RESILIENCE IN CRITICAL INFRASTRUCTURES

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But in the end it's only a passing thing, this shadow; even darkness must pass.

— *Samwise Gamgee*
The Lord Of The Rings - The Two Towers (2002)

ABSTRACT

To the present day, the resilient operation of energy grids relies on the continuous supply of electricity provided by conglomerates of power plants, which adjust their production to the demand of the consumers. Transregional and international connections enable these conglomerates to maintain large amounts of reserve capacities for mitigating deviations from the crucial balance between demand and supply.

However, for years, energy grids have been undergoing drastic changes as part of the energy transition towards more economic and ecological smart grids. As a result, a growing amount of electricity is produced by increasingly volatile producers that are distributed throughout the energy grid. Furthermore, formerly passive consumers evolve to so-called prosumers capable of producing electricity locally.

Whilst these changes support the goals of the energy transition, they also exacerbate the already challenging task of maintaining a continuous balance between the demand and supply of electricity and threaten the resilient operation of energy grids. This thesis makes the following three main contributions to improve the resilient operation of smart energy grids:

We propose a *semi-formal model* for structuring energy distribution grids as *holarchies*—dynamic hierarchies that facilitate the autonomous operation of sub-parts (holons). The resilient operation of these holons is improved by involving heterogeneous stakeholders into processes for mitigating the impact of hazardous situations on the continuous supply of electricity. Towards this end, our model empowers stakeholders to offer local resources dynamically as so-called *flexibilities* to support compensating deviations from the balance between demand and supply. We demonstrate our model by integrating it as a discrete-time simulation environment called HOLEG, which was developed as a part of this thesis. To assess the willingness of people to be increasingly involved in processes for mitigating hazardous situations in energy grids, an online survey was conducted. The results show that people are indeed willing to be more involved; however, numerous concerns related to IT-security and privacy remain.

The second main contribution addresses the combined *technical challenge* of organizing holons within holarchies and allocating available flexibilities to mitigate demand and supply deviations. First, we specify the joint challenge (In this work referred to as the *Holon Problem*) as a multivariate optimization problem and customize three prominent *metaheuristic optimization approaches* based on particle

swarm optimization (PSO), genetic algorithms (GAs), and ant colony optimization (ACO) to find near-optimal solutions to the problem at hand. Towards this end, we propose and formalize a *cost function* that allows assessing the quality of solutions to the Holon Problem quantitatively, taking into account operational constraints of holonic energy grids as well as numerous ecological, economic, and resilience criteria. The three metaheuristics are evaluated within a simulated large-scale holonic distribution grid using the HOLEG simulation environment. The results show that metaheuristics are well-suited to find near-optimal solutions to the Holon Problem in situations with both, strict and relaxed time constraints.

The final contribution deals with *social challenges* that emerge from operating energy grids as holarchies and involving people into processes for mitigating hazardous situations. First, we emphasize that *knowledge* about energy grid topics is a crucial component for people to become more aware and take on an increasingly responsible role within holonic energy grids. Second, we provide reasons why laypersons currently lack energy grid knowledge and discuss the potential benefits of increasing their domain knowledge about the resilient operation of energy grids. Third, we stress that knowledge—by itself—is insufficient to motivate people to become increasingly active and highlight strategies to increase their motivation based on *monetary* and *non-monetary* incentives. Finally, we propose a *serious game prototype* as a means to increase the knowledge of people about energy grid topics. The evaluation results show that the serious game prototype is well-suited to educate people about energy grid topics. Moreover, people experience the serious game as significantly more exciting, motivating, and entertaining compared to a text-based learning approach.

In conclusion, this dissertation addresses both technical and social challenges that emerge from the transition of energy grids towards smart grids. Our contributions aid the understanding of socio-technical interdependencies within future energy grids and advance concepts and methods to facilitate their resilient operation.

ZUSAMMENFASSUNG

Der resiliente Betrieb von Stromnetzen basiert heutzutage größtenteils auf der kontinuierlichen Bereitstellung von Strom durch Konglomerate von Kraftwerken, die ihre Produktion kontinuierlich an die Nachfrage der Verbraucher anpassen. Durch überregionale und internationale Vernetzung sind diese Konglomerate in der Lage große Mengen an Reservekapazitäten vorzuhalten, um Abweichungen vom Gleichgewicht zwischen der Produktion und dem Bedarf an Strom entgegenzuwirken.

Durch das Voranschreiten der Energiewende werden Stromnetze seit Jahren starken Veränderungen unterzogen. Diese dienen dazu konventionelle Stromnetze zu wirtschaftlicheren und ökologischeren "Smart Grids" weiterzuentwickeln. Dabei wird Strom von zunehmend volatilen Erzeugern produziert, die über das gesamte Stromnetz verteilt sind. Außerdem entwickeln sich ehemals passive Verbraucher zu so genannten Prosumern, die zunehmend in der Lage sind, Strom vor Ort zu produzieren. Diese Veränderungen unterstützen zwar die Ziele der Energiewende, verschärfen aber auch gleichzeitig die ohnehin schon schwierige Aufgabe, ein kontinuierliches Gleichgewicht zwischen Strombedarf und -produktion aufrechtzuerhalten, und gefährden damit den resilienten Betrieb der Stromnetze. Die vorliegende Thesis liefert die folgenden drei Hauptbeiträge zur Verbesserung des resilienten Betriebs intelligenter Stromnetze:

Wir schlagen ein *semi-formales Modell* zur Strukturierung von elektrischen Verteilnetzen als *Holarchien* vor—dynamische Hierarchien, die den autonomen Betrieb von Teilnetzen (Holonen) ermöglichen. Der resiliente Betrieb dieser Holone wird anschließend durch das Einbeziehen heterogener Netzteilnehmer in Prozesse zur Abmilderung der Auswirkungen von Gefahrensituationen auf das Gleichgewicht zwischen der Produktion und dem Bedarf an Strom verbessert. Zu diesem Zweck befähigt unser Modell die Netzteilnehmer dazu, einen Beitrag zu den Abmilderungsprozessen zu leisten, indem sie lokale Ressourcen als sogenannte *Flexibilitäten* dynamisch zur Verfügung stellen, um Bedarfs- und Produktionsabweichungen zu kompensieren. Wir demonstrieren unser Modell, indem wir es in eine zeitdiskrete Simulationsumgebung namens HOLEG integrieren, die im Rahmen dieser Thesis entwickelt wurde. Um die Bereitschaft der Menschen zu beurteilen, sich als Netzteilnehmer in Prozesse zur Abschwächung von Gefahrensituationen in Energienetzen einzubringen, wurde eine Online-Umfrage durchgeführt. Die Ergebnisse zeigen, dass die Menschen bereit sind, sich stärker zu engagieren; allerdings bestehen weiterhin zahlreiche Bedenken in Bezug auf IT-Sicherheit und Datenschutz.

Der zweite Hauptbeitrag befasst sich mit der kombinierten *technischen Herausforderung*, Holone innerhalb von Holarchien zu organisieren und verfügbare Flexibilitäten zu allokieren, um Bedarfs- und Produktionsabweichungen zu reduzieren. Zunächst spezifizieren wir die gemeinsame Herausforderung (in dieser Arbeit als *Holon-Problem* bezeichnet) als ein multivariates Optimierungsproblem und passen drei bekannte *metaheuristische Optimierungsansätze* an, die auf Verfahren zu Partikel-Schwarm-Optimierung, Genetischen Algorithmen und Ameisen-Kolonie-Optimierung basieren, um nahezu optimale Lösungen für das vorliegende Problem zu finden. Zu diesem Zweck schlagen wir eine *Kostenfunktion* vor und formalisieren sie. Die Kostenfunktion ermöglicht es, die Qualität von Lösungen für das Holon-Problem quantitativ zu bewerten, wobei betriebliche Beschränkungen holarer Stromnetze sowie zahlreiche ökologische, ökonomische und Resilienz-Kriterien berücksichtigt werden. Die drei Metaheuristiken werden in einem simulierten, großen holaren Verteilnetz unter Verwendung der Simulationsumgebung HOLEG evaluiert. Die Ergebnisse zeigen, dass die Metaheuristiken gut geeignet sind, um sowohl in Situationen mit strengen als auch mit lockeren Zeitbeschränkungen nahezu optimale Lösungen für das Holon-Problem zu finden.

