

# Cybersecurity in the Smart Grid: Practitioners’ Perspective

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## ABSTRACT

The Smart Grid (SG) is a cornerstone of modern society, providing the energy required to sustain billions of lives and thousands of industries. Unfortunately, as one of the most critical infrastructures of our World, the SG is an attractive target for attackers. The problem is aggravated by the increasing adoption of digitalisation, which further increases the SG’s exposure to cyberthreats. Successful exploitation of such exposure leads to entire countries being paralysed, which is an unacceptable—but ultimately inescapable—risk.

This paper aims to mitigate this risk by elucidating the perspective of real practitioners on the cybersecurity of the SG. We interviewed 18 entities, operating in diverse countries in Europe and covering all domains of the SG—from energy generation, to its delivery. Our analysis highlights a stark contrast between (a) research and practice, but also between (b) public and private entities. For instance: some threats appear to be much less dangerous than what is claimed in related papers; some technological paradigms have dubious utility for practitioners, but are actively promoted by literature; finally, practitioners may either under- or over-estimate their own cybersecurity capabilities. We derive four takeaways that enable future endeavours to improve the overall cybersecurity in the SG. We conjecture that most of the problems are due to an improper communication between researchers, practitioners and regulatory bodies—which, despite sharing a common goal, tend to neglect the viewpoint of the other ‘spheres’.

## KEYWORDS

Cybersecurity, Smart Grid, Interviews, Cyber Physical System, Europe, Power Generation

## 1 INTRODUCTION

Among the infrastructures that sustain the modern world, one in particular stands out: the Smart Grid (SG). Tasked to provide the energy empowering our society, without the SG most services, commodities, and advances, would be either significantly impaired, or simply impossible to deliver [18].

We provide a schematic representation of some exemplary elements<sup>1</sup> of the SG in Fig. 1 (which is our adaptation from [21]). After some energy is generated at a given source, the SG must transmit such energy (in the form of electricity) to various devices which ensure the proper energy distribution to the end-users. Given its strategic importance, the SG is increasingly relying on Information Technology (IT) to further enhance its functionalities [44]. For example, IT improves the reliability [9] and efficiency of the SG [51], and facilitates the collection and distribution of energy in remote areas [40], or in resource-constrained settings [26].

<sup>1</sup>All such elements can be considered as Cyber-Physical Systems (CPS) [29] or part of Industrial Control Systems (ICS) [10].

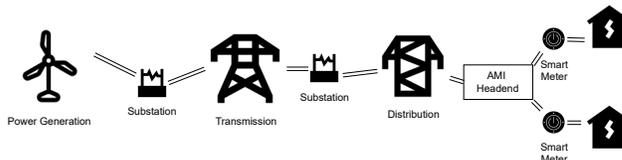


Fig. 1: Overview of the Smart Grid.

Unfortunately, the SG is well-known to be a preferred target for attackers [46], and reliance on IT inevitably exposes to the risk<sup>2</sup> of cyberthreats [4]. Early cyberattacks date back to 2003, when the David-Besse nuclear power plant in the USA was affected by the well-known Slammer malware [5]. Other notable examples include famous Advanced Persistent Threats (APT), such as Stuxnet in 2006 [56] or the attack to the Ukrainian SG in 2015 [13]. The latter, in particular, caused outages to over 200K households as a result of the compromise of three major country-wide energy suppliers. To safeguard the correct operation of the SG, it is paramount to constantly improve its cybersecurity—which is a topic covered by abundant literature (e.g., [21, 39, 44]).

Our paper is inspired by two recent works by Kumar et al. [33] and Grosse et al. [25]. Despite focusing on a different context, these works highlight a stark “disconnection” between (a) the claims made by researches and (b) the viewpoint of real practitioners. Indeed, scientific papers tend to make assumptions that deviate from real-world scenarios—typically, due to the lack of information on how real IT systems work. Such a lack is even more common in critical infrastructures [8], because any information leak can be exploited by attackers for their offensive campaigns [46, 52]. Simply put, many papers focus on issues that, from the practitioners’ perspective, have unclear relevance to real systems. As we will show, this gap is present also in the SG context—which is further complicated by the regulations that govern the complex relationships of the SG ecosystem. It is well-known that resources are limited in cybersecurity [7], and hence priority should be given to the most relevant and impactful issues—but only if such issues are brought to light. We aim to rectify this problem.

**OUR CONTRIBUTION.** This paper bridges the gap between research and practice in the SG context, with the intention of improving the cybersecurity of real SG systems. To reach our objective, we begin by summarizing the limitations of existing literature from a ‘practical’ viewpoint (§2). Then, we make three major contributions.

- We conduct an extensive survey with real practitioners involved in the SG’s cybersecurity (§3). Our survey elucidates the viewpoint of 18 entities, spanning across all seven domains of the SG, and operating in diverse countries in Europe.

<sup>2</sup>A recent report [1] quantifies such risk, stating that attacks against the Swiss SG can cause losses of up to 12 billion CHF (2% of Swiss’ GDP).

Our questions cover generic cybersecurity aspects, e.g.: risk assessment, dangerous threats, utility of recent technologies.

- After transparently presenting our major findings (§4), we perform an objective analysis *highlighting the disconnections that emerge from our survey* (§5). We show: the discrepancy between research and practice (§5.1); and the differences between the public and private sector (§5.2).
- We then provide an *original interpretation* of our results (§6). We explain the role of *regulations* in operational cybersecurity (§6.1); and derive *takeaways* for the four ‘spheres’ contributing to the cybersecurity of the SG (§6.2): companies, legislative bodies, researchers, and authorities.

To the best of our knowledge, this is the first paper that provides such an holistic coverage of ‘practical’ cybersecurity in the European SG in the recent years.

## 2 MOTIVATION AND RELATED WORK

Many papers investigated various cybersecurity aspects of the SG. We identify four categories of related works: *novel attacks and defenses*, *literature reviews*, *case studies*, and *interviews*. Let us explain the necessity of our study by comparing our paper with prior work.

**Attacks and Defenses.** Proposing novel attack scenarios, as well as corresponding countermeasures, is common in research. Yet, all such evaluations are performed through simulations, and therefore have *poor practical value*. For instance, Zuo et al. [63] propose unbounded attacks on microgrids: despite being rooted on sophisticated mathematical foundations, the assessment is carried out in a hardware-in-a-loop testbed. Rrushi et al. [47] propose a physics-driven approach to counter CPS malware: although the reference data is collected from real substations, the experiments are carried out in a synthetic environment. A similar issue also affects other attacks, such as False Data Injection (FDI) [17, 36, 60], Denial of Service (DoS) [29, 38], spoofing [15], or Man-in-the-Middle (MitM) [59]. Put simply: no system is foolproof, and it is positive that research papers also investigate similar scenarios. However, practitioners have limited resources: according to the cyber-resilience best practices [16, 42], such resources should be spent on threats that are more likely to endanger the real SG (which cannot be gauged through ‘attack/defense’ papers).

**Reviews.** Most reviews are *exclusively based on scientific papers*. For instance, Awad et al. [8] focus on techniques for digital forensics in SCADA systems, and although they cover frameworks, methodologies, and implementations, all such considerations are based on past scientific literature. Furthermore, Peng et al. [44] provide an in-depth analysis and identify some cybersecurity challenges in the SG, but their main focus is on specific threats (e.g., DoS and FDI), preventing a holistic coverage. Such limited scope is addressed, e.g., by El et al. [21], which also provide actionable recommendations. However, all findings of [21, 44] are purely theoretical or derived from prior research, overlooking the insight of practitioners.

