Research Article

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Towards Resilient Critical Infrastructures – Motivating Users to Contribute to Smart Grid Resilience

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Abstract: Smart cities aim at improving efficiency while providing safety and security by merging conventional infrastructures with information and communication technology. One strategy for mitigating hazardous situations and improving the overall resilience of the system is to involve citizens. For instance, smart grids involve *prosumers*—capable of producing and consuming electricity—who can adjust their electricity profile dynamically (i. e., decrease or increase electricity consumption), or use their local production to supply electricity to the grid. This mitigates the impact of peak consumption periods on the grid and makes it easier for operators to control the grid. This involvement of prosumers is accompanied by numerous socio-technical challenges, including motivating citizens to contribute by adjusting their electricity consumption to the requirements of the energy grid. Towards this end, this work investigates motivational strategies and tools, including nudging, persuasive technologies, and incentives, that can be leveraged to increase the motivation of citizens. We discuss long-term and side effects and ethical and privacy considerations, before portraying bug bounty programs, gamification and apps as technologies and strategies to communicate the motivational strategies to citizens.

Keywords: Smart Grid, Motivation, Nudging, Prosumers, Critical Infrastructures, Citizens, Resilience

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1 Introduction: The Smart Grid, Prosumers and Resilience

Smart cities are envisioned to encompass highly digitized and strongly interconnected infrastructures, like the energy grid, water supply, and telecommunication. Some of these systems or organizations, called Critical Infrastructures (CIs), provide vital services for nations' society and economy. Failures or attacks on these CIs can impair crucial services and severely threaten public safety and security [81].

This is particularly true for the energy grid, which provides a continuous supply of electricity for millions of consumers, despite the ever-increasing energy-technical demand of modern societies [50]. However, since failures and attacks cannot be fully prevented, a high degree of resilience is crucial for minimizing hazardous consequences for all involved. Resilience can be defined as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" [52, p. XXXVI].

In the context of energy grids, conglomerates have always been responsible for maintaining a stable operation by adjusting production to the needs of the consumers. In recent years, energy grids have transitioned from the conventional fossil-fuelled and top-down controlled systems towards increasingly distributed Smart Grids that strongly rely on renewable energy sources. Whilst these developments have obvious benefits, they introduce their own share of challenges, such as high volatility as the production of renewable energy depends on ever-changing environmental factors, like wind and solar radiation. On top of that, the role of consumers changes. Traditionally, their role within conventional energy grids was a passive one, where they freely consumed electricity provided by large producers, whilst being largely unaware of the impact of their actions and the feats that need to be accomplished by operators to provide a continuous supply with electricity. These consumers have evolved into increasingly active *prosumers*, supported by information and communication technology (ICT) and capable of producing and consuming electricity [28]. This means that the balancing of demand and supply in SGs becomes more complex as the set of interdependent participants in a SG strongly increases.

Consequently, notions of safety and security in these complex and interconnected systems cannot solely be based on technical aspects but increasingly depend on the behavior of citizens. It is thus important to consider citizens as active contributors to safety and security, in terms of stabilizing the SG to prevent hazardous incidents as well as in terms of coping with and recovering from emergency situations such as blackouts, e. g., through emergency preparation and coping strategies [103].

Numerous options for citizens to contribute to the safety and security of SGs are already available in current energy grids, e. g., adapting consumption behavior to avoid high consumption during peak hours, and studies have investigated the conditions under which citizens are prepared to cease control over energy consumption [31] or motivations for reducing consumption [75]. Yet, some of these aspects cannot be regulated or mandated without compromising the autonomy and freedom of choice of individuals, while others require the provision of certain technologies and technological knowledge. Thus, one challenge lies in enabling and motivating users to voluntarily contribute to the safety and security of smart grids, especially if their "resilient" behavior might result in compromises or restrictions for themselves for the benefit of others. An additional challenge lies in sustaining motivation and the targeted behaviors in the long term.

Across different disciplines, strategies such as nudges or incentives have been explored to shift citizens' decisions or behaviors [91, 77]. Yet, motivating citizens to "resilient" behaviors within complex and interconnected CIs remains a new and unsolved challenge.