Der letzte Beitrag befasst sich mit *sozialen Herausforderungen*, die sich aus dem Betrieb von Energienetzen als Holarchien und der Einbeziehung von Menschen in Prozesse zur Abmilderung von Gefahrensituationen ergeben. Erstens betonen wir, dass *Wissen* über Stromnetz-Themen eine entscheidende Komponente ist, damit Menschen aufmerksamer werden und eine zunehmend verantwortungsvolle Rolle innerhalb von Stromnetzen einnehmen können. Zweitens nennen wir Gründe, warum es den meisten Menschen derzeit an Wissen über Stromnetze mangelt, und erörtern die potenziellen Vorteile von mehr Fachwissen für den resilienten Betrieb von Stromnetzen. Drittens betonen wir, dass vermehrtes Fachwissen nicht ausreicht, um Menschen zu motivieren, zunehmend aktiv zu werden, und präsentieren Strategien, um deren Motivation durch *monetäre* und *nicht-monetäre* Anreize zu steigern. Schließlich schlagen wir einen *Serious-Game-Prototypen* vor, um das Wissen der Menschen über Stromnetzthemen zu steigern. Die Evaluierungsergebnisse zeigen, dass der Prototyp gut geeignet ist, um Menschen über Stromnetz-Themen aufzuklären, und dass die Menschen ihn im Vergleich zu einem textbasierten Lernansatz als wesentlich spannender, motivierender und unterhaltsamer beurteilen.

Zusammenfassend lässt sich sagen, dass sich diese Dissertation sowohl mit den technischen als auch mit den sozialen Herausforderungen befasst, die sich aus der Entwicklung von Stromnetze hin zu "Smart Grids" ergeben. Unsere Beiträge tragen zum Verständnis der sozio-technischen Interdependenzen innerhalb zukünftiger Stromnetze bei und fördern Konzepte und Methoden, die deren resilienten Betrieb ermöglichen.

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LIST OF ALGORITHMS

ACRONYMS

RES	renewable energy source
ICT	information and communication technology
HEMS	home energy management system
EV	electric vehicles
PIF	prosumer integration framework
PSO	particle swarm optimization
BPSO	binary particle swarm optimization
GA	genetic algorithm
ACO	ant colony optimization
BACO	binary ant colony optimization
AI	artificial intelligence

1 INTRODUCTION

Consider a distribution system with pervasive AMI[1], extensive DA[2], and high levels of DER[3]. [. . .] Each of these technologies has certain implications for system design. However, a true Smart Grid will not treat these technologies as separate issues. Rather, a Smart Grid will integrate the functions of AMI, DA, and DER so that the total benefits are greater than the sum of the parts.

- Richard E. Brown, Exponent (2008)

1.1 MOTIVATION & PROBLEM DEFINITION

Energy grids have been recognized as a critical infrastructure for over a century, and they are an integral part of our modern society. Millions of consumers and numerous other infrastructures, such as information and communication technology (ICT), water supply, and the financial system depend on the continuous supply of electricity provided by the energy grid.

TRADITIONAL ENERGY GRIDS. To the present day, this steady supply of electricity is mainly provided by conglomerates of large fossil-fueled and nuclear power plants that generate enormous amounts of electricity at central locations within the energy grid. This electricity is then transmitted through millions of kilometers of energy grid infrastructure until it reaches the consumers [58]. This top-down producer-to-consumer electricity delivery concept facilitates a stable and reliable supply of electricity for the consumers. In particular, the average interruption time (i.e., the average amount of time consumers are not provided with electricity) for each consumer in Germany during 2018 was only 13.91 minutes [24]. For the remaining time, the majority of consumers perceived the grid as a system that provides electricity continuously and without any noticeable limitations.

VULNERABILITY OF ENERGY GRID INFRASTRUCTURE. Maintaining this high degree of service quality requires the energy grid to be operated in a stable manner. However, this task is extremely chal-

1 Advanced metering infrastructure comprising numerous smart meters and communication networks to facilitate two-way communication within energy grids.
2 Distributed automation technology that allows monitoring and controlling electrical components in energy grids.
3 Distributed energy resources are typically small-scale renewable energy sources distributed throughout the energy grid.

lenging since various properties of the energy grid leave it vulnerable to internal and external influences that may affect the quality of the provided service.

One predominant aspect is the large size of the energy grid infrastructure. Energy grids have always been expanded to adjust to the changing needs of our modern society. Due to this expansion, the energy grid became a gigantic and complex infrastructure with millions of active participants [20]. Operating such an extensive infrastructure resiliently is challenging, as it is exposed to numerous harmful influences.

Power lines and transformer stations suffer from extreme meteorological events, like storms and drastic temperature changes. If these components malfunction, this can lead to severe disruptions of the energy grid's capability to distribute electricity. According to the Department of Energy's disturbance database, approximately 78% of all reported disturbances between 1992 and 2010 were caused by meteorological events [33]. Additionally, the size of the grid also increases the probability of accidents and malicious attacks on the energy grid infrastructure. Many components of the grid infrastructure are pervasive and easily accessible (e.g., overhead lines). Therefore, perimeter security is required to prevent unauthorized access. However, providing this protection for numerous highly distributed components would either require extensive financial investments, or might even not be possible at all. Nowadays, such measures are mainly applied at "important" locations in the grid, like large transformer stations and producers whose malfunctioning would result in severe service degradation. In contrast, protective measures are established poorly, or are unavailable at lower levels of the grid (e.g., distribution grids). In these areas, regional wildlife, like birds, squirrels, and snakes can easily access parts of the infrastructure and may cause severe power outages [196]. Likewise, these areas can be exploited for sabotage attempts and attacks on the energy grid [207].

MAINTAINING STABLE ENERGY GRID OPERATION. To maintain a continuous supply of electricity, it is of paramount importance to prevent the harmful events stated above or, at least, mitigate their impact on the energy grid. Towards this end, several concepts and mechanisms exist, which support the stability of energy grids.

One prominent concept that aims to protect individual energy grid areas is the so-called N-1 security criterion [65]. The goal of the N-1 criterion is to improve the availability and robustness of the energy grid infrastructure and to prevent cascading failures. More precisely, the N-1 criterion specifies that (multiple) disruptions in one area of the grid must not lead to cascading disruptions in connected areas and the grid must be capable of compensating disruptions caused by failing devices. To achieve this, energy grids require redundant components, or devices that remain operable within an affected area need to accommodate the new situation and maintain the stability of the grid, e.g., by taking over the processes of the malfunctioning device.

In addition to service impairments caused by damaged energy grid infrastructure, events that may occur during the mundane operation of the energy grid can threaten its overall stability [165, 168]. As it is well known, the amount of produced electricity needs to match the demand of the consumers at any point in time. This balance is necessary to enable a continuous flow of electricity from producers to consumers. If severe deviations from this balance occur, this can affect the stable operation of the grid and—if not mitigated properly—lead to blackouts [66]. In conventional energy grids, such deviations are compensated by reserve capacities—on-demand resources that can be used to quickly adjust the demand and supply [70]. If these capacities are insufficient, parts of the grid can be separated to restore the balance between demand and supply [19].

1.1.1 *Challenges of the Energy Grid Transition*

The term *energy transition* was initially defined in 1980 in a book that describes different scenarios for a future energy supply based on alternative energy sources compared to oil and uranium [128]. Since about that time, the energy grid has been undergoing significant changes driven by political, ecological, and economic goals. These changes directly or indirectly exacerbate the challenges for maintaining a stable operation of the energy grid and providing a continuous supply of electricity.

For instance, Germany decided to shut down all electricity production that is based on nuclear power by 2022. Furthermore, a related subsequent decision for shutting down production is approved for coal-powered electricity producers, which are planned to be deactivated in several steps until 2038 as a measure to reduce overall CO_2 emission §[52, 64]. Although these decisions are of political and ecological nature, they have a significant impact on the stable operation of energy grids. To compensate for the emerging effects of these decisions, further changes to the grid as well as technical advancements are required:

- Electricity needs to be increasingly provided by renewable energy sources (RESs), like solar- and wind-based producers. While these resources present a more sustainable way of electricity production, they introduce their own share of challenges. The majority of RESs provides a lower power output compared to conventional producers. Consequently, more RESs are required to produce the same amount of electricity. Moreover, the electricity production of many

RESs is highly volatile since they rely on meteorological conditions, like wind and solar radiation.

- The lower power output of RESs also exacerbates the challenge of transmitting electricity over long distances. To minimize transportation losses, RESs need to be installed in the vicinity of consumers. This affects various requirements for the energy grid infrastructure since former consumers may become prosumers—capable of consuming and producing electricity using local means of production (e.g., private solar panels). Furthermore, maintaining a stable supply with electricity becomes increasingly challenging since these producers are distributed throughout the energy grid.

- With an increasing number of RESs and prosumers participating in the production of electricity, the demand for operating reserve capacity is expected to increase significantly [8]. In conventional grids, some of this reserve capacity is provided by fossil-fueled producers; therefore, alternative sources for providing reserve capacity are required.

- With the fade-out of conventional producers and the growing impact of distributed RESs the overall top-down grid structure needs to be adjusted to accommodate the ongoing changes. Many deployed coponents in the grid, like transformers, are designed to support a unidirectional flow of electricity (from producers to consumers); however, distributed electricity production may alter the flow of electricity in situations, where parts of future energy grids produce excess electricity locally. This excess electricity needs to be used or stored locally; otherwise, a reverse flow of electricity from former consumers on lower levels in the grid (e.g., distribution grid) to higher levels may occur [74]. Therefore, concepts and technologies are required to extend the energy grid to cope with these new requirements.