**Case Studies.** Many papers provide exhaustive analyses on real APT targeting the SG. For instance, the authors of [3] considers the evolutions of the original Stuxnet, while Case et al. [13] focus on the Ukrainian SG. A more recent overview of reported APT is provided by Kaura et al. [27]. These papers are useful to provide some practical takeaways; however, *they focus on attacks launched*

*many years prior*, and do not allow to assess the current state-of-the-art of cybersecurity in the SG.

**Interviews.** *Few works directly interviewed practitioners*, and especially those related to the SG. For instance, Fischer et al. [22] focus on general cybersecurity challenges in critical infrastructures. Despite providing insights derived from 63 stakeholders, such experts pertain to different contexts (e.g., Smart Cities) than the SG. Some papers report ‘outdated’ findings—e.g., Line et al. [37] carry out 19 interviews, but in 2012. Nonetheless, Siemens et al. [50] conduct a “workshop” in 2021 entailing participants (23 in total) from industry and academia, there is no information about the composition of these two groups, preventing to distill meaningful knowledge of the practitioners’ viewpoints. Perhaps the closest effort to our paper is [45], which focuses on the perspective of 10 organizations in the power industry. However, their findings only span across a single country (the US), and only focus on information sharing—preventing a broad coverage of the topic.

**RESEARCH GAP.** Existing works do not provide a holistic vision of the current cybersecurity in the SG from the perspective of practitioners. Our paper aims to fix this gap by elucidating the recent opinion of SG experts (operating in diverse countries in Europe) to the research domain.

## 3 RESEARCH METHODOLOGY

The main contribution of this paper are the findings of our survey with 18 entities related to the SG. Our findings, and corresponding survey, revolve around a broad research objective: *investigating the state-of-the-practice of cybersecurity in the European SG*.

In what follows, we describe our research methodology—for which we provide an overview in Fig. 2. At the end of this section, we make some considerations on our study and elucidate some of the challenges we encountered (§3.3).

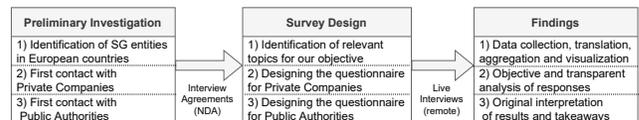


Fig. 2: Overview of our adopted research methodology.

### 3.1 Preliminary Investigation

We began our study by identifying a suitable set of entities that (i) allowed to address our main objective and that (ii) were willing to contribute to our research. Let us briefly summarize the complexity of the modern SG, so as to enable understanding why reaching our objective is difficult for research endeavours.

**Background.** The SG is a network of components (see Fig. 1) that, despite having the same underlying goal (i.e., delivering energy from a source to a destination), are owned, managed and operated by diverse entities. In particular, a common way to view the SG is through the NIST conceptual model [23], schematically depicted in Fig. 3. It identifies seven interconnected domains which have a crucial role in the SG network. All such domains relate to each other—either directly (via electrical flows) or indirectly (via, e.g.,

functional dependencies or market demands). Simply put, the SG is a complex ecosystem in which each domain solves a specific function—hence, even a single failure can impair the entire system. For this reason, we conduct our research by interviewing entities *from all seven SG domains*. Such design allows our study to overcome the limitations of past work and provide a holistic understanding of the current state of the SG from a cybersecurity viewpoint.

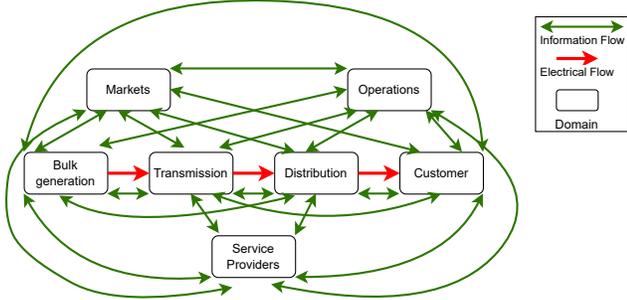


Fig. 3: The NIST conceptual model of the SG, spanning across 7 domains—all of which are covered in our research.

**Interviewed Entities.** After contacting dozens of entities related to the SG in diverse countries in Europe, we reached an ‘interview agreement’ with 18 entities, which we divide in two groups.

- **Private Companies.** We reached an agreement with 14 private companies covering the ‘operational’ domains of the SG, namely: Bulk Generation, Transmission, Distribution, Operations, Markets, Service Providers. Moreover, these companies are intertwined via business relationships, hence they can also be considered as part of the Customer domain. All companies operate the SG in diverse countries in Europe.
- **Public Authorities.** We reached an agreement with 4 public authorities, representing the ‘final-customer’ domain of the SG. The idea is providing a complementary perspective whose focus is not on the “actual security of the SG”, but rather on the “perceived security of the SG”. Such public authorities respond to the European countries in which the 14 private companies have their main headquarters.

For simplicity, in the remainder we will use  $\mathbb{C}$  to denote (private) companies, and  $\mathbb{A}$  to denote (public) authorities. Due to NDA, we cannot reveal further information on either  $\mathbb{A}$  or  $\mathbb{C}$ .

### 3.2 Survey and Interviews

The next step after finding an agreement was designing a set of questions (i.e., a *questionnaire*) that (i) allowed to reach our objective, but which (ii) could be answerable by our interviewees.

**Scope and Questions.** Given the heterogeneity of our population (which cover all SG domains), we only consider *high-level* questions pertaining to cybersecurity. Moreover, we follow established practices (e.g., [22]) and thereby our interviews are mostly *structured*. Such format is appropriate because it allows to derive *quantitative* results, and it protects against possible violations of NDA. In particular, we asked 10 closed questions to  $\mathbb{A}$ ; and 30 questions to  $\mathbb{C}$ , split into 27 closed questions with pre-defined answers, and 3 open questions—hence resembling a semi-structured [35]

interview design (as also done in [37]). The 27 closed questions are the same for all  $\mathbb{C}$ ; whereas the 3 open questions are tailored for the specific domain of a given  $\mathbb{C}$ . Overall, our questions span across several generic cybersecurity aspects, e.g.: experience with past attacks, risk-assessment, utility of novel technologies, and the most challenging cyberthreats<sup>3</sup>.

**Interviews.** The interviews consisted in remote one-on-one meetings, conducted between one of the authors and a representative person (with technical expertise) of the corresponding entity. During such meetings, we asked the questions and showed the possible answers to the respondent, granting them the option of not answering<sup>4</sup>. The interviews with  $\mathbb{C}$  lasted ~1 hour, whereas those with  $\mathbb{A}$  lasted ~30 minutes. During the interviews we took plenty of notes—amounting to more than 200k characters overall. We used such notes to derive our own interpretations of our findings (§6).

**Timeline.** An important remark concerns the timeline of our survey. We interviewed  $\mathbb{C}$  from Jan. 2022 until Feb. 2022, i.e., *before* the breakout of the Russian/Ukrainian conflict [49]. On the other hand, we interviewed  $\mathbb{A}$  in Mar. 2022, i.e., *after* the conflict erupted. Such an event was not planned, and although there is a slight chance that it may have affected the responses of  $\mathbb{A}$ , we emphasize that we treat the two groups as independent from each other. Therefore, our results are consistent across all of  $\mathbb{C}$  and all of  $\mathbb{A}$ .