Applying insights from various disciplines, we will shed light on the following research question: *How can citizens be motivated to actively contribute to the safety and security of connected CIs, such as smart grids?* This paper presents and discusses different strategies for motivating citizens to contribute to safety and security of CIs from an interdisciplinary point of view. As a prominent representative of CIs, smart grids are used as an example to illustrate each strategy with practical examples.

The remainder of the paper is structured as follows: Section 2 on motivational approaches presents strategies to motivate citizens to contribute to SG safety and security along with practical examples from an interdisciplinary viewpoint. We then discuss the presented strategies with regard to their long-term effects, ethical challenges, as well as practical implications in Section 3 and present visions of citizen participation through bug bounty programs, gamification, and the use of apps in Section 4. Section 5 summarizes the findings.

2 Motivating Users and Citizens to Contribute to Safety and Security in Smart Cities

In general, motivation can be defined as the overall desire or willingness of someone to do something [73]. This section presents theoretical frameworks and approaches for motivating users to choose certain options for action or to show specific behaviors. The approaches represent an interdisciplinary perspective with insights from various disciplines, such as pedagogy (e. g., information provision), behavioral economics (e. g., nudging), psychology (e. g., persuasive technologies), and politics (e. g., incentives). While the approaches differ in their theoretical background, their perspective on the human being, and their intentions, they rely on similar mechanisms to transfer these intentions. Each approach is presented with some examples for motivating citizens to contribute to smart grid safety and security. Furthermore, the differences, overlaps, and possibilities for combining approaches will be discussed in Section 2.5.

2.1 Information and Education

Information provision serves to bridge a potential knowledge gap between citizens (or laypersons) and a knowledgeable third party, such as an organization, the state, or experts of various kinds to improve the decision-making process [18]. Education and information provision can be regarded as essential for achieving transparency and for empowering citizens with different levels of background knowledge and skills to make informed privacy and security decisions where incomplete or asymmetric information is the norm [2]. However, too much information can be overwhelming for the user.

For example, research found that information provision through notices is seldom working in practice [18]. Obar and Oeldorf-Hirsch [71] showed that privacy policies and terms of service are rarely read and Florêncio et al. [35] found that password creation suggestions are seldom followed, despite year-long advice. Previous work from the security and privacy area thus suggests that information should be provided in a concise format considering the user's mental models (e. g., using known metaphors) [76], and that standardization of information (e. g., standardized labels) [57] may support understanding. Examples for standardized labels related to smart grids are energy labels on electric devices and suggestions for standardized privacy labels indicating how organizations make use of the citizens' personal data [56].

Information and Education Examples

Examples for practical information provision to motivate citizens in contributing to smart grid safety and security are already discussed in the literature [40, 45]. This research confirms that the simple provision of information (e. g., using in-house displays that provide information about the electricity consumption) is insufficient to motivate citizens. In comparison, if information provision is combined with other techniques, such as incentive-based approaches, the probability of citizens contributing to the safety and security of the grid can be increased [49, 14, 5]. For example, it was shown that the decision-making of citizens can be improved by providing information on smart meters and facilitating the choice of time-of-use tariffs in combination with personalized estimated costs as an incentive [14].

2.2 Nudging

Nudges [97] are small tweaks of physical or digital decision interfaces aiming to encourage "wiser" decisions, e. g., secure behavior, without limiting or significantly influencing peoples' choice set. Nudges generally work by activating automatic cognitive processes such as biases or heuristics [18, 43].

Nudges have been successfully applied in a large range of physical contexts such as encouraging healthy nutrition [60], organ donation [104], or physical activity [102]. In addition, nudging has found its way into the digital and cyber space, including password creation [78, 46], WiFi selection [101], and privacy-friendly app choices [12]. An example is that of using a position effect to make people choose a secure WiFi option in a public place such as an airport. When the secure WiFi option appeared first in the selection list, more people tended to choose that option [107]. As such, nudging might be a promising strategy to encourage certain decisions within the smart city context in which physical and digital spaces become increasingly intertwined.