- The previously explained challenges increase the complexity of maintaining the stable operation of the energy grid. Digitization is considered as a strong enabler that supports operating an increasingly complex energy grid. The deployment of an ICT-infrastructure that is tightly coupled to the underlying electrical grid is envisioned to support the transition of the energy grid in numerous ways. Among the benefits are, controlling distributed RESs digitally, the development of novel business areas, and supportive functionalities for consumers and prosumers alike. However, this digital enhancement introduces new failure- and attack-vectors into a system that was predominantly based on electrical and mechanical control. Therefore, safety and security mechanisms are required that allow the energy grid to remain operable while facing the challenges emerging from increased digitization.

1.1.2 *The Need for Resilience in Future Energy Grids*

Failing components and malfunctioning processes threaten the continuous and safe operation of energy grids. Simultaneously, from a security perspective, a "perfectly secure" system that is immune to attacks does not exist. Both, failures and attacks must be expected in complex systems like energy grids and past incidents have shown their impact on the continuous operation of energy grids [165, 168, 191, 233].
The same assumption holds for future energy grids and may even be exacerbated for interim stages of the transitioning process towards smart grids. As not all of these events can be prevented, at least, their impact on the grid needs to be mitigated to minimize the harmful consequences for all involved. In particular, blackouts can have far-reaching consequences for various sectors of public life and the general population [174].

LIMITED APPLICABILITY OF CURRENT APPROACHES. Conventional energy grids mainly rely on preemptive measures, like perimeter security, the N-1 criterion [65], and maintaining large quantities of reserve capacity. Additional measures for maintaining grid stability are based on severe load- and production-shedding mechanisms. The majority of these measures require a hierarchically structured energy grid comprising large producers and a top-down electricity dissemination process. However, the transitioning process of energy grids is highly dynamic and, therefore, changes can be difficult to predict. Consequently, the applicability of the aforementioned measures is either strongly limited, insufficient, or infeasible due to changing requirements.

An energy grid capable of addressing current and upcoming challenges while supporting the ongoing transitioning process, needs to be capable to adjust and react flexibly to changing requirements.

RESILIENCE. Such flexibility cannot be fully achieved by conventional measures that aim to improve stability by increasing the availability, reliability, and robustness. These established measures resulted from decades of operational experience and risk assessment; however, such information is only available to a limited extent and may change during the transitioning process of energy grids.

In comparison, *resilience* is a holistic system property that encompasses the previously described measures and reflects the ability of a system to absorb the impact of hazardous events by reacting flexibly and adjusting itself to changing circumstances [132]. A resilient energy grid aims to remain operable during hazardous situations by making adjustments to its structure and operational processes, and is capable to recover positively from detrimental impacts [9].

A promising concept for improving energy grid resilience is the concept of microgrids [137], which can leverage local RESs and electric storage technologies [133, 218, 236] to operate autonomously (i.e., separated from the main grid). However, for microgrids to remain operable while being separated from the grid sufficient resources need to be available locally. Furthermore, these resources need to be accessible and controllable to support maintaining microgrid stability [235]. This requires an ICT-infrastructure, corresponding actuators and the collaboration of local stakeholders. While the technical advancements can be assumed to be widely deployed within future smart grids [74], their availability during interim stages of the energy grid transition may be limited. Therefore, concepts are required that can improve the resilience of energy grids during the transitioning process.

1.2 RESEARCH GOALS & OBJECTIVES OF THIS THESIS

This thesis aims to provide novel concepts and methods for increasing the resilience of smart grids during hazardous situations. The following research questions will be addressed in this thesis.

- *What concept is suitable for representing smart grids and the increasing number of heterogeneous stakeholders? How can such a concept and the strong integration of stakeholders be leveraged to facilitate the resilient operation of future energy grids?*
- *How can individual prosumers be empowered to participate in processes for mitigating hazardous situations to support the resilient operation of the grid.*
- *What mechanisms are able to handle the complex optimization problems emerging from energy grids that can dynamically adjust their structure and the need for controlling an increasing number of distributed resources and stakeholders.*
- *Given the changing roles of individual consumers in future energy grids, how can they effectively be educated about energy grid topics and motivated to participate actively in processes for maintaining the resilient operation of energy grids?*

HOLONIC SYSTEM MODELING AND SIMULATION. The ongoing transition of energy grids towards smart grids strongly affects the majority of participants in the grid. Moreover, emerging changes are difficult to predict and introduce various challenges. Among those are, the growing number of heterogeneous stakeholders, like prosumers and enterprises [74, 182] and the increasing number of distributed RESs. Smart grids are envisioned to address these challenges and be resilient in the presence of hazardous events, like failures and attacks [73]. Holonic system architectures are a promising concept for improving resilience of complex systems. Suppose energy grids can be structured as holons in a holarchy. In that case, heterogeneous stakeholders can be smoothly integrated into the energy grid, as holarchies feature the combination of different system architectures. Furthermore, stakeholders can be empowered to support the continuous operation of the energy grid locally, especially during hazardous situations. By integrating and grouping stakeholders as self-sustaining holons, holonic energy grids facilitate the autonomous operation of parts of the grid. Such capabilities allow holons to remain operable during situations when problems on higher layers in the grid occur and communication between the layers is disrupted [79, 161, 162]. Figure 1.1 visualizes an exemplary part of a distribution grid $h_{1,2}$ organized as autonomous holons $h_{1,1}$ and $h_{2,1}$ that are connected via the medium voltage grid (MV). Each of these holons encompasses numerous lower layer holons as houses $h_{1,0}$–$h_{6,0}$.

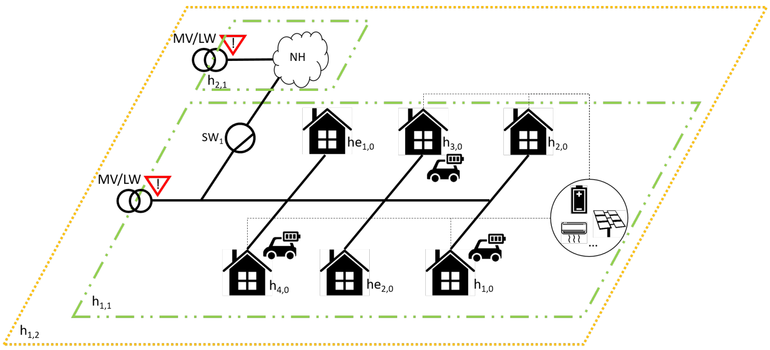

Figure 1.1: Conceptual representation of a three-layer holarchy with recursively aggregated holons.

The semi-formal holon model proposed in Chapter 3 enables a detailed representation of control-relevant data of the stakeholders within a holonic energy distribution grid. The main goal of the holonic model is to improve the resilience of energy grids by enhancing their capabilities for mitigating hazardous situations locally. Towards this end, the model facilitates the active integration of stakeholders on lower layers of the grid into processes for mitigating hazardous situations. Furthermore, the model allows prosumers to offer locally available resources as flexibilities (i.e., dynamically adjustable resources that can be leveraged to compensate changes in demand and supply). The combination of local flexibilities and the inherent structural reconfiguration capabilities of a holonic system structure improve the overall resilience of smart grids during hazardous situations.

HOLONIC GRID ADAPTION Once energy grids are structured as holarchies and advancements towards smart grids are made, the challenge of operating the holonic grid resiliently during hazardous situations becomes apparent. Numerous heterogeneous stakeholders and their resources need to be controlled to maintain a continuous supply with electricity. In particular, since many distributed resources are located on lower layers in the grid and their types can vary significantly (e.g., battery storage, RESs, appliances), the allocation of these resources to mitigate demand and supply deviations poses a complex challenge. The capability of holons to operate autonomously can exacerbate this challenge if parts of the grid that mainly comprise consumers get separated from producers of electricity. Furthermore, hazardous situations need to be mitigated quickly to maintain stability and prevent cascading consequences that can destabilize the grid further. Therefore, resources need to be controlled efficiently while adhering to strict time constraints.

Various scientific work investigates metaheuristic optimization approaches as a suitable mechanism for solving large-scale resource allocation problems, like the one that results from low-layer resource control; however, these approaches consider mundane operation situations with relaxed time constraints while mainly optimizing the operational costs of the grid and occurring losses of electricity [172, 205, 222, 241]. Thus, their applicability during hazardous situations in energy grids remains largely unresolved.