### 3.3 Correctness and Challenges

Before presenting our results, let us make some insightful remarks, with the twofold purpose of (i) validating our efforts; and (ii) providing a source of inspiration for future studies.

**Preventing Bias.** All our interviews and subsequent analyses have been carried out so as to minimize the introduction of bias.

- The *questionnaire* was designed by two authors, who had frequent meetings aimed at formalizing questions that could be answered by each of the considered entities (i.e.,  $\mathbb{C}$  or  $\mathbb{A}$ ).
- During the *interviews* (done by one of the authors), participants were explicitly asked to respond objectively, and to clearly state whether they were unsure of their answers. In case of uncertainty, we still registered their response (if given), but we then used our notes to derive the correct option by weighing the individual response against those given by other similar entities. If – even after analysing our notes – we could not infer a clear response, we assigned the response to the ‘not provided’ category to avoid generating noise.
- During the *analysis* (done by one of the authors), regular breaks were taken to fairly interpret the answers received during the interviews [11]. Such analyses have been repeated three times to account for the possibility of honest mistakes. At the end of this process, two of the authors discussed the findings to reach a consensus.

We can safely assume that our results are scientifically correct.

**Challenges.** We find instructive to report some details about the difficulties we encountered: getting in touch with companies is a challenging endeavour for researchers.

<sup>3</sup>The questionnaires containing all closed questions to  $\mathbb{C}$  and  $\mathbb{A}$  are in this repository: [https://github.com/hihey54/smartgrid\\_survey](https://github.com/hihey54/smartgrid_survey).

<sup>4</sup>The interviews were done with single individuals, who – despite their technical expertise – may not have had the necessary knowledge to provide an exhaustive answer (or simply could not respond due to NDA).

- We initially aimed to interview more than 30 private companies, but ultimately only 14 accepted: some were unresponsive, or were not willing to release any kind of information (even under NDA).
- In contrast, the 4 public authorities (which we contacted *after* finding some agreements with the private companies) were more willing to cooperate.
- Out of the 14 private companies, 5 agreed to help us only after phone calls lasting more than 60 minutes.
- Only 5 of the interviews with the 14 private companies were carried out on the initial scheduled date (many had to be postponed at the last minute).
- To set up the interviews with all our entities, we sent a total of 145 emails between Nov. 2021 and Feb. 2022.
- Overall, our entities pertain to diverse countries—hence, the interviews were carried out in the interviewee’s official language. This required us to (i) create language-specific versions of our questionnaire; and (ii) translate all responses into English before analyzing them.

All such difficulties make us believe that the ‘gap’ between research and practice could be reduced if (private) companies were more willing to cooperate with academia. We acknowledge, however, that companies dealing with critical infrastructures (such as the SG) have valid reasons for not disclosing sensitive security information.

## 4 MAJOR FINDINGS

We now present the most insightful findings<sup>5</sup> of our survey. In particular, we report those results that: (i) allow to gauge the state-of-practice of cybersecurity in the SG—described in this section; but that also (ii) reveal the presence of some *blind spots*. The latter—which we objectively analyse (§5) and attempt to interpret (§6)—represent a valuable avenue for future work. (Due to NDA, we provide the aggregated results for C and A: fine-grained analyses could be used to identify some of our respondents.)

### 4.1 Overview

Some of our findings confirm what is already well-known. For instance, 64% of C (reportedly) were *targeted by cyberattacks* in the last decade. Only 20% of C entirely manage their cybersecurity, while 80% *outsources* it at varying degrees. All C adopt both *backup* and *data-replication* strategies. Moreover, C considers that *data confidentiality* to be problematic, with an average of 8 on a [1–10] scale (higher is more problematic). We report in Fig. 4 the viewpoint of C with respect to established cybersecurity strategies; perhaps surprisingly, two companies do not (nor plan to) integrate any security standard (e.g., the ISO27001 [23]).

We inquired C about the toughest phase of the security lifecycle (i.e., *prevention*, *detection*, *reaction*), and report their answers in Fig. 5: we can see that 42% of C consider *prevention* to be the toughest stage of the security lifecycle—while 28% consider *detection* to be

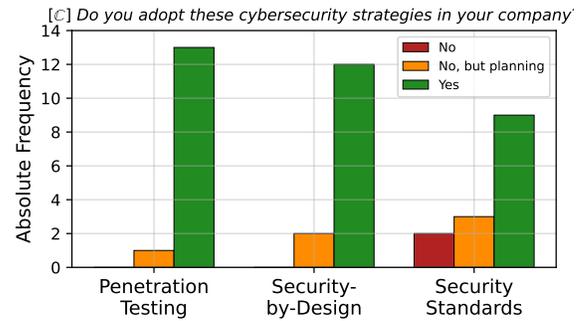


Fig. 4: Answers of C on their adoption of security strategies.

harder.<sup>6</sup> We asked the same question also to A: accordingly, 100% of A believe that it is the *detection* phase that is the hardest for C.

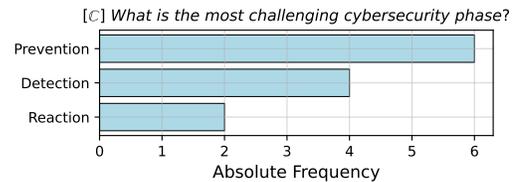


Fig. 5: Most challenging phases of cybersecurity (for C).

### 4.2 Education and Information Sharing (C & A)

One of the greatest barriers towards the creation of secure systems is convincing executives of the importance of cybersecurity [7]. Furthermore, it is well-known that employees are the weakest link in the security chain. Hence, we asked C to provide a rough estimate about the *awareness* of cybersecurity across their organizations, and report the results in Table 1. According to this table, the impression is that the overall quality of awareness/education is satisfactory for all C—although there is still room for improvement.

Table 1: Cybersecurity awareness and education across diverse organisational levels—as reported by C.

Mid-/Top-level management	
Option	Freq.
They are fully aware of the risks and prioritise cyber-security	64.29%
They are fully aware of the risks, but cyber-security is not a priority	21.43%
They are not aware of the risks, but are educated on the topic	7.14%
No answer	7.14%
Employees	
Option	Freq.
They are aware fully of the risks and education is evaluated regularly	50.00%
They are not fully aware of the risks, but are educated on the topic	42.86%
They are not aware of the risks, and unlikely to improve in the short-term	0.00%
No answer	7.14%

We also investigated the importance of *information sharing* from the perspective of both C and A. Indeed, a C can improve their cybersecurity by studying attacks targeting other C: 78% of C already

<sup>6</sup>Interestingly, two companies provided an independent answer to such a question: one stated that “all phases are equally challenging,” and another stated that “the real challenge is determining which assets (and threats) should be prioritized.”

<sup>5</sup>Due to space limitations, reporting and analyzing *all* questions of our survey is not possible within a single paper. Upon request, however, we are willing to disclose a ‘question-by-question’ analysis of our survey—alongside all the operations we followed to derive our results. Our repository contains the source-code of our graphs.

do this (the remaining 22% plans to). With respect to A, we inquired about their perceived willingness (on a [1–10] scale) of C to disclose information to other entities, namely: academia, different C, and A. The answers, in Fig. 6, confirm our own impressions (§3.3): C are reluctant to cooperate with scientific researchers.