Nudge Examples

Nudges towards pro-environmental decisions have often been summarized under the term "Green Nudges" [87]. Previous research on green nudges showed that users can be nudged towards saving electricity by providing them feedback on their consumption behavior or comparisons with other users [11, 6]. However, these nudges may also create unintended effects. For example, those households that usually consumed less than average, unexpectedly increased their energy consumption [88], perhaps because of a tendency to go with the norm. These side effects could be mitigated by including an indication of desirable behavior [88]. On the level of providers, exemplary nudges include enrolling clients in green energy sources in their contracts per default [93] and research confirmed that more people select green energy choices when those are presented as the default [74].

Schubert [87] suggests the use of an *Ambient Orb*, as a green nudge, which changes its color to indicate the current smart grid load. Even though imagined in the context of climate change, a similar intervention could serve to increase users' awareness of the grid's load factor and may encourage users to contribute to the grid's stability.

Zhao and John [105] examined the use of framing nudges to encourage users to build community resilience through preparation for natural disasters, e. g., by storing food or household retrofitting. They used the examples of a hurricane, earthquake, or flood and applied the choices to invest in physical mitigations, an insurance, or to do nothing with the chance that no adverse consequences arise. In general, the percentage of people choosing to invest was higher when the decision was framed as a gain. Even though the contexts of the study slightly differed from the smart grid one, the results might be transferable.

2.3 Persuasive Technologies

Persuasive technologies are interactive technologies that aim to change the attitude or behavior of the respective user [37]. Whereas nudges can exert influence on a subconscious level, influence from persuasive technologies always comes from a conscious interaction with the technology. Hence, users make an active decision to change their behavior in a certain way (e. g., to reduce CO_2 emissions) and use technologies that support them in this desired behavioral change. Consequently, persuasive technologies are designed for more far-reaching behavioral changes than nudges, which are not intended to restrict the user's scope for decision-making.

The concept of persuasive technologies was first described by Fogg [37]. He postulates that three factors must be present at the same time for a change in behavior to occur: motivation, ability, and a prompt [36]. Possible motivators include gaining pleasure (or preventing pain), hope (or overcoming fear), and winning social acceptance (or preventing social rejection). The aspect of ability focuses on one's resources, e. g., in terms of time, money, or physical strength. However, according to the Fogg Behavior Model (FBM), even if people score high on motivation and ability, they still need to be prompted to exercise a certain behavior.

Persuasive Technology Examples

Multiple studies examine the potential of persuasive technologies to encourage energy saving. Beheshtian et al. [13] explore the possibilities of a persuasive social robot aiming to facilitate sustainable behavior—such as saving energy—in shared living spaces. Most of their 20 participants agreed that social components such as comparing their energy consumption with other flats and competing against others could motivate them to save energy. They also liked the idea of getting points and rewards as well as information about how to save energy. Takayama et al. [94] describe the successful gamification approach, which implements several social feedback mechanisms, e. g., by allowing families to compare their CO_2 emissions against those of their neighbors.

Bourgeois et al. [15] developed and tested four different interventions aiming to motivate households who produce their own "green" energy to shift their laundry activities to maximize the use of their self-generated energy. The results of an 8-month field study with 18 households suggest that while feedback mechanisms fail to motivate a behavior change, proactive suggestions as well as contextual control (e. g., replacement of the control panel with a tablet that offers the opportunity to either start the washing process immediately or automatically at the best time) seem promising for facilitating behavior change.

2.4 Incentives

The participation of laypersons in processes for maintaining the continuous operation of CIs is often—if not always—accompanied by some kind of *burden*, such as a partial blackout for prosumers who offer reserve capacity. Therefore, rational choice strategies suggests that such burdens should be adequately compensated. In this context, *incentives* aim to alleviate the participation of laypersons by directly or indirectly providing a compensation. In comparison to persuasive technologies (see Section 2.3), which aim to motivate people in making active decisions, incentives use direct or indirect mechanism for reimbursing certain user behaviors.