Chapter 4 investigates the suitability of metaheuristic optimization approaches for supporting the resilient operation of holonic energy grids during hazardous situations. Towards this end, the proposed approaches aim to mitigate situations that threaten the demand and supply balance of the holonic energy grid by leveraging local resources provided by prosumers and the inherent reconfiguration capabilities of holarchies. In this context, adapted metaheuristic optimization approaches are used to find near-optimal solutions to the *Holon Problem* quickly. This problem comprises two sub-problems, which need to be addressed together: the first problem requires the reconfiguration of the holonic energy grid (i.e., topological changes resulting from separating or joining parts of the grid) to adjust to the problem situation and to prevent further degradation; the second problem is based on the challenge of allocating local resources (flexibilities) within all holons of the holarchy to provide a stable supply of electricity. The metaheuristics solve the Holon Problem while considering the economic and ecological implications of using local flexibilities. Furthermore, the impact of reconfigurations and the use of local resources on the satisfaction of prosumers is taken into account. The algorithms are evaluated, and their ability to find near-optimal solutions while adhering to strict operational time constraints is investigated.

IMPROVED ENERGY GRID RESILIENCE THROUGH PROSUMER AWARENESS AND ACTION Energy grids have always been enormous socio-technical systems that provide millions of consumers with electricity. However, these consumers are, willingly or unwillingly, mostly unaware of the feats that need to be accomplished by energy grids in order to maintain a continuous supply of electricity. They are, in other words, *passive*. However, within holonic smart grids, consumers are envisioned to be strongly involved into operational processes and take on an increasingly responsible role for maintaining a continuous supply with electricity.

However, to facilitate this transition, a more aware, active set of consumers is needed. Increased information exchange between traditional producers (and infrastructure owners) and both prosumers and consumers is required to support operational processes in holonic smart grids. Finally, more acceptance of important facts is required: first, we are in a transition period in which the traditionally black box yet overwhelmingly stable grid is being slowly replaced by an increasingly distributed smart grid. Moreover, this grid may require local management and, in the interim, perhaps provides less overall stability. Second, stability is a function of how previously passive consumers behave in future smart grids. Finally, notions of resilience, instead of stability, are needed to help mitigate and manage (emerging) problem situations.

Chapter 5 explores some of these socio-technical challenges, why they matter and approaches to deal with them based on what is known and done in current energy grids. We highlight the importance of *knowledge* about the energy domain and discuss why people currently lack profound domain knowledge. We present the potential impact of increasingly aware and responsible people on energy grid resilience and discuss *monetary* and *non-monetary* incentivization methods for motivating people to become active. Finally, a prototypical serious-game approach is presented and evaluated as a means for educating people about energy grid topics.

THESIS GOALS This thesis addresses several challenges. First, the challenge of integrating heterogeneous stakeholders and their resources into smart grids and improving the resilient operation of the grid is tackled. Towards this end, a semi-formal model is proposed that supports the specification of energy grids based on the concept of holons. Holons provide capabilities that enable dynamic reconfiguration of the energy grid and allow integrating heterogeneous stakeholders to support the stable operation of the resulting holonic structure. Moreover, the concept of *flexibilities* is presented as a part of the holon model, which empowers prosumers to offer local resources for supporting the mitigation of demand and supply deviations. Second, metaheuristic optimization approaches are investigated for their use within problem mitigation processes of holonic energy grids. Towards this end, prominent metaheuristics are customized for solving the combined problem of reconfiguring holonic energy grids and allocating flexibilities for mitigating hazardous situations. Solutions to this combined problem can be used to mitigate the impact of demand

and supply deviations and improve the resilient operation of holonic energy grids. Finally, as energy grids are socio-technical systems, the thesis investigates the role of people in holonic energy grids. The thesis discusses challenges related to motivating and educating people about energy grid topics to increase their awareness and empower them to take on an increasingly responsible role in holonic energy grids. In this context, monetary and non-monetary mechanisms are discussed, which aim at motivating people to take on a more active role and participate within processes for operating holonic energy grids resiliently. Furthermore, a serious game prototype is presented, which aims to educate people about the feats that need to be accomplished in order to maintain a continuous supply of electricity and the challenges within smart grids.

1.3 THESIS STRUCTURE

The remainder of this thesis is structured as follows: Chapter 2 establishes the relevant background knowledge and presents related work about system architectures and the mode of operation of conventional energy grids. The chapter then continues with an introduction of the concept of holons as a paradigm for structuring energy grids and provides general information about smart grids. Finally, Chapter 2 elaborates on resilience as a holistic system property and introduces technical and social challenges, which are considered throughout this work. The chapter concludes with a brief introduction of established concepts for digital knowledge transfer.

Chapter 3 presents a semi-formal energy grid model based on the concept of holons. The model allows joining fine-grained information of heterogeneous stakeholders and energy grid infrastructure. Furthermore, flexibilities are introduced as a mechanism to empower stakeholders to offer local resources for mitigating severe demand and supply deviations during hazardous situations. Subsequently, the chapter discusses simulation tools for representing current energy grids and smart grids and elaborates on their suitability for representing holonic energy grids. To show the feasibility of the holonic model, the simulation environment HOLEG is presented, which allows modeling and simulating simplified energy grids based on a holonic system model. Finally, an online survey is conducted to assess the willingness of people to actively contribute to the resilient operation of holonic energy grids by offering local resources.

Chapter 4 shows the applicability of metaheuristic optimization approaches for improving the resilience of holonic energy grids by quickly finding solutions to complex multivariate optimization problems. In this context, metaheuristic optimization is applied to mitigate the effects of hazardous situations by solving the joint problem reorganizing the holonic energy grid and allocating flexibilities to mitigate demand and supply deviations. The results show that metaheuristics are well-suited to quickly find near-optimal solutions and corresponding resource allocations for mitigating demand and supply problems in holonic energy grids.

Chapter 5 discusses non-technical challenges for integrating heterogeneous stakeholders into holonic energy grids. The chapter highlights the importance of people for facilitating the transition of the energy grid towards a holonic smart grid and presents monetary and non-monetary mechanisms that aim to increase the motivation of people for participating in processes for problem mitigation. In the chapter, the importance of knowledge about energy grid topics is emphasized, which is crucial to increase the awareness of people and empower them to take on an increasingly active and responsible role within energy grids. As a means for educating people about energy grid topics, a serious game approach is presented and evaluated.

Chapter 6 summarizes this thesis and highlights the contributions and the insights gained from the research performed. The chapter concludes with an outlook on future research perspectives.

2 BACKGROUND AND RELATED WORK

This chapter introduces concepts, terminology, and important background knowledge related to energy grid system structures and resilience. These concepts will be used throughout the work for discussions on the state-of-the-art and the contributions made in each chapter of this thesis (i.e., from Chapter 3 to Chapter 5). This background chapter is structured as follows: Section 2.1 introduces prominent structural concepts for organizing complex systems and introduces the general concept of holarchies and holons. Section 2.2 explains important information about the structure of conventional energy grids and the corresponding mode of operation for electricity generation and distribution. Afterward, Section 2.3 presents the concept of resilience as a holistic system property, which is used throughout this work. The important aspects of resilience are highlighted for both the technical aspects of the grid and for the social domain. Relevant domains, where people influence the resilient operation of energy grids are highlighted in Section 2.4. Finally, prominent strategies that could be leveraged for educating people about energy grid topics are introduced in Section 2.5.

2.1 SYSTEM STRUCTURES

Energy grids are highly complex systems that may encompass millions of electronic components connected via an energy grid infrastructure. Several system structures are used for organizing complex systems. In the following, prominent system structures are briefly introduced.

2.1.1 *Hierarchy*

Hierarchies are among the most prominent system structures established in numerous organizations, like political and social organisms, enterprises, and not to the least complex technical systems like the Internet and almost all structures called “systems-of-systems”. The underlying idea is to order participants based on power, role, and/or importance within the system. We will allude to such conventional hierarchies as “mono-hierarchies”. Figure 2.1 shows an exemplary strict mono-hierarchy where each participant is associated to *at most* one higher-level participant and an *arbitrary* number of lower-level participants. The decision-making in such systems is organized as a top-down chain of commands (i.e., tasks are delegated by higher-level participants to lower-level ones). While the "flow" of decisions is usually top-down, information flow is usually bidirectional. For practical reasons, strict hierarchies may be complemented by additional relationships, like extended reporting duties within enterprises, groups, and task-forces.

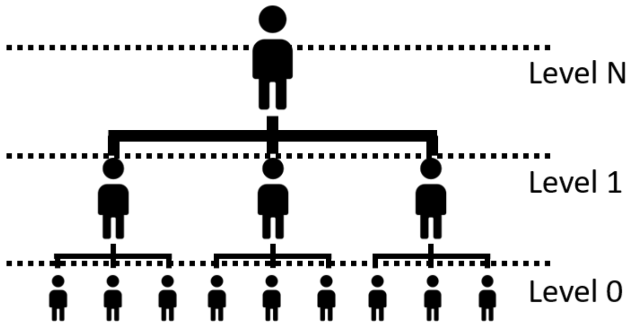

Figure 2.1: A conceptual representation of a strict mono-hierarchy, where participants are ordered based on the importance of their role for the system. Each participant is associated to at most one higher-level participant and an arbitrary number of lower-level ones.