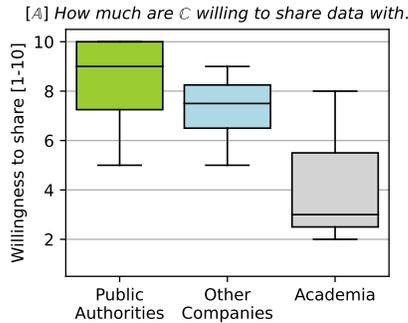


Fig. 6: Perceived (from A) willingness of C to share information with other entities—on a [1–10] scale.

### 4.3 Risk Assessment

The SG can be targeted by a plethora of cyberthreats (§2). Our survey covers such topic from the twofold perspective of *cyber-* and *physical-risk*. When inquired about how such risks are assessed, all C responded that they rely on *qualitative* metrics—whereas quantitative metrics are often neglected.

**Cyber-risk.** All C consider their systems to be at risk from APT. Moreover, only 14% of C consider illegitimate *access to consumer data* to be ‘not threatening’, and none of C consider *DoS* to be problematic. We report in Fig. 7 the perceived risk (according to C) of well-known cyberattacks, namely: FDI, MitM, spoofing.

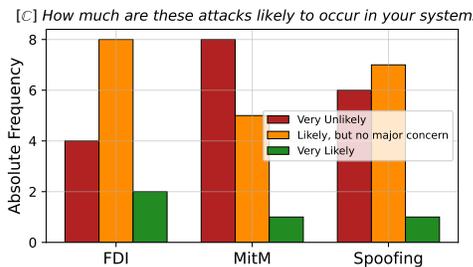


Fig. 7: Threat of FDI, MitM, and Spoofing attacks (for C).

We asked similar questions (i.e., “how feasible are these cyberthreats to the SG?”) to A, whose responses are shown in Fig. 8. We also inquired A to estimate the cybersecurity capabilities of C. Accordingly, none of A consider C to have ‘excellent’ cybersecurity measures in terms of *prevention* or *detection*; however, 25% of A considers C to have excellent *reaction* capabilities.

**Physical-risk.** None of C consider ‘physical’ security to be *more important* than ‘cyber’ security. As a matter of fact, when asked about the likelihood of malware inducing equipment malfunction *harmful to humans* (shown in Fig. 9), 70% of C stated that it is “very

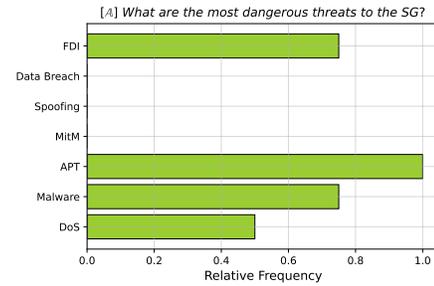


Fig. 8: Most dangerous threats to the SG (according to A).

unlikely.” Moreover, inspired by a 2021 report from Gartner [57] announcing the term “killware”, we asked both C and A whether it was possible that “malware can lead to human death” in SG. Results differed between C and A: 14% of C believe that such a risk to be completely unrealistic, and 71% think that it is unlikely. In contrast, 50% of A agree that “killware” is a very likely threat in SG, and none believe that it is unrealistic.

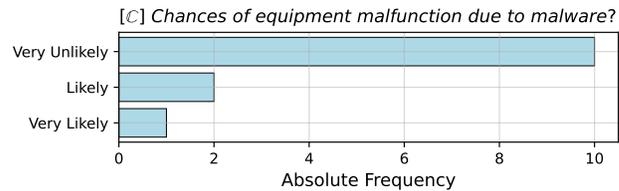


Fig. 9: Opinion on C on the likelihood of malware inducing equipment malfunction.

### 4.4 Technological Paradigms

Due to its increasing reliance on IT, the SG is an enticing setting for modern technological paradigms [32], such as Blockchain, Artificial Intelligence (AI), Internet of Things (IoT), or Cloud Computing.

We first asked C about their perspective on similar technologies, starting from their opinion on *Blockchain* for the SG. The answers, in Fig. 10, suggest that C does not hold *Blockchain* in high-regards.

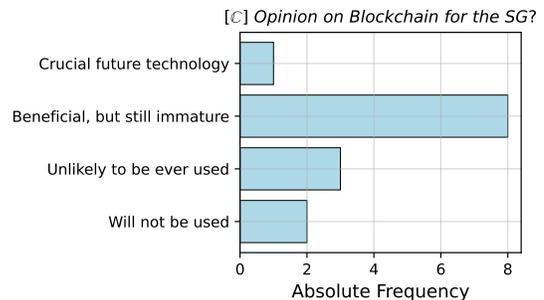


Fig. 10: Opinion of C on the utility of blockchain for SG.

With regards to AI and IoT, we report the answers of C in Fig. 11, showing a wide adoption of *IoT* (only 14% do not use it), a much

smaller one for AI (50% do not use it). Lastly, we report that only 7% of C does not use Cloud solutions.

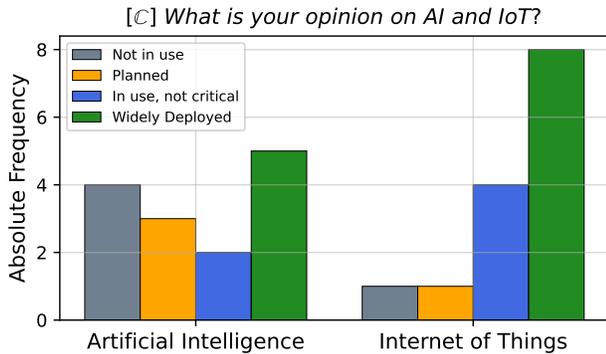


Fig. 11: Answers of C on their adoption of AI and of IoT.

We then asked A about their opinion on the relevance of all such paradigms for the SG, and report their answers in Fig. 12.

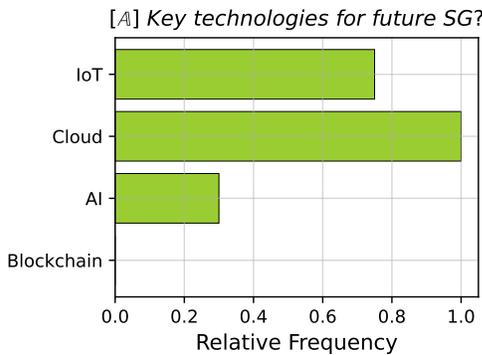


Fig. 12: The perspective of A on the technologies that will have a biggest impact in the future for cybersecurity in SG.

Finally, we report that 86% of C use smart meters [21], while the remaining 14% plans to deploy them in the short-term.

## 5 ANALYSIS (CONTRAST)

After a transparent presentation of our findings, we now provide a deeper and objective analysis addressed at elucidating some blind spots—which may inspire constructive developments of cybersecurity in the SG. Specifically, we focus on the points of contrast that emerge from our survey. We first consider the viewpoint of practitioners w.r.t. those of researchers (§5.1), and then focus on the contrasting opinions of private companies and public authorities (§5.2). Finally, we make some considerations on our study (§5.3).