Psychological theories differentiate between intrinsic or extrinsic motivation, i. e., whether the motivator lies within the execution of a certain action or in the consequences of the completed action [82]. Exemplary findings analyzing the intrinsic motivators behind graffiti spraying identified, e. g., sensation seeking, a flow experience, creativity, and camaraderie [83]. Extrinsic motivators include monetary, social, or other rewards, such as job-related benefits [62, 86]. The differentiation can be relevant when designing interventions or choosing incentives to motivate a certain behavior. Research showed that intrinsically motivated behavior can be crowded out when offering extrinsic incentives, e. g., when offering children a reward for an action they formerly enjoyed doing [21].

Incentive Examples

Incentivization is a strategy that has been used within the energy grid for decades. Various pricing strategies exist, which aim to encourage the consumers in the grid to adjust their behavior, like time-of-use prices, real-time pricing, and inclining block-rate pricing [1, 49, 14, 5]. The majority of these strategies is based on indirect reimbursement strategies, where consumers can manage to *pay less* if they adhere to the behavior, which is suggested by the strategies (e. g., avoid strong electricity consumption during peak-consumption hours, where prices are high). Such strategies have been successfully used within Home Energy Management Systems (HEMSs) as an incentive for automatically scheduling the use of appliances to maximize the monetary benefits of the consumers [67].

2.5 Combination of Approaches

The presented interventions differ with regard to their theoretical background, their disciplinary viewpoints, and their intentions even though they may sometimes make use of similar measures to achieve their aim (see Table 1). However, the approaches also show a certain degree of overlap in the mechanisms they use. For example, incentivization encourages users to pick a certain option and to overcome burdens e. g., increased efforts or downsides. Persuasive technologies instead make use of incentives to support users in their self-chosen behavior changes and

Table 1: Overview over the criteria for differentiating the presented interventions.

	Information Provision	Nudges	Persuasive Technologies	Incentives
Cognitive process	reflective	automatic	reflective	reflective
Primary target	decision & behavior	decision	behavior	decision
Degree of coercion	low	medium	low	high
Degree of interaction	low/medium	low	high	low
Resources provider	low	low	high	high
Resources user	high	low	high	low

aims. Incentivization also partially overlaps with nudging. Even though Thaler and Sunstein [97] exclude "significant" economic incentives from the nudge definition, the criterion is rather vague so that other incentives such as social rewards may still fulfill the nudge definition.

Research showed that the combination of interventions, such as several persuasive technology mechanisms [65] or information provision and nudging [60, 107, 92] can even be beneficial.

Yet, researchers and practitioners should be aware of these overlaps to clearly position, design, and purposefully combine their interventions. Additionally, they should bear in mind the different theoretical concepts behind and the implications of different approaches in order to anticipate and avoid potential negative side effects or unintended outcomes.

3 Evaluation and Discussion

The analysis of motivational aspects and technologies to implement them shows that there are many avenues to enhance the integration of prosumers to contribute to the resilience of CIs. While the given examples mainly portray the energy sector, similar challenges exist with regard to other CIs. The water sector is also grappling with involving citizens in reducing and steering water consumption and with communicating with consumers [48, 69, 61]. In choosing and adapting motivational strategies, ethics, privacy aspects, as well as potential side effects should be considered.

3.1 Ethical Considerations

Guidelines for ethical psychological research [9, 29, 98] suggest to respect persons and their autonomy, to maximize beneficence, to practice justice, to work according to scientific integrity standards, and to take on social responsibility. These meta guidelines can also well inform the depletion of measures to motivate citizens to or to make citizens behave in a certain way.

For example, citizens could be respected by being informed transparently about the measures and their purpose, and by looking for solutions that do not unnecessarily compromise citizens' autonomy. Exemplary strategies following that approach are educational approaches aiming to increase knowledge and awareness, persuasive technologies that foster the active interaction with the user, or nudges that aim to encourage certain choices without limiting the choice set. In terms of nudges, research suggests that transparent "hybrid nudges", i. e., the combination of nudges with information provision, may be especially favorable due to the enhanced transparency of the intervention [78].

