholder opinions. One of the weighted factors is based on the investment level of the stakeholders in the system. More investment led to higher weight scores of the stakeholder in assessing the system (Hassler et al., 2019). Stakeholders could be weighted in future efforts according to their level of expertise in the field (Daneshvar et al., 2019). Despite the bias of the stakeholder and its effect on the result, there is an advantage to using the approach of this paper that makes bias accountable and transparent. This bias reflects changeable interests of the stakeholder in the lifecycle of the system. The paper has used multiple experts, sought data from independent sources, characterized conflicts of interest across stakeholders, collected objective data, and tried other ways to elicit relevant evidence of stakeholders and experts during the interviews.

6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Negin Moghadasi is pursuing the Ph.D. degree in systems engineering at the University of Virginia, VA, USA. She received the M.S. in construction management from University of Southern California, CA, USA, the M.A. in industrial design from University of Tehran, Iran, and the B.Eng in architectural engineering from Shiraz Azad University, Iran. She worked as senior associate project management consultant in construction law for three years and worked as a virtual design and construction coordinator for a year. She is also the co-founder of Monarch architectural and industrial design group. She is a member of American Institute of Architects and Construction Management Association of America.

Zachary A. Collier earned the Ph.D. in Systems Engineering from University of Virginia, a Master of Engineering Management from Duke University, and a Bachelor of Science from Florida State University. He is Assistant Professor in the Department of Management at Radford University. He is President of Collier Research Systems, a consultancy providing decision making and analytics services. His prior work experience includes the U.S. Army Engineer Research and Development Center, where he was a member of the Risk and Decision Science Team. He has also held consulting positions in the area of accident reconstruction. He is Managing Editor of the Springer journal "Environment Systems & Decisions". He is an active member of the

Society for Risk Analysis where he is President of the Decision Analysis and Risk Specialty Group, is a Fellow of the Center for Risk Management of Engineering Systems at University of Virginia and contributes as a subject matter expert to the development of industry standards through SAE International.

Andrew Koch received the B.S. in Systems Engineering from the University of Virginia, Charlottesville, VA, USA in 2021.

David L. Slutzky earned the B.A. and pursued graduate studies in Political Science at the University of Chicago and received his law degree from the Program on Energy and the Environment at Chicago-Kent College of Law. He is currently a Research Associate Professor in the Science, Technology and Society Program of the Department of Engineering and Society at the University of Virginia. Prof. In 2011, Slutzky founded Fermata Energy, a tech start-up that is using Vehicle-to-Grid technologies. Professor Slutzky is widely recognized as a thought leader in the V2G industry. In addition to his business activities and his service to the federal government, Mr. Slutzky was elected to serve on the Albemarle County Virginia Board of Supervisors from 2005 -2009 and was chosen to Chair the Charlottesville-Albemarle Metropolitan Planning Organization. major environmental laws that created significant liability concerns for the commercial real estate industry. He then founded ERC and co-founded ERIIS.

Thomas L. Polmateer received the B.A. in English from Canisius College, Buffalo, New York, in 1974 and a M.S. in logistics management from the Florida Institute of Technology, Melbourne, Florida in 1985. He also graduated from the U.S. Army Command and General Staff College, Fort Leavenworth, Kansas in 1983 and the Armed Forces Staff College, Norfolk, Virginia, in 1987.From 1974 to 1996 he served on active duty with the U.S. Army as a field artillery and quartermaster officer. From 1996 to 2013 he served on the staff and faculty of the U.S. Army Force Management School. He is currently a senior research program director at the University of Virginia, Charlottesville, Virginia. His research interests include advanced logistics systems, container port operations, sustainable energy, supply chain risk and resilience, and hardware security and trust. Mr. Polmateer's awards and honors include the Society of Logistics Engineer Award, MacArthur Leadership Award, and the Valley Forge Freedom Foundation Award. He was the distinguished graduate at both the U.S Army Logistics Executive Development Course and the 8" Atomic Projectile Assembly Course. His military honors include the Legion of Merit and the Bronze Star.

Mark C. Manasco received the B.A. in economics from the University of Richmond in 1974, two-year graduate study in economics at the University of Virginia from 1975-1976 and a M.S in economics from the Virginia Commonwealth University in 1980 Richmond, Virginia. From 2004 to 2009 he served as Director of Workforce Development for the Greater Richmond Chamber of Commerce. From 2003-2004 he served as Director of the Center for the University of Richmond Systems Assurance, Richmond Virginia. From 1995-2003 he served in various leaderships and executive position with Venturi Technology Partners. He is currently the President and Executive Director of the Commonwealth Center for Advanced Logistics Systems (CCALS), Petersburg, Virginia. His research interests include advanced logistics systems, data analysis, cost control, quality assurance, and demand forecasting. Mr. Manasco currently serves on the Virginia United Methodist Foundation board. He was an Adjunct Lecturer at James Madison University for ten years and served on the JMU Information Systems Advisory Board for the same duration. Past board memberships include Richmond

Society of Human Resource Management, American Society of Training and Development, Greater Richmond Technology Council, and Board of Global Ministries, United Methodist Church, Virginia Conference.

James H. Lambert is a Professor of Engineering Systems and Environment, Site Director of the NSF CHEST Center, Director of the Center for Risk Management of Engineering Systems, and a Member of the Technical Advisory Council of the Commonwealth Center for Advanced Logistics Systems, each at the University of Virginia. His research interests include engineering systems and risk analysis. He is a Past President (2015–2016) of the Society for Risk Analysis (SRA). He is the Editor-in-Chief of the Springer journal *Environment Systems and Decisions*. He is an Area Editor of the Wiley journal *Risk Analysis*. He is a Fellow of the AAAS, Fellow of the ASCE, Fellow of the SRA, Fellow of the IEEE, D.WRE, and licensed Professional Engineer (P.E.).