### 5.1 Practitioners vs Researchers

Our survey highlights a stark disconnection between the perspective of practitioners (i.e., C and A) and researchers—at least according to what is reported in scientific literature related to the SG. In particular, we identify five major points of divergence.

- i) **Blockchain.** Both C and A agree that blockchain technologies are not very significant in the SG context (see Fig. 10 and Fig. 12). However, many recent research papers endorse the application of blockchain in the SG (e.g., [14, 32, 41, 62]).
- ii) **Artificial Intelligence.** Only half of C uses AI solutions (Fig. 11), whereas A does not believe that AI will have much impact in the future of the SG (Fig. 12). In contrast, recent papers (e.g., [7, 31, 32]) claim that AI will (or already does) play a substantial role in critical infrastructures—especially from a cybersecurity standpoint (e.g., detecting cyberthreats [34]).
- iii) **Dangerous Cyberthreats.** Most C do not believe that MitM or spoofing attacks are dangerous to their systems (Fig. 7), which is an opinion also shared by A (Fig. 8). However, abundant (and recent) research papers claim that MitM and spoofing are extremely dangerous to the SG (e.g. [15, 59]).
- iv) **Risk Assessment Methods.** All C adopt qualitative approaches for their risk assessment (§4.1). In contrast, such methods are only marginally considered in scientific literature, which mostly focuses on quantitative methods [61].
- v) **Reaction Phase.** Most C primarily focus on reaction to cyberthreats, due to the acknowledged difficulty in preventing/detecting them. However, in research it is the complete opposite: very few papers focus on reaction [48].

(Citing all research papers that support these points of divergence is outside our scope—and is also unfeasible in this single publication.)

Given its importance, we also emphasize the viewpoint of practitioners and research with regards to **malware leading to physical harm**. Specifically, both A and C tend to agree that “killware” [57] is a possibility—albeit not very likely (§4.3). In contrast, some very recent works already used the term “killware” (e.g., [12, 55]), whereas many research papers (e.g., [19]) are citing [20] to claim that exploiting cyber-vulnerabilities can lead to “human death”. (According to Google Scholar, [20] has 30 citations as of Sept. 2022.)

**OBSERVATION:** there is a relevant mismatch between the opinions of practitioners and the focus of research papers in the context of SG cybersecurity.

### 5.2 Private Companies vs Public Authorities

We find instructive to compare the viewpoints of the private (C) and public (A) sector. Despite C and A agree on some aspects (e.g., which technological paradigms will play a pivotal role in the future SG, §4.4), some differences emerge when comparing some responses of C against those of A. Let us illustrate five significant ones.

- i) **Detection phase.** Although all A consider detection to be the toughest phase of cybersecurity, such opinion is shared only by 28% of C (§4.1).
- ii) **Capabilities.** Most C believe to be well-equipped in terms of cybersecurity (only APT, apparently, endanger C); A, however, have a significantly different opinion (§4.3).
- iii) **Data Confidentiality.** Most C consider data confidentiality (§4.1) to be a problem, while A believe that data breaches are not a severe threat to the SG (Fig. 8).
- iv) **Data Replication.** All C adopt data replication strategies—sometimes by leveraging cloud solutions (§4.1). In contrast, some A believe that such strategies should be discouraged.

- v) **FDI and DDoS.** While C do not consider FDI or DDoS attacks to be problematic, A frequently named them among the most threatening scenarios (§4.3).

**OBSERVATION:** The *public* and *private* sectors have some diverging opinions on the current state of SG cybersecurity.

### 5.3 Considerations

Let us reflect on three aspects of our study, and then provide a disclaimer to prevent generating harmful misunderstandings.

(1) **Focus.** Our goal is providing a holistic overview of cybersecurity in the entire SG. Therefore, deriving conclusions that apply for individual domains of the SG (e.g., electricity market [53]) or for specific components deployed in such domains (e.g., CPS [6] or ICS [37]) is outside our scope. Nonetheless, the entities interviewed in our study pertain to *all segments of the SG*, all of which employ state-of-the-art components and practices in their infrastructures.

(2) **Area.** Our study focuses on entities operating in *Europe*. Hence, some of our findings may not apply to SG located in different areas of the world (e.g., the USA). However, *research is universal*: a novel solution proposed in a scientific paper can very well be deployed in a country that is different from that of the paper's authors, or of the paper's publication venue. This is the reason why our analysis (§5.1) is not confined to 'European' papers.

(3) **Population.** Our study covers 18 entities, spanning across both private companies and public authorities. Such a number may appear small compared to, e.g., the interviews carried out by some papers (e.g., the one by Grosse et al. [25]). However, our population is comparable to the one in [37] in terms of raw-numbers. Moreover, our interviews reflect the viewpoint of (i) public authorities that represent entire countries—having *millions* of citizens; and (ii) private companies, some of which count *thousands of employees* and large IT departments. Furthermore, a given country in Europe may have only one or two companies that focus on power generation—and such companies can also operate in other countries within Europe. Therefore, our interviews allows to meet our research objective: investigating the current state of cybersecurity in the European SG.

**Disclaimer.** Insofar, the purpose of our study was providing an *objective* assessment of the SG's practitioners' viewpoint on some cybersecurity aspects. We do not make any general claim, nor attempt to make any hypotheses that will be subject to 'statistical testings'. It is unfair (and dangerous) to derive, e.g., that "MitM attacks are not important for practitioners" (cf. Fig. 7): despite being a minority, *some* companies feel endangered by MitM, and hence it is important that some researchers continue to study such threats.

## 6 INTERPRETATION (ORIGINAL)

As a last contribution of this paper, we provide an original interpretation of our study. Our intention is twofold: (i) *explaining* the reasons behind some of our findings; and (ii) deriving *actionable recommendations* for future works.

To this purpose, we rely on the abundant notes we took during our interviews, and combine them with our own expertise. Hence, in the remainder of this section, we: provide our explanations for each identified point of *contrast* (presented in §5) in Table 2; present how *regulations* affect the cybersecurity in the SG (§6.1);

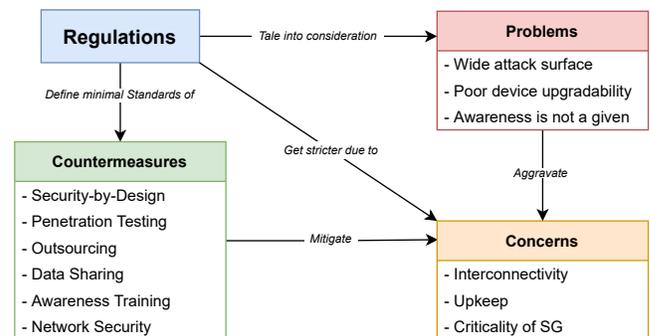
and highlight the major *takeaways* (§6.2) that can lead to significant improvements of cybersecurity in the SG.

### 6.1 The role of Regulations in the SG

A recurrent theme during our interviews with C involved the role of regulations the the cybersecurity of the SG.