The beneficence of deployed measures for the safety, security, and welfare of citizens could be weighed against potential costs and risks for individuals, e. g., the need to give up on privacy or certain privileges in emergency situations. Citizens could be motivated to accept potential constraints by highlighting desirable social norms and the contribution to the common good or by compensating downsides with suitable incentives.

Deployed measures could be rated in terms of justice such as whether certain societal groups are discriminated or excluded. This could be the case if certain benefits or functionalities are only available to people with certain devices or levels of expertise. For example, persuasive technologies should be designed to be usable and accessible for different age groups such as children and seniors.

It is reasonable to evaluate all deployed measures in terms of their scientific integrity and quality to ensure effectiveness and to identify possibly unanticipated or unintended consequences. An example is the intervention aiming to reduce energy consumption through social comparison and which found that people who were below the average surprisingly increased consumption. This outcome could only be identified and mitigated through suitable evaluation [88].

Finally, decision-makers bear considerable social responsibility. They should be aware of the potential short-term and long-term consequences of their actions considering the before-mentioned guidelines. For example, the use of high financial incentives might lead people to engage in activities against their will out of financial despair. This might not only negatively affect the citizens themselves, but may also compromise the long-term effectiveness of the measure, especially when the incentive is taken away at some point.

Yet, the decision to deploy certain measures is definitely not an easy one. Challenges remain, such as when to compromise autonomy and limit freedom of choice. Which situations justify constraining strategies such as laws or restrictions? In case of limited resources, who should benefit in which way? How can accessibility and non-discrimination be ensured given different age groups, technical equipment, and varying levels of expertise? Which measure should be deployed when scientific evidence is scarce or contradictory? An approach for targeting these important questions, that is already practiced in some cases [25], is the depletion of an interdisciplinary ethical committee that evaluates processes and deployed measures from various perspectives.

3.2 Privacy Aspects

With the ongoing digitalization of cities and public spaces, the privacy of citizens is gaining in importance. Here, the General Data Protection Regulation (GDPR) is of relevance, which since 2016 is part of EU law on data protection. By addressing data transfer in particular, the aim of the GDPR is to give individuals control over their data and to provide uniform regulations for privacy in IT in the EU. The GDPR holds users accountable for the protection of their data by requesting informed consent for the use of their data [99]. However, with increasing data collection in public spaces, e. g., by cameras and sensors, it quickly becomes impossible for citizens to keep track of the collection of their data. It is furthermore hardly possible to decline the collection of one's data in public spaces without restricting one's behavior, e. g., by avoiding to visit certain public places.

Yet, cities sometimes might need to collect data of their citizens for safety or security purposes. This has been subject of heated discussions before, e. g., when the interior ministry in Germany tested facial recognition cameras at the Berlin-Südkreuz station in 2018 [23], or recently in the course of the introduction of the German Corona-Warn-App [17]. German citizens tend to express concerns about governmental surveillance, but in an Orwellian manner they usually lack concern in the context of data collection by private organizations like Google or Facebook [8]. While this is often explained by the historical experiences of being spied on and prosecuted by the Gestapo and Stasi [38], it remains unclear how governmental agencies should deal with this fear of their citizens of being under surveillance. Research is needed to address this issue and explore possibilities for communicating decisions about technical implementations regarding data collection and privacy protection to the general population. This is especially important in case the population is expected to collaborate in the data collection, e. g., by installing and using the Corona-Warn-App, by reporting information about safety or security related incidents, or by participating as prosumers in SGs [27].

However, research on crisis apps suggests that users are willing to make privacy concessions to increase security [96]. A possible solution for supporting citizens in keeping track of and managing the collection of their data could be the provision of a digital privacy assistant [20]. This assistant could be implemented, e. g., as a mobile solution in the form of an app. Combining machine learning and manual input, the assistant would be able to semi-automatically identify the privacy preferences of its user and communicate and enforce them to data collecting devices in the public space.