2.1.2 *Heterarchy*

A heterarchy, in the strict sense, represents the opposite of a hierarchy. The precise definition varies between different disciplines, but the core idea of the concept states that all participants of the system are considered to be either equal (no hierarchical dependencies), or their order can change in multiple different ways (i.e., is not fixed as in a hierarchy). Note that a heterarchical concept does not imply the absence of other structural concepts. In particular, sub-systems of a heterarchy may still be organized as hierarchies; however, from the perspective of the whole system, the sub-systems are organized as a heterarchy. Obviously, the boundaries between hierarchies with practical extensions and heterarchies comprising hierarchical sub-structures are blurred. Figure 2.2 shows an exemplary heterarchy of four different sub-systems that are considered as equals.

2.1.3 *Holarchy*

Holarchies represent hybrid system structures that combine important traits of both hierarchical and heterarchical systems. A holarchy organizes a system by grouping participants as *holons*. Each holon is representing a *whole* in its own right (e.g., individual or subsystem) and, simultaneously, acts as *part* of a larger holon (e.g., parent company). From this organization emerges a system of holons that are existing on different layers in a holarchy, where holons within the same layer form a heterarchical system structure and their interdependen-

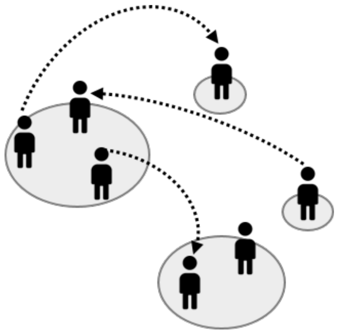

Figure 2.2: A conceptual representation of a heterarchical system structure, where participants can be individuals or entire sub-systems (gray) that are considered to be equal.

cies between different layers is based on hierarchical principles. Since encompassed systems can vary in their structure, the communication of holons may be coordinated by a central control entity (i.e., a participant in the holon responsible for managing the holon operation), but can also be distributed among the participants. Figure 2.3 shows a conceptual holarchy, where participants are organized in holons, which are, simultaneously, (autonomous) wholes and sub-parts of larger holons.

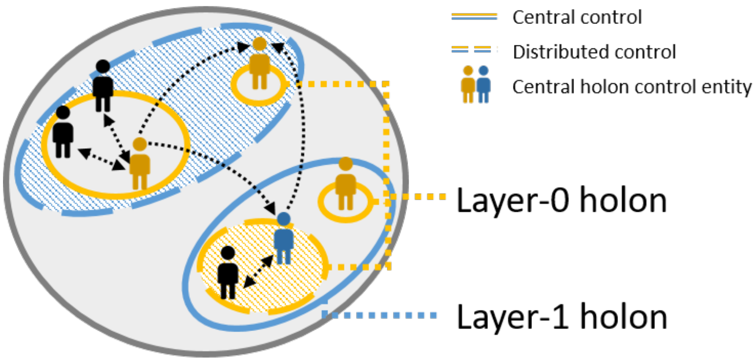

Figure 2.3: A conceptual representation of a holarchy, where hierarchical and heterarchical aspects are combined to organize participants as a holarchy. Holons are a part of larger holons, forming hierarchical dependencies between layers. Simultaneously, individual holons of the same layer in a holarchy are considered as equals. Holons can be centrally controlled by an entity which is part of the holon, or they can be organized in a distributed manner, where all participants are responsible for maintaining the operability of the holon.

HOLONS The concept of *holons* was first defined and explained by A. Koestler in 1967 [122]. He describes holons as entities that exist as subordinate entities in a hierarchical system (i.e., a *part* of the system) but are at the same time *whole* entities in their own right. This means that a holon itself represents an (intermediate) entity that follows intrinsic goals but simultaneously subordinates itself to goals pursued by higher layer entities. A prominent example of holons are living beings, like animals and humans. In this context, individual cells are considered as whole entities, which pursue their inherent tasks (goals) and interact with their environment. Simultaneously, cells are essential parts of higher-order systems, like organs, which in turn are a part of a whole body. While individual cells and organs are not capable of maintaining there operation autonomously, a whole animal or human can. However, despite the possibility of surviving autonomously, numerous positive benefits emerge from grouping them, e.g., animals living in a herd or flock. In this case, an animal can survive at his own, but benefit from emerging capabilities, like improved chances for finding food and increased safety. Figure 2.4 provides an exemplary representation for the concept of holons.

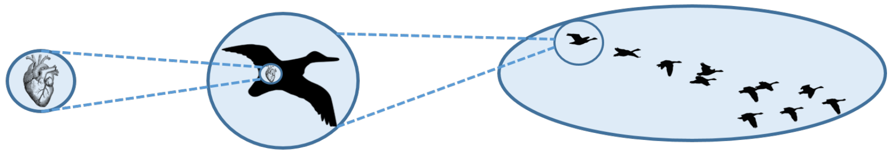

Figure 2.4: A conceptual representation of holons, where organs can be considered as a *whole* and a *part* of a larger system, like and body.

Holons represent self-encompassed systems that can form a recursively interlaced system structure comprising numerous layers. A system of organized interlaced holons is called a *holarchy*. While organizing a system as a holarchy combines the perks of heterarchical and hierarchical systems, holons themselves possess unique properties. Among the most prominent ones are *autonomy*, *Janus-faced*[1] and their *proclivity to recombine*.

A holon's ability to act autonomously and its Janus-faced nature allows it to sustain itself and maintain "its purpose", even if problems appear at higher layers of the holarchy (i.e., if the higher-layer holons do not delegate decisions to the lower layer system). In contrast, hierarchically structured systems may suffer from problems on higher levels, as the operation of sub-systems depends on control information delegated from higher levels. The recursive nature of holons within holarchies allows representing hierarchical interdependencies between holons. This property is beneficial for representing systems with various stakeholders, like the energy grid. Moreover, holarchies are considered to be dynamic systems that facilitate system adaptions to adjust to changing situations. Such adaptability is commonly realized by means of a well-defined set of operations: among the most

1 Derived from the two-faced image of the roman deity "Janus". One of the faces is directed upwards towards higher entities, and one is directed downwards to subordinate entities

prominent ones are *splitting* (separating entities in a holon to form more but smaller holons), *merging* (combining holons to form a new larger holon), and *changing affiliation* (reorganizing a holon that is encompassed in a higher layer holon to be contained in another holon of the higher layer) of holons. Consequently, the properties mentioned above provide holarchies with numerous advantages compared to hierarchical or fully decentralized system structures and mark them as suitable candidates for addressing the challenges that emerge from the transition of the energy grid towards a smart grid.

2.2 ENERGY GRID STRUCTURE

The energy grid is a large-scale infrastructure that requires a well-defined structure to be operated efficiently. In this section, the currently established hierarchical energy grid structure is explained. Subsequently, important changes emerging from the transition towards a smart grid are presented.

2.2.1 *Hierarchical Energy Grid*

Energy grids are mainly operated based on a centralized, top-down producer-to-consumer electricity production and dissemination process. In this process, electricity is produced by (1) large adjustable and often mainly fossil-/nuclear-fueled producers (e.g., coal and nuclear power plants). The production is adjusted depending on the current demand in the grid and available forecast information (e.g., day-ahead demand predictions). The majority of the producers are located in remote areas. Therefore, to transfer the generated electricity to the consumers, electricity is produced using high-voltage and is then (2) transferred via transmission lines over long distances. Once the electricity reaches the vicinity of consumers (e.g., cities, industrial areas), (3) transformers are used to step-down the voltage level of the electricity to make it usable for the equipment of the consumers (e.g., 230V for typical appliances in Germany). Note that this stepping-down process may appear multiple times during the transmission process. Furthermore, adjusting the voltage level depends on the requirements of the consumers located in the vicinity of the transformer (industrial appliances may require different voltage levels than residential appliances). Finally, (4) distribution lines transport the electricity to the (5) consumers, where it is consumed by electrical appliances. This process is visualized in a simplified example as Figure 2.5.