**A hidden issue.** Most C revealed that one of the greatest challenges for companies (not just their own) is represented by the constantly mutating and often unclear regulations that C must abide to. Such a situation is indeed problematic: ultimately, C are *businesses*, with a finite amount of resources. Hence, if the regulations are difficult to interpret, C either (a) delay their application—perhaps until after other C found a way to implement them; or (b) must invest resources in legal consultants—resources that could be spent in improving their own systems. It then follows that such regulations—despite representing a protection mechanism *in principle*—can be detrimental *in practice*. For example, consider the divergent opinion of A and C with regards to data confidentiality (§5.2). A state that it is not a big concern—which makes sense, as there are far more disruptive hazards that can stem from failures in the SG. However, C report that ensuring that all data are kept secure is very tough—because C *must* ensure such confidentiality to comply with regulations. Put differently: A—who must oversee compliance with regulations by C—lack the operational perspective of C and hence overlook most of the difficulties originating from such regulations.

**Our Model.** To exemplify how regulations affect the current (and future) cybersecurity in the SG, we review all our notes, abstract them, and then derive an original model shown in Fig. 13. Such model elucidates the relationships between the regulations (i.e., the legal foundations that bind C) and: the *concerns* of practitioners (both C and A) regarding current developments; the major cybersecurity *problems* in SG; and the potential *countermeasures* to face such problems.



**Fig. 13: Our original model displaying the relationships between regulations the cybersecurity of the SG.**

Let us describe Fig. 13. The concerns of practitioners are aggravated by the problems posed by current developments in IT related to the SG. At the same time, such concerns are mitigated by the fact that effective countermeasures are available. **Legislative bodies** then consider (a) the current problems defined by the constantly evolving threat landscape, and (b) how such problems can be addressed via existing countermeasures; and enact 'stricter'

**Table 2: Points of disagreement and our comment.**

Sphere	Disagreement	Our Explanation/Recommendation
Research vs Practice (§5.1)	Blockchain	Our explanation is that either researchers <i>overestimate</i> the real-world impact of blockchain; or the benefits of blockchain are not communicated in a <i>convincing way</i> (or both). Nevertheless, a huge barrier is represented by the difficulty [28] in implementing real blockchain systems <i>in practice</i> .
	Artificial Intelligence	We believe the poor consideration of AI by practitioners stems from two reasons: the impending <i>regulations</i> [2], which make it difficult for practitioners to setup and use AI in the SG; and the lack of <i>explainability</i> [7] of most AI methods which prevent determining the root cause of ‘failures’ in AI systems (recall that cybersecurity is mostly outsourced in the SG §4).
	MitM and Spoofing	We endorse research to keep investigating also MitM and spoofing attacks. However, such threats should be exemplified in the <i>broad context of APTs</i> targeting the SG, since they are of major interest for practitioners (e.g., MitM can very well be part of APT [43]).
	Qualitative Assessments	We conjecture that the lack of qualitative assessments <i>in research</i> is due to the difficulty in devising a ‘scientifically sound’ and ‘generally applicable’ qualitative assessment method—whose application <i>in practice</i> is case-specific, and present high-degrees of subjectivity [54].
	Reaction phase	The <i>reaction</i> phase is difficult to model <i>in research</i> , because <i>in practice</i> such phase is tailored for the specific asset involved in the cyberattack. Nonetheless, we endorse future research to put more emphasis on this phase because improving its efficiency allows practitioners to invest more resources in other—tougher—phases (e.g., detection).
	“Killware”	Given the sensitivity of this subject, we endorse future research to <i>treat it with care</i> . In particular, we recommend to avoid using such term to “sell” a given paper: it is well-known that cyberattacks are dangerous (especially in the SG), and mentioning a problem that (for the time being) is just a remote possibility can cause more harm than good.
Public vs Private (§5.2)	Prevention phase	We conjecture that A consider <i>detection</i> to be more challenging for C due to the well-known difficulty in adopting significant <i>prevention</i> measures. Hence, it is likely that A either: did not consider ‘prevention’ to be a meaningful answer; or a phase actively pursued by C.
	Capabilities	Two possibilities can explain why the viewpoint of A does not align with that of C in terms of overall cybersecurity capabilities: either C <i>overestimate</i> their cybersecurity (either their own, or the outsourced one); or A <i>underestimates</i> the capabilities of C (or both of these). Nevertheless, a better cooperation between C and A can allow to reach a consensus.
	Data Confidentiality	We believe that A does not consider data confidentiality to be a problem because <i>privacy violations do not lead to outages</i> . In contrast, such violations are a big threat to C, because to <i>comply with regulations</i> they must protect their customers’ data—which is challenging.
	Data Replication	The reason why A discourage such strategies (commonly used by C) is that data replication inevitably extends the surface that can be exploited by attackers to access private data. Although the concerns of A are well-founded, we believe that—in the SG—privacy is not as critical as reliable functionality of the entire network. Nonetheless, future works can improve such privacy.
	FDI and DDoS	A possible explanation as to why A considers FDI or DDoS to be threatening is that such attacks are very popular in papers and reports (e.g., [24, 36]), thereby increasing their perceived threat (according to A). However, C are well-aware of whether their systems are at risk of FDI or DDoS. A better information exchange between A and C could lead to a more even distribution of opinions.

regulations that simultaneously (i) aim to better protect the SG, and (ii) fuel the concerns of private companies operating the SG.

## 6.2 Takeaways

In this paper, we mentioned four distinct ‘spheres’: (i) private companies, (ii) public authorities, (iii) research and academia, and (iv) legislative bodies. By aggregating all our findings and interpretations, we now derive four takeaways—one for each of these spheres.

- **Private companies** should be *more open* in cooperating with research institutions. The latter can greatly benefit C (by, e.g., devising new standards [30], or developing novel devices [58])—but significant developments cannot be expected unless C become more willing to share some of their concerns with academia.<sup>7</sup>

<sup>7</sup>We observe that a similar message was sent by Awad et al.[8] in 2018: unfortunately, as demonstrated by our own difficulties (§3.3), the problem is still open.

- **Research and academia** should account for the *viewpoint of practitioners* (i.e., **A** but especially **C**) by prioritizing the most likely (and dangerous) threats to the SG, avoid over-exaggerations, and better communicate (by, e.g., using economical terms) the benefit of novel technologies. Moreover, future research should not neglect the reaction phase, as it can greatly benefit operational cybersecurity.
- **Legislative bodies** should enact *actionable and stable regulations*. **C** are often overwhelmed, leading to 'closeness' w.r.t. information sharing (due to, e.g., privacy), as well as to 'waste' of resources to interpret the ever-mutating rules.
- **Public authorities** should better engage with private companies. Indeed, **C** 'must' respond to **A**, and hence **A** should use this opportunity to better understand the concerns of **C** and serve as the *glue* between all the other spheres, as well as with the citizens of their respective countries.

**RECOMMENDATION:** we endorse all such spheres to better communicate and interact with each other. Ultimately, they have a common goal: improving the security of the SG.

## 7 CONCLUSIONS

Our paper aims to elucidate the 'internal' perspective of the Smart Grid (SG) with respect to cybersecurity. To this purpose, we carry out and present the results of a large survey conducted with practitioners, spanning over both *private companies* and *public authorities* from diverse countries in Europe. After objectively presenting our major results and highlighting some contrasting points of disagreement, we provide our interpretation of our findings—casting light on some concealed problems that impair a smooth development of the SG. Our paper will hopefully inspire future endeavors that – by improving the security of the Smart Grid – will pave the way to a reliable growth of our society.