3.3 Long-Term and Side Effects

Long-term and side effects of relying on technology to communicate with and motivate prosumers can be the exclusion of segments of the population. Therefore, different preferences of various socio-demographic groups should be considered. While age differences should not be overstated, certain aspects such as internet self-efficacy are often different for older or younger people [19]. Research on warning apps indicates that while many preferences are universal, women are partly interested in different warning topics than men [55]. Similarly, women and men are likely to have deviating considerations for their energy use, leading to differences in peak energy consumption and thus requiring different motivations for desired behaviors. The implementation of motivational strategies and choice of technologies should consider such differences and ensure that no groups are excluded. Such differences may also be relevant for motivating various demographic groups, who may respond differently to motivation strategies.

Introducing technologies that connect prosumers and CIs creates further vulnerabilities in the system. At the same time, citizens typically behave insecurely online [108], potentially leading to another weak link when it comes to securing CIs. Any technology used to integrate prosumers should thus consider the cybersecurity risk and CI resilience [51]. Moreover, nudging may compromise users' autonomy if they are not aware of the subtle or covert influence [64, 44], or cause reactance on the users' side due to the perceived manipulation. This issue could be addressed by making nudges more transparent [97, 70], e. g. by combining them with other approaches such as information provision. Initial research indicates that increasing the transparency of the nudge does not necessarily comprise its efficacy but may even be useful [60, 107]. In addition, involving users should ensure that psychological needs are considered. For example, research indicates that even without additional extrinsic motivation such as praise, the mere recognition of the contribution goes a long way in keeping participants motivated [10].

4 Visions for Citizen Participation

This section discusses the contribution of citizens to infrastructure resilience as an aspect of citizen participation. As such, it introduces bug bounty programs, gamification, and apps as strategies to foster citizen involvement and highlights the use of apps to engage citizens in different contexts.

4.1 Bug Bounty Programs

BBPs can be understood as a form of crowdsourced penetration testing, where the identification of IT system weaknesses are financially rewarded [26]. While using bug bounty rewards is cheaper than employing many cybersecurity experts for penetration testing, individuals who participate are mainly motivated by their contribution to public safety and the recognition of their community [59].

However, the (cyber-)security of any CI should be preserved when involving individuals, since they are crucial for a functioning society [51]. Hence, it is prohibited to let civilians interact directly with critical parts in such systems or to test them for crisis scenarios [4]. However, when looking at the field of Critical Information Infrastructures (CIIs), which are considered a subset of CIs [22], we see a shift towards the participation of individuals to secure these systems. For example, BBPs are used by large IT companies like Microsoft, Facebook, and Google. Such programs allow white-hat hackers to hack promoted systems and report vulnerabilities found in exchange for a (usually monetary) reward. This has been shown with great success, since large IT infrastructures are becoming too complex for teams to find vulnerabilities and defend systems against cyber attacks. Not only companies, but also agencies in the U.S. like the Department of Defense (DoD) [68] use this kind of civil participation to strengthen the security of their IT infrastructure. Since then, it has become a trend in the U.S. to use BBPs as a method of discovering vulnerabilities, even in CI [30]. With the emergence of more ICT systems in CIs, these systems are getting inherently insecure, due to insecure hard- and software components [32, 72]. A bug bounty approach could potentially increase the security of such, thus, increase the reliability and resilience, due to the lack of aforementioned vulnerabilities. IT security experts (or even less skilled participants) would be able to directly interact with the CIs, to report vulnerabilities, and eventually to confirm strong defensive measures in terms of IT security. Another benefit of this approach is the potentially increasing trust of civilians in these infrastructures, because of a direct participation possibility.

However, this approach requires a controlled involvement of individuals. Precautions must be taken to exclude criminal actors from interacting with security-relevant information and systems. In addition, when vulnerabilities are triggered, users interact with systems in unexpected ways, i. e., by crashing the system or escalating privileges. Hence, it is imperative to provide enough backup systems to seamlessly swap out compromised systems or even to separate active and inactive (e. g., backup) facilities and replicate a realistic workflow in the systems under investigation (e. g., by replicating old protocols), before enabling BBPs. Moreover, due to the possible installation of backdoor software, a thorough observation of system logs and user behavior is necessary to mitigate both problems. IT forensics might be necessary to ensure a proper functioning of the system state after investigation before reinstalling the systems into the real world. Otherwise, *testing systems* might never be allowed to enter as live-system, but may solely be used for security testing in this simulated environment.