2.2.2 *Smart Grid*

The smart grid represents the next generation energy grid that is envisioned to improve conventional energy grids and is well-suited for

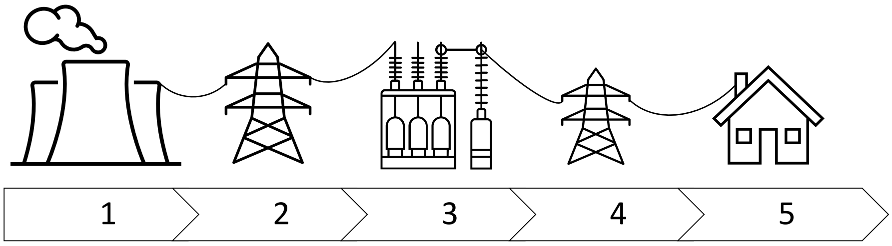

Figure 2.5: A conceptual representation of a hierarchical energy grid with a top-down producer-to-consumer electricity generation and distribution process. Few, large producers are responsible to supply numerous consumers with electricity.

the challenges that emerge from the ongoing energy transition [74]. Among the most prominent changes are: an increasing introduction of distributed RESs, which strongly affect the stable electricity production of the grid; the increasing integration of an ICT-infrastructure; and a growing number of heterogeneous stakeholders that participate in processes for ensuring the stable operation of the energy grid (e.g., sector coupling, private RESs). To understand the conceptual structure of smart grids and to identify gaps and interoperability potential for stakeholders and processes, the smart grid architectural model (shown in Figure 2.6) has been developed [35]. The model dis-

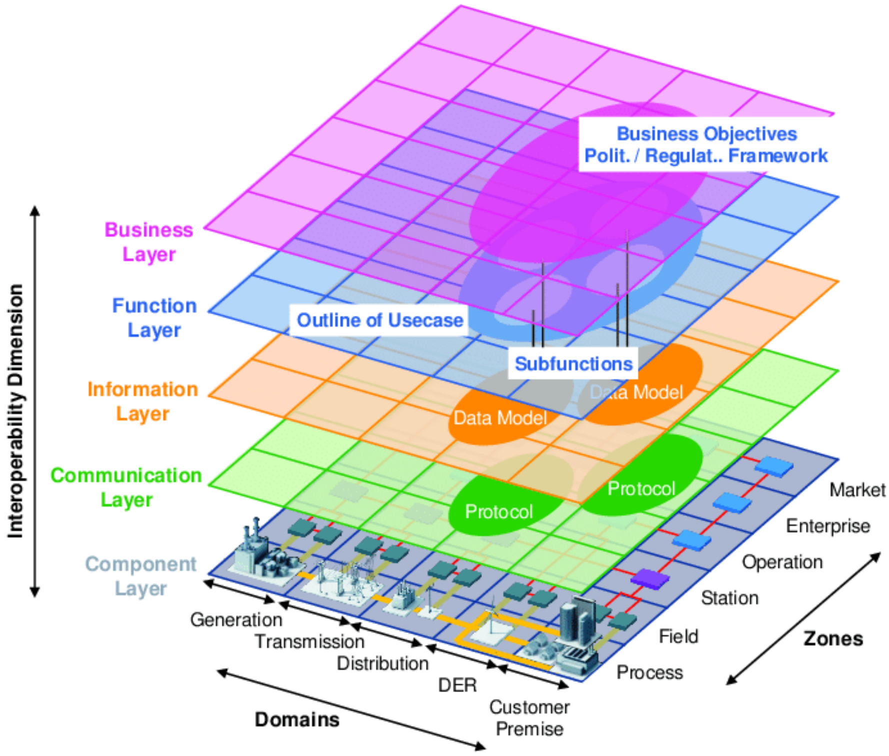

Figure 2.6: The smart grid architectural model represents a framework for structuring future smart grids including different stakeholders, operational zones and interoperability domains [35].

tinguishes between three main dimensions: first, the *domains* involved in the electricity delivery value chain; second, the *zones* consider data- and spatial-aggregation of aspects in power system management (e.g., data from different processes is aggregated in a field); third, the *interoperability dimension* comprises five aggregated layers that define numerous aspects of interoperability between stakeholders. The smart grid architectural model provides an abstract representation of important areas that are involved within a smart grid.

However, a detailed model that specifies how future smart grids can be defined to face the various upcoming challenges, is not available yet. Moreover, the transitioning process towards smart grids is, in many aspects, unpredictable and depends, for instance, on technological advancements, political decisions, and the acceptance of (necessary) changes by the people. Organizations like the National Institute of Standards and Technology are working deliberately on specifying numerous aspects required to establish such a model, but due to the tremendous complexity of this task, the process is slow [12]. Therefore, in this work we consider an interim state of the energy grid during the transitioning process. This means, that envisioned changes, like the strong integration of RESs, advanced metering infrastructure, actuators, and ICT are in progress and start effecting the energy grid, but they are not fully deployed throughout the entire grid. Consequently, fossil-fuelled producers are assumed to be still present, parts of the grid may lack ICT, and numerous "simple" consumers remain without means of local electricity production.

2.3 RESILIENCE

The word resilience originated from the Latin word "resiliere", which means to "bounce back". The word is commonly used to describe the ability of an entity or system to return to normal operation, after the occurrence of a disruption. Numerous definitions of resilience have been provided and many of them describe resilience as a system property that is strongly related to established measures, like, for example, robustness, fault-tolerance, and availability [108]. In this section, the general concept of resilience is introduced and details are provided on how the property is used within this work. Afterward, the need for resilience within future energy grids is motivated.

2.3.1 *Resilience - a Holistic System Property*

Resilience was first defined as an abstract property of ecological systems concerned with the capabilities of systems to cope with changes and their behavior in the presence of disturbances. More precisely, resilience represents a property that describes the persistence of a system and its ability to maintain its characteristic functionalities while facing changes [105]. This definition was later extended by Gunderson *et al.* [93] to reflect a certain degree of endurance in the face of disturbances. This endurance specifies that a system needs to be capable of maintaining its current state despite a disturbance until it changes to adjust. Further extensions extend the resilient definition to express capabilities for conducting *self-healing* during the disturbance-phase [232], which allows a system to make adjustments to compensate for some effects that emerge from the occurring disturbance. Moreover, Kendra & Wachtendorf [116] extend the notion of resilience to include a *recovery*-process after the disturbing situation. The ability to recover from a disturbance denotes a system's ability to go back to a similar or better state compared to its state prior to the disturbance. In other words, resilient systems are capable of repairing the damage caused by disturbances. They may even improve themselves in the process and reach a state that allows them to be better prepared for upcoming events.

2.3.1.1 *Resilience in Energy Grids*

One of the main goals of energy grid is to provide a stable supply with electricity for its participants. Resilience represents a complex system property that aims to establish system stability as a part of its comprising properties. While stability indicates the speed of reestablishing operational equilibria *after* a disturbance occurred [132], resilience is concerned with multiple aspects in different phases of a disturbance. In these phases, resilience is concerned with aspects that impact the ability of a system to remain functional [185]. Commonly, resilience is used in the context of four phases that describe a period of time relative to a severe disturbance. The naming of these phases is not clearly specified within the literature, therefore, we specify them within this work as *anticipation*, *adaption*, *mitigation*, and *recovery*. The different phases are explained in the following in more detail and Figure 2.7 presents a corresponding example:

- *Anticipation*. The anticipation phase is concerned with events and corresponding measures taking place *prior* to the occurrence of a disturbance. This phase is the default phase since a system aims to identify and predict events that may lead to disturbances and threaten the stability of the system. In this phase preemptive measures are used to provide a degree of *robustness* in the presence of hazardous events and potential disturbances [153]. More precisely, robustness specifies the degree of resistance a system can provide against a disturbance without losing stability. For energy grids, the most prevalent preemptive measures related to its core-functionalities are well-designed and accurate forecast mechanisms and the provision of operating reserve capacity.

- *Adaption*. The adaption phase represents the time interval between the detection/anticipation of an event that may lead to a disturbance and the moment the disturbance takes effect (e.g., a weather forecast announces a reduction of electricity production of RESs). The border between the adaption phase and the anticipation phase can be blurry, as adaptions may change with new information about events and disturbances. A resilient system is capable of adapting itself to endure hazardous events and prepare for upcoming disturbances while maintaining its core functionalities [93]. The adaption of a system comprises measures to increase the robustness similar to the anticipation phase, but is also concerned with the subsequent mitigation phase. For instance, based on information provided by weather forecasts producers may maintain additional reserve capacity. This can increase the robustness of the energy grid by increasing its capability to make adjustments to the production of electricity quickly.

  Additionally, adaptions can be made which already consider the further destabilization of the energy grid. Among the actions are, for instance, information dissemination to control authorities and emergency response organizations, who can prepare themselves for the upcoming event.

- *Mitigation*. The mitigation phase encompasses flexible actions and behavior, which aims to mitigate the impact of the disturbance on the core-functionalities of the system. At this point, preventive measures are exhausted, and the system may start to lose stability; however, resilient systems are capable of undergoing a certain amount of dynamic changes and adaptions for mitigating the problem while maintaining core-functionalities [232]. For energy grids, established mitigation mechanisms are, for instance, controlled load-shedding and rolling blackouts. These measures aim to maintain a continuous supply with electricity for as many consumers as possible, while balancing the demand and supply in the grid [9]. These severe mitigation processes may change the operational boundaries of the system; therefore, continuous situation assessment and reaction to changes are essential processes for problem mitigation [106].