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## REFERENCES

- [1] 2018. *Cyber-risk in Switzerland*. Technical Report. Swiss Insurance Association.
- [2] 2020. *On Artificial Intelligence - A European approach to excellence and trust*. Technical Report. European Commission. 27 pages. [https://ec.europa.eu/info/sites/info/files/commission-white-paper-artificial-intelligence-feb2020\\_en.pdf](https://ec.europa.eu/info/sites/info/files/commission-white-paper-artificial-intelligence-feb2020_en.pdf)
- [3] Sumayah Al-Rabiaah. 2018. The "Stuxnet" virus of 2010 as an example of a "APT" and its "Recent" variances. In *IEEE Saudi Nat. Comp. Conf.*
- [4] Ehab Al-Shaer, Mohammad Ashiqur Rahman, et al. 2016. Security and Resiliency analytics for Smart Grids. *Springer Advances in Information Security* (2016).
- [5] Tejasvi Alladi, Vinay Chamola, and Sherali Zeadally. 2020. Industrial control systems: Cyberattack trends and countermeasures. *Elsevier Computer Communications* (2020).
- [6] Wissam Aoudi, Mikel Iturbe, and Magnus Almgren. 2018. Truth will out: Departure-based process-level detection of stealthy attacks on control systems. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security*. 817–831.
- [7] Giovanni Apruzzese, Pavel Laskov, Edgardo Montes de Oca, Wissam Mallouli, Luis Búrdalo Rapa, Athanasios Vasileios Grammatopoulos, and Fabio Di Franco. 2022. The Role of Machine Learning in Cybersecurity. *ACM Digital Threats: Research and Practice* (2022).
- [8] Rima Asmar Awad, Saeed Beztchi, Jared M Smith, Bryan Lyles, and Stacy Prowell. 2018. Tools, techniques, and methodologies: A survey of digital forensics for scada systems. In *Proceedings of the 4th Annual Industrial Control System Security Workshop*. 1–8.
- [9] Abdullah Aydeger, Nico Saputro, Kemal Akkaya, and Selcuk Uluagac. 2019. SDN-enabled recovery for Smart Grid teleprotection applications in post-disaster scenarios. *Elsevier J. Netw. Comp. Appl.* (2019).
- [10] Adeen Ayub, Hyunguk Yoo, and Irfan Ahmed. 2021. Empirical study of PLC authentication protocols in industrial control systems. In *2021 IEEE Security and Privacy Workshops (SPW)*. 383–397.
- [11] Erik Blair. 2015. A reflexive exploration of two qualitative data coding techniques. *J. of Methods and Measurement in the Social Sciences* (2015).
- [12] Gerald M Bowers, Mary L Kleinpeter, and William T Rials. 2022. Securing Your Radiology Practice: Evidence-Based Strategies for Radiologists Compiled From 10 Years of Cyberattacks and HIPAA Breaches Involving Medical Imaging. *Perspectives in Health Information Management* 19, 3 (2022).
- [13] Defense Use Case. 2016. Analysis of the cyber attack on the Ukrainian power grid. *Electricity Information Sharing and Analysis Center (E-ISAC)* (2016).
- [14] Panagiotis Chatzigiannis, Foteini Baldimtsi, Constantinos Koliass, and Angelos Stavrou. 2021. Black-Box IoT: Authentication and Distributed Storage of IoT Data from Constrained Sensors. In *Proc. Int. Conf. IoT Design Implementation*.
- [15] Shubhendra Vikram Singh Chauhan and Grace Xingxin Gao. 2021. Synchronphor data under GPS spoofing: Attack detection and mitigation using residuals. *IEEE T. Smart Grid* (2021).
- [16] William Arthur Conklin, Dan Shoemaker, and Anne Kohnke. 2017. Cyber resilience: Rethinking cybersecurity strategy to build a cyber resilient architecture. In *Int. Conf. Manag. Leadership Govern.*
- [17] Rulong Deng and Hao Liang. 2018. False data injection attacks with limited susceptibility information and new countermeasures in smart grid. *IEEE T. Industrial Inf.* (2018).
- [18] G Dileep. 2020. A survey on smart grid technologies and applications. *Elsevier Renewable energy* (2020).
- [19] Nesara Dissanayake, Mansoor Zahedi, Asangi Jayatilaka, and Muhammad Ali Babar. 2021. A grounded theory of the role of coordination in software security patch management. In *Proc. ACM Joint Meeting on European Software Engineering Conference and Symposium on the Foundations of Software Engineering*.
- [20] Melissa Eddy and Nicole Perloth. 2020. Cyber attack suspected in German woman's death. *The New York Times* (2020).
- [21] Zakaria El Mrabet, Naima Kaabouch, Hassan El Ghazi, and Hamid El Ghazi. 2018. Cyber-security in smart grid: Survey and challenges. *Elsevier Comp. Elec. Eng.* (2018).
- [22] Simone Fischer-Hübner, Cristina Alcaraz, Afonso Ferreira, Carmen Fernandez-Gago, Javier Lopez, Evangelos Markatos, Lejla Islami, and Mahdi Akil. 2021. Stakeholder perspectives and requirements on cybersecurity in Europe. (2021).
- [23] Gerald J FitzPatrick and David A Wollman. 2010. NIST interoperability framework and action plans. In *IEEE PES General Meeting*.
- [24] Gartner. 2021. *What Is Cybersecurity?* Technical Report. <https://www.gartner.com/en/topics/cybersecurity>
- [25] Kathrin Grosse, Lukas Bieringer, Tarek Richard Besold, Battista Biggio, and Katharina Krombholz. 2022. "Why do so?" – A Practical Perspective on Machine Learning Security. In *Int. Conf. Machin. Learn.: New Frontiers of Adversarial Machine Learning*.
- [26] Yacoub Hanna, Mumin Cebe, Suat Mercan, and Kemal Akkaya. 2021. Efficient Group-Key Management for Low-bandwidth Smart Grid Networks. In *Proc. IEEE Int. Conf. Commun. Contr. Comp. Tech. Smart Grids*.
- [27] Cheerag Kaura, Nidhi Sindhvani, and Alka Chaudhary. 2022. Analysing the Impact of Cyber-Threat to ICS and SCADA Systems. In *IEEE Int. Mobile Embedded Tech. Conf.*
- [28] Yasanur Kayikci, Nazlican Gozacan-Chase, Abderahman Rejeb, and Kaliyan Mathiyazhagan. 2022. Critical success factors for implementing blockchain-based circular supply chain. *Business Strategy and the Environment* (2022).
- [29] Marina Krotofil, Alvaro A Cárdenas, Bradley Manning, and Jason Larsen. 2014. CPS: Driving cyber-physical systems to unsafe operating conditions by timing DoS attacks on sensor signals. In *Proceedings of the 30th Annual Computer Security Applications Conference*. 146–155.
- [30] Marina Krotofil, Klaus Kursawe, and Dieter Gollmann. 2019. Securing industrial control systems. In *Security and Privacy Trends in the Industrial Internet of Things*. Springer, 3–27.
- [31] Nir Kshetri. 2021. Economics of Artificial Intelligence in Cybersecurity. *IEEE IT Professional* (2021).
- [32] Nallapaneni Manoj Kumar, Aneesh A Chand, Maria Malvoni, Kushal A Prasad, Kabir A Mamun, FR Islam, and Shauhrat S Chopra. 2020. Distributed energy resources and the application of AI, IoT, and Blockchain in Smart Grids. *Energies* (2020).
- [33] Ram Shankar Siva Kumar, Magnus Nyström, John Lambert, Andrew Marshall, Mario Goertzel, Andi Comissoneru, Matt Swann, and Sharon Xia. 2020. Adversarial Machine Learning—Industry Perspectives. In *IEEE Secur. Privacy Workshops*.
- [34] Sungmoon Kwon, Hyunguk Yoo, and Taeshik Shon. 2019. RNN-based anomaly detection in DNP3 transport layer. In *2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (Smart-GridComm)*. IEEE, 1–7.
- [35] Beth L Leech. 2002. Asking questions: Techniques for semistructured interviews. *PS: Political Science & Politics* (2002).
- [36] Gaoqi Liang, Junhua Zhao, Fengji Luo, Steven R Weller, and Zhao Yang Dong. 2016. A review of false data injection attacks against modern power systems.