Overall, BBPs have a high potential to increase the security of CIs. Currently existing bug bounty formats need to be adapted to the high security needs of CIs and additional security measures must be installed to be of use in this domain.

4.2 Gamification

Gamification refers to a concept that transfers designs, mechanics, and heuristics of games into a non-gaming context to enrich the user experience by invoking feelings like excitement and joy [24]. The goal is to leverage the users' intrinsic motivation for playing games in a pragmatic context that aims to fulfill specific goals [47]. To achieve these goals, game mechanics aim to increase the motivation of users to adjust their behavior [89]. Literature shows that gamification has been successfully applied in various domains, like mobile education [90], redesigning of business processes [58], and cybersecurity [33]. Furthermore, gamification has been successfully applied in the context of urban infrastructures. For instance, prominent examples aim at influencing the water consumption of citizens and aid water utilities in improving their strategies for system operation [84, 63]. In the domain of energy grids, gamification is used to achieve reductions in peak demand and costs for infrastructure operators [39, 7, 53, 54].

In practice, commonly applied game mechanics are, among others, scoring systems, levels, and achievements [106]. For instance, Gnauk et al. [39] proposed a prototypical demand dispatch system for energy grids, which allows citizens to communicate available flexibilities (i. e., variable consumption periods for local appliances) to control authorities. Authorities can leverage these variable consumption times to optimize the operation of the grid by scheduling the consumption accordingly or negotiate changes. For decisions citizens make that improve the overall demand dispatch operations, they are rewarded with *Earth Saver Points* which can be used to earn titles in the context of the application (e. g., Eco Hero) or gain small extrinsic rewards.

Despite the success of gamification in various fields, the effective application of the concept is challenging [42]. Several concepts and methods that have been discussed within this work need to be combined carefully. For instance, the representation of information for citizens must be carefully designed, to prevent overwhelming effects and discouragement (see Section 2.1). Furthermore, interaction interfaces need to be designed thoroughly to support citizens in conducting beneficial actions intuitively (see Section 2.2). Furthermore, aspects like the voluntariness of tasks, the nature of the system (e. g., pragmatic or hedonic), and the general citizen involvement and attitude can strongly influence the applicability of gamification [42, 41].

Overall, gamification represents a promising technique to increase the involvement of citizens with actions to improve safety and security of smart city infrastructures. The possibilities for potential applications are numerous, but each concept needs to be carefully designed in order to be effective.

4.3 Crisis Communication and Apps

Due to the importance of time in communicating the state of the energy system and potential crises, typical tools for a day-to-day interface would be apps. For example, warning apps typically deal with the communication between emergency services and citizens, but ICTs are also used for coordination among citizens or among agencies [79]. Due to the dynamic nature of crises, mobile crisis applications are commonly used for (1) gathering data from the crowd, (2) organizing collaboration during disasters, (3) spreading official information, (4) collecting and processing data for situational awareness, (5) allowing users to notify others during disasters [95]. Apps are also already commonplace for owners of solar panels, to adapt their energy use to their own production. Technologies such as home energy management systems are being developed that help prosumers manage their energy reserves and consumption [85]. Such tools that enable prosumers to make situation and device specific choices are particularly relevant as prosumers are more resistant to remotely versus personally controlled changes to device operations for balancing the grid [66]. Typically, such information would be offered on demand, as *pull* rather than *push* information, requiring prosumers to proactively search for the relevant information, e. g., by opening their app. In case of emergencies, *push* messages increase the likelihood that crisis information is noticed immediately. These systems are already used in warning apps. Typical warnings include information about the incident as well as instructions on how to behave [34]. However, CIs do not typically have channels particularly for emergency communication. Instead, their communication with citizens relates mainly to public relations and corporate crisis management.