- *Recovery*. Recovery processes take place after the disturbance. Resilient systems should return to a stable mode of operation after active mitigation of the preceding disturbance is no longer required [116]. These recovery processes do not necessarily lead to the same state in which the system was prior to the disturbance but aim at returning the system to a stable state, where the operation can be conducted normally. For the energy grid this may be the partial operation of islanded[2] sub-grids, which maintain a stable electricity supply and can be reconnected to the main grid after some time. Another example of recovery processes is concerned with providing electricity to parts of the energy grid that were previously shut down (black-start) and their re-connection to the main grid.

Throughout these different phases, resilience represents the ability of the grid to maintain its capability to provide a continuous supply of electricity. We want to emphasize that such continuous supply can be achieved in a "reduced" state of operation, which may represent a different equilibrium compared to the situation prior to the disturbance. Therefore, one important property of a resilient system is a controlled change between operational states (e.g., controlled reduction of service quality until a stable state is achieved). This controlled change may happen during all phases presented above.

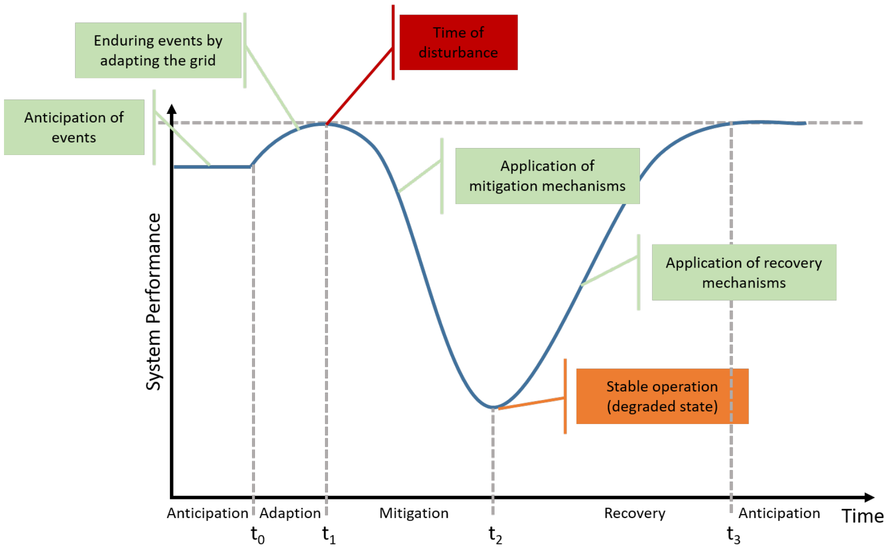

Figure 2.7: An exemplary case showing the system performance during the four presented phases. During the *anticipation* phase (until t_0) the grid aims to predict events that may cause disturbances. To prepare for the events and potential disturbances, the grid adjusts itself during the *adaption phase* (until t_1). Once a disturbance occurs, the grid deploys mechanism to reduce the impact of the disturbance during the *mitigation* phase (until t_2). Finally, after the mitigation of the disturbance is over, the grid aims to fix the damage caused by the disturbance during the *recovery* phase (until t_3). Afterward, the anticipation phase starts again.

2.3.1.2 *Stability in Energy Grids*

Stability represents a system's capability to return to an equilibrium state after being affected by a temporal disturbance. For defining the

2 A (sub-)grid that operates in an islanded mode is separated from the main grid and relies on local resources to sustain itself

stability of conventional energy grids, Kundur *et al.* [132] provide the following definition.

> *"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact"*

This definition specifies an energy grid as stable if it is capable of reestablishing an operational equilibrium (or rather, one of potentially many equilibria) after smaller disturbances. This means that the system is not strongly oscillating in the process of stabilizing itself but converges quickly towards a stable state.

Conventional energy grids aim to achieve stability by preventing severe disturbances from happening in the first place, e.g., by providing strong perimeter security for important components in the grid, sophisticated forecast mechanisms to support the planning of electricity production, and redundancy (e.g., N-1 criterion). Once a disturbance occurs, conventional energy grids aim to mitigate the effects on the stability of the grid by applying different techniques, which are explained next.

OPERATING RESERVE Providing backup power generation or reducing production/consumption is one of the most common methods for maintaining the balance between the demand and supply in energy grids. This *operating reserve* encompasses power sources responsible for compensating situations of high demand or sudden drops in power production [47] but can also be used to reduce the amount of provided power. After an *inertial response*, where small balance deviations are automatically compensated by the inertia of the (heavy) rotating masses of generators in conventional energy grids, active mitigation methods are required. These active methods use a part of the power generation capacity of producers, which is kept in a "stand-by" state and can be actively used to improve the balance between demand and supply by increasing or decreasing the provided power. The European Network of Transmission System Operators for Electricity (ENTSO-E) distinguishes mainly between three different methods for addressing this imbalance, namely *primary*, *secondary* and *tertiary* control [71].

- *Primary Control*. Primary control mechanisms are actively increasing or decreasing the electricity provided by generators actively involved in the primary frequency control of energy grids. These mechanisms need to take effect within the first 30 seconds after being activated. The whole grid is responsible for offering primary control capacity.

- *Secondary Control*. The secondary control will take over the frequency balancing process between 15 to 30 seconds after the primary control started and the situation is not resolved. This process can leverage resources that require more time until they are available to support the balancing process. Typical resources for secondary control are hydro-electric or gas power plants [164]. After secondary control takes over, primary control power is supposed to be made available again. In contrast to primary control, only the area affected by the frequency disturbance is participating in the secondary control operation.

- *Tertiary Control*. This frequency control mechanism—often also referred to as minute-reserve—is based on resources that are required to be available 10–15 minutes after the frequency deviation was detected. As the time limit for this approach is relatively long, many resources can be made available for both production and consumption. If these resources do not suffice to restore frequency balance, additional measures need to be involved, such as *controlled load-shedding*, *rolling blackouts*, or the deactivation of producers.

INTERRUPTIBLE LOAD MANAGEMENT This problem mitigation method represents a severe frequency stabilization method that is deployed when operating reserves are not sufficient to resolve the demand and supply imbalance in the grid [181]. Towards this end, the load of consumers in the energy grid is made interruptible (e.g., by installing demand limiters), such that control entities, like transmission system operators can issue commands to reduce the load. Upon receiving such a command, the demand limiters reliably reduce the load by an amount that has been specified in the corresponding contract. After the problem situation has been resolved, control entities decide when the load can be connected again.

ROLLING BLACKOUTS Rolling blackouts represent a more severe form of the previously described interruptible load management. In contrast to reducing the load in the grid by relying on contractually guaranteed resources, rolling blackouts lead to blackouts within changing parts of the grid. Towards this end, the grid is logically separated into parts that represent loads of equal magnitude. Afterward, one or more of these parts are separated from the grid until the balance between demand and supply is restored. The separated parts experience a blackout situation for a specified amount of time until they are reconnected to the main grid, and other parts of the grid are separated in turn [19]. This separation process is then conducted in a round-robin based manner (rolling blackouts). With this strategy, control entities aim to maintain fairness based on equal supply time for all entities within the grid during hazardous situations.

INCENTIVE-BASED CONTROL Incentive-based approaches aim at encouraging consumers to adapt and improve their local use of electricity by incentivizing compliant behavior [39, 158]. Such mechanisms are used by control entities in the grid to alleviate their task of operating the grid, e.g., by reducing peak-consumption, smoothing consumption valleys, and reducing the base load in the grid [134, 209]. However, the actions required on the consumer side may have negative consequences for the consumers, since appliances may not work properly, their operation may be delayed such that people have to adjust their daily routines, or they do not function at all [189].

In the conventional grid, monetary compensation is the main incentive as this effectively reduces the overall expenses of consumers. Among currently available incentive-based strategies are, *variable time-of-use prices* (i.e., varying prices for electricity consumption within certain periods of the day), *critical peak pricing* (i.e., high time-of-use prices at so-called peak-times during a day, when the electricity demand is exceptionally high) and *real-time pricing* (i.e., repetitively informing consumers about changing electricity prices in such a way that they can adapt their behavior) [4, 21, 101]. These strategies try to encourage consumers to change their consumption behavior in two ways: firstly, consumers are provided with information that allows them to change their consumption behavior to reduce their electricity bill (e.g., information about points in time when prices are low); secondly, consumers are charged with higher prices for consuming electricity during specific times of the day. As a consequence, people are expected to avoid consuming large amounts of electricity during these times. However, these approaches are not very successful (e.g., only 6% peak-load reduction for the US in 2018 [48]). One of the reasons stated for this lack of success is that consumers strongly appreciate the uninterrupted service of their electrical appliances. Moreover, Centolella *et al.* [36] found that consumers are willing to pay between $0.73\$$ and $2.51\$$ per kWh to avoid interruptions, which is an order of magnitude higher compared to the regular electricity prices.