- IEEE Transactions on Smart Grid* 8, 4 (2016), 1630–1638.
- [37] Maria B Line. 2013. A case study: preparing for the smart grids-identifying current practice for information security incident management in the power industry. In *IEEE Int. Conf. IT Secur. Incident Manag. IT Forensics*.
- [38] Kang-Di Lu, Guo-Qiang Zeng, Xizhao Luo, Jian Weng, Yue Zhang, and Ming Li. 2020. An adaptive resilient load frequency controller for smart grids with DoS attacks. *IEEE T. Vehic. Tech.* (2020).
- [39] Daisuke Mashima. 2021. Securing smart-grid infrastructure against emerging threats. In *Solving Urban Infrastructure Problems Using Smart City Technologies*. Elsevier, 359–382.
- [40] Luca Mendicino, Daniele Menniti, Anna Pinnarelli, and Nicola Sorrentino. 2019. Corporate power purchase agreement: Formulation of the related leveled cost of energy and its application to a real life case study. *Elsevier Applied Energy* (2019).
- [41] Muhammad Baqer Mollah, Jun Zhao, Dusit Niyato, Kwok-Yan Lam, Xin Zhang, Amer MYM Ghias, Leong Hai Koh, and Lei Yang. 2020. Blockchain for future Smart Grid: A comprehensive survey. *IEEE Internet of Things J.* (2020).
- [42] Steven Noel, Deborah Bodeau, and Rosalie McQuaid. 2017. Big-data graph knowledge bases for cyber resilience. In *NATO IST-153 Workshop on Cyber Resilience*.
- [43] Kyuchan Park, Bohyun Ahn, Jinsan Kim, Dongjun Won, Youngtae Noh, Jinchun Choi, and Taesic Kim. 2021. An advanced persistent threat (apt)-style cyberattack testbed for distributed energy resources (der). In *2021 IEEE Design Methodologies Conference (DMC)*. 1–5.
- [44] Chen Peng, Hongtao Sun, Mingjin Yang, and Yu-Long Wang. 2019. A Survey on Security Communication and Control for Smart Grids Under Malicious Cyber Attacks. (2019).
- [45] Rick G Randall and Stuart Allen. 2021. Cybersecurity professionals information sharing sources and networks in the US electrical power industry. *Int. J. Critical Infrastructure Protection* (2021).
- [46] Neil C Rowe. 2015. The attribution of cyber warfare 1. In *Cyber Warfare*. Routledge, 61–72.
- [47] Julian L Rrushi. 2022. Physics-driven Page Fault Handling for Customized Deception against CPS Malware. *ACM Transactions on Embedded Computing Systems (TECS)* 21, 3 (2022), 1–36.
- [48] Luis E Salazar and Alvaro A Cardenas. 2019. Enhancing the Resiliency of Cyber-Physical Systems with Software-Defined Networks. In *Proceedings of the ACM Workshop on Cyber-Physical Systems Security & Privacy*. 15–26.
- [49] Dimitrios Serpanos and Theodoros Komninos. 2022. The Cyberwarfare in Ukraine. *IEEE Computer* (2022).
- [50] Björn Siemers, Shadi Attarha, Jirapa Kamsamrong, Michael Brand, Maria Valliou, Ruta Pirta-Dreimane, Jamis Grabis, Nadezhda Kucina, Mike Mekkanen, Tero Vartiainen, et al. 2021. Modern Trends and Skill Gaps of Cyber Security in Smart Grid. In *IEEE Int. Conf. Smart Tech.* 565–570.
- [51] Neeraj Kumar Singh and Vasundhara Mahajan. 2021. End-user privacy protection scheme from cyber intrusion in smart grid advanced metering infrastructure. *Int. J. Critical Infrastructure Protection* (2021).
- [52] James M Taylor and Hamid R Sharif. 2017. Security challenges and methods for protecting critical infrastructure cyber-physical systems. In *IEEE Int. Conf. Selected Topics Mobile Wireless Netw.*
- [53] Aklilu Daniel Tesfamicael, Vicky Liu, Matthew Mckague, William Caelli, and Ernest Foo. 2020. A design for a secure energy market trading system in a national wholesale electricity market. *IEEE Access* 8 (2020), 132424–132445.
- [54] Md Touhiduzzaman, Sri Nikhil Gupta Gouriseti, Crystal Eppinger, and Abhishek Somani. 2019. A review of cybersecurity risk and consequences for critical infrastructure. *2019 Resilience Week (RWS)* 1 (2019), 7–13.
- [55] Hilary Tuttle. 2022. 2022 Cyber Landscape. *Risk Management* (2022).
- [56] Nikos Virvilis and Dimitris Gritzalis. 2013. The big four-what we did wrong in advanced persistent threat detection?. In *IEEE Int. Conf. Availability, Reliability, Secur.*
- [57] Wam Voster. 2021. *The Emergence of Killware, the Lethal Malware*. Technical Report. Gartner. <https://blogs.gartner.com/wan-voster/2021/07/21/the-emergence-of-killware-the-lethal-malware>
- [58] Aaron W Werth and Thomas H Morris. 2020. Prototyping PLCs and IoT Devices in an HVAC Virtual Testbed to Study Impacts of Cyberattacks. In *International Congress on Information and Communication Technology*. Springer, 612–623.
- [59] Patrick Wlazlo, Abhijeet Sahu, Zeyu Mao, Hao Huang, Ana Goulart, Katherine Davis, and Saman Zonouz. 2021. Man-in-the-middle attacks and defence in a power system cyber-physical testbed. *IET Cyber-Physical Systems: Theory & Applications* (2021).
- [60] Hyunguk Yoo, Sushma Kalle, Jared Smith, and Irfan Ahmed. 2019. Overshadow PLC to detect remote control-logic injection attacks. In *International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment*. Springer, 109–132.
- [61] Derek Young, Juan Lopez Jr, Mason Rice, Benjamin Ramsey, and Robert McTasney. 2016. A framework for incorporating insurance in critical infrastructure cyber risk strategies. *International Journal of Critical Infrastructure Protection* 14 (2016), 43–57.
- [62] Tianyu Zhao, Ernest Foo, and Hui Tian. 2022. A Lightweight Blockchain-Based Trust Management Framework for Access Control in IoT. In *Secure and Trusted Cyber Physical Systems*. Springer, 135–175.
- [63] Shan Zuo, Omar Ali Beg, Frank L. Lewis, and Ali Davoudi. 2020. Resilient Networked AC Microgrids Under Unbounded Cyber Attacks. *IEEE T. Smart Grid* (2020).