Borrowing from crisis informatics, modes of communication should be established that (1) communicate the state of the system so that prosumers can make informed decisions and (2) communicate urgently needed action or emergency concessions to increase prosumers' timely cooperation. One aspect to consider is whether to use general-purpose or built-for-purpose tools. General-purpose tools are familiar and relevant in daily life [95], because they primarily fulfill a function not related to warnings, such as weather apps that also warn about extreme weather or the German Ministry of Health's use of the messenger apps WhatsApp and Telegram for COVID-19 related information and behavioral recommendations [16]. Built-for-purpose tools, in contrast, are only used in emergencies, which are rare, but they are more adaptable to their specific functions. In warning apps, such as FEMA or KATWARN, this includes the option to determine a geographic area of interest or content areas, such as traffic, weather, or cyber crime [55, 80]. Regarding the use of specific apps for communication with prosumers to increase resilience, we suggest that four main challenges exists. Firstly, despite the fact that a large proportion of citizens regard warning apps as important, they are seldom used. In 2019, only 16,5 % of German citizens were using any warning app, although over 60 % agreed that they were relevant and 65 % demanded that all warnings should be centralized in one app [55]. Therefore, secondly, the relevance of a tool is dependent on the number and relevance of the organizations providing it. Hence, a warning tool that involves prosumers should be relevant to users' daily life and include several infrastructures. This could mean combining a general energy consumption and production app with a warning or motivational feature or building on channels that are already wide-spread, such as commonly used messaging apps. The third challenge relates to indications that citizens prefer tools that enable them to be active contributors, e. g., to help as witnesses and in the search for missing people, and that have elements of two-way communication [55]. Finally, apps for specific purposes have specific usability requirements. While many insights from crisis informatics can be applied to resilience communication, warning apps' usability requirements [96] may not be identical with the requirements for motivating the co-production of resilience with prosumers. In order to be appealing, prosumers should be involved in studying the particular usability requirements for such tools, e. g. the personalization and notification options.

Likewise, many nations are currently focusing on the use of tracing apps to combat the COVID-19 pandemic, thereby relying on citizens to collaborate in data collection and notification, i. e., tracing social contacts and notifying potential contacts of a positively tested person [3]. Which features are relevant for the mass acceptance of such an app seems to depend on how citizens feel about the general concept of such an app. While critics seem to place particular emphasis on privacy and societal benefit, the undecided may be mainly convinced by the app's convenience, and advocates are likely to use the app regardless of its features [100]. All motivating approaches introduced in Section 2 are suited for implementation in form of a mobile app. Further, these approaches could (1) increase citizen engagement to participate in apps they have already installed, such as contact tracing apps in the context of COVID-19, (2) motivate more citizens to install such apps in the first place, e. g., by educating citizens about the app's functionality and privacy aspects or by rewarding them for the app installation, and (3) serve as a framework for the development of new apps which aim to maximize users' motivation for collaboration. To increase the relevance of such an app, it may combine several aspects of citizens' contributions to the common good, which may require the coordination between several infrastructure providers or the coordination by administrative agencies. In this context, smart city initiatives may be a good place to start, as they are already implementing public digitization, of which CIs could be one of several areas for involving citizens.

5 Conclusion

The energy sector represents a leading example for increasingly involving citizens to actively participate and contribute to resilience of the system as a whole. With the changing role of consumers towards prosumers—capable of consuming and producing electricity—the potential for participation is further increased. While this introduces numerous technical challenges, social aspects like awareness and motivation become increasingly important. For instance, studies have already investigated prosumers' conditions for ceding different levels of autonomy over their electricity consumption, combined with different compensation schemes. Furthermore, social and intrinsic motivations have been explored in the context of consumption reduction and sustainability. In this work, we showed that a variety of options are available for motivating prosumers in the energy sector. These motivational strategies can be enhanced by ICTs that offer new ways of communicating with prosumers, of informing about the state of the system, about crises, or prosumers contributions. Infrastructure providers should thus explore recreating their communication strategies in manners that involve their users and prosumers. While the examples presented in this work mostly refer to the energy sector, we emphasize that presented concepts and strategies can be applied to other sectors as well.

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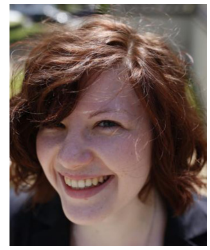

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