DIRECT LOAD CONTROL Direct load control approaches do not encourage local decisions towards changing consumption behavior but directly affect the demand of consumers. A prominent technique is based on remotely controllable loads at the consumer sites [166, 187]. Towards this end, loads are made controllable via ICT and a contract between the consumer that hosts such devices and a control entity (e.g., energy provider) is established. This contract allows control entities to shed specific consumer loads remotely, if the overall demand in the grid needs to be reduced [38]. Typical appliances that are used for direct load control are water heaters and air conditioning devices [67, 234]. Consumers that participate in direct load control schemes are usually reimbursed financially. One major drawback of direct load control is the high probability of reducing satisfaction of users that rely on the correct functionality of those devices. For instance, water-heaters or air conditioning may not work as expected, which may cause undesired situations due to hot temperatures or the absence of hot water.

HOME ENERGY MANAGEMENT SYSTEMS & ENERGY CONSUMPTION SCHEDULER Improving the local management of electricity consumption supports economic and ecological goals for both consumers and control authorities. To maximize the effectiveness of demand response action on the side of consumers and to avoid extensive effort for managing electricity consumption manually, home energy management systems (HEMSs) and energy consumption schedulers are tools and mechanisms that support the local energy management [6, 112, 243]. These mechanisms optimize the local energy consumption and production by scheduling devices in such a way that both consumers and control authorities benefit in the process (e.g., based on real-time pricing some appliances can be shifted to reduce the overall demand during peak-hours and, simultaneously, lower the electricity bill of the consumer) [156, 195, 199, 237]. Consequently, the amount of electricity that needs to be provided during these times decreases, which alleviates the burden on control authorities. As a negative consequence, consumers may need to adapt to change how they interact with their devices, but such changes are compensated by a lowered electricity bill. Furthermore, these systems can provide auxiliary services, like analysis and visualization of relevant energy-related information [167].

2.3.2 *The Need for Resilience in Smart Grids*

The continuous operation of energy grids is crucial for our modern society since the loss of electricity can lead to severe financial losses (e.g., estimated average costs for a blackout in Germany is 430M € per hour [91]) and can have devastating consequences for the affected people [174]. As such severe impairments of the energy grids can result from both safety- and security-related events, energy grids are required to be operated in a safe and secure manner [33, 165, 168, 191, 196, 207]. Some of the challenges for operating the grid safely and securely are exacerbated by the ongoing transition of energy grids towards smart grids. Consequently, since harmful events cannot be fully prevented, resilient energy grids are required to mitigate both safety- and security-related threats to the system. In the following, meaningful changes that impact the safe and secure operation of energy grids are explained, and the necessity for resilience is emphasized.

SAFETY THREATS In general, safety is concerned with preventing (accidental) harm caused by the energy grid. Such harm involves damage to the environment as well as damage to individuals participating in the energy grid. Safety-critical is a term often used to define properties and mechanisms that are essential for enabling (or guaranteeing) the safe operation of the energy grid [31, 177]. Smart grids introduce several new challenges for operating an energy grid safely:

- *Reduced Perimeter Protection*. With an increasing distribution of electricity producers throughout the grid, the overall safety of these components—formerly provided by the perimeter protection measures at large production facilities (e.g., access control, encapsulated environment that was highly specialized for maintaining safety and security regulations)—is drastically reduced. The installation of sufficient protective measures at all distributed locations may not be economically viable (many small scale producers) or cannot be conducted at all (producers located on private property).

- *Increasing number of Stakeholders*. An increasing number of stakeholders participate in processes of energy grid operation, like, for example, enterprises that provide operating reserve capacity, organizations offering sector-coupling services[3], but also private small-scale prosumers are increasingly present. Compared to the conventional grid, where production is monitored and maintained by well-trained experts mostly within large power plants, the different stakeholders do not necessarily have a strong power domain knowledge and will likely not employ additional personnel that supports their involvement. Consequently, mundane operation and especially the handling of safety and security issues may become increasingly challenging, which poses a threat to the overall stable operation of the energy grid.

SECURITY THREATS Security is concerned with the ability of the grid to handle malicious impacts on the system. The ability of a system to withstand such impacts is mostly referred to as robustness and reliability. The causes for occurring impacts on the energy grid operation can result from internal and external events [31, 142]. For future grids, many of the aspects that threaten the safety of the grid simultaneously pose a challenge for system security. For example, the reduced perimeter protection and the increasing number of stakeholders does not only increase failure probabilities but can also be exploited by adversaries for sabotage attempts and system infiltration. In the following, we highlight two important aspects, which can exacerbate the security-related threats within energy grids:

3 Sector coupling refers to a stronger connection between energy consuming technologies, like heating, cooling, and public transport and the operational processes of energy grids

- *Cyber-physical interdependencies*. The envisioned strong coupling of the energy grid with an ICT-infrastructure introduces an entirely new attack vector into the grid. The conventional grid is mainly based on electrical and mechanical components, and ICT-based systems, like supervisory control and data acquisition systems, are scarce and are mainly operated isolated and at the central control points within the grid. In comparison, the envisioned advanced metering infrastructure of smart grids and the corresponding automated control and ICT-infrastructure within all parts of the energy grid require long-range data exchange over the Internet or similar technologies. As a consequence, the risk of potential cyber-attacks is increased since access points to this networks are distributed throughout the grid. Furthermore, the tight coupling of these digital systems to the underlying physical grid challenges system security as attackers can use this digital environment to launch attacks affecting physical components [44, 191].

- *Growing system complexity*. The increasing distribution of electricity production and the involvement of more and more stakeholders increases the complexity of energy grids. Controlling these systems in a safe and secure manner becomes increasingly challenging, as more entities need to be secured and coordinated in the case of problem situations.

The transition of energy grids towards smart grids exacerbates existing challenges for their safety and security. For example, new attack vectors are introduced by the integration ICT-infrastructure and a growing number of heterogeneous stakeholders that are strongly integrated into operational processes. Consequently, the probability of failures and attacks on the grid increases. Additionally, conventional measures to guarantee the stable operation by improving the robustness, reliability, and availability of energy grids are difficult to apply within smart grids, or may not be applicable at all. Resilience takes into account that failures and attacks will happen and may cause disruptions that will affect the operational processes in the grid. However, resilient energy grids are capable of facing such events by adjusting themselves and, if required, gradually decrease their performance to remain operable and prevent more severe consequences, like blackouts. Within this thesis, we consider resilience as a crucial system property that can be improved by different means within different phases, like anticipation, adaption, mitigation, and recovery. Our contributions support the resilience of energy grids, especially during interim stages of the transitioning process, within the anticipation, adaption, and mitigation phase. The recovery phase remains an important aspect of resilient energy grids, but exceeds the scope of this thesis.

2.4 THE IMPACT OF PEOPLE ON THE RESILIENCE OF ENERGY GRIDS

Energy grids are complex socio-technical systems whose seamless operation depends on both technical and social aspects. In this section, we elaborate on how these aspects are jointly involved in operational processes of energy grids. First, the involvement of people within processes for supporting the stable operation of conventional energy grids is explained and important assumptions about this involvement are presented. Afterward, important changes of the involvement of people in the context of future smart grids are elaborated.

2.4.1 *People Involvement in Conventional Energy Grids*

While the energy grid appears to be an overwhelmingly technical system, the involvement of people in the operation of energy grids is ubiquitous. In this work, two types of involved people are distinguished, namely ones that *actively* contribute to the resilient operation of energy grids and ones that participate *passively*.

ACTIVE PARTICIPANTS. Numerous processes for operating energy grids are only partially automated and require manual interaction by people. Commonly, these people are expert personnel that conduct the required actions as part of their jobs within the energy domain. In general, people are involved in numerous processes along the whole value chain for electricity production, transmission, and distribution, where they are responsible, for instance, for monitoring, controlling, and problem handling. People involved in the aforementioned processes are directly supporting the resilient operation of energy grids and represent an essential part of the resilience of the overall system. Therefore, they are considered as *active* participants.

PASSIVE PARTICIPANTS The second group of people involved in operational processes of energy grids is *passive* consumers. This group of people is willingly or unwillingly mostly unaware of the feats that need to be accomplished to maintain a continuous supply of electricity and, for them, electricity appears as an "invisible" resource, which can be freely used but is mostly not noticed actively [204]. This largely oblivious interaction with the energy grid can mainly be attributed to the mode of operation of the conventional grid, where producers are responsible for adjusting production to meet the demand of consumers at any point in time. Nonetheless, electricity consumption is required for maintaining a stable grid since electricity is only able to flow if there is a balance between demand and supply. In the majority of energy grids, a continuous amount of consumption exists, which depends, for instance, on industrial processes (e.g., smelting), street lights, and some house appliances (e.g., fridges). This so-called *base-load* represents the minimum amount of consumption that is present during a certain period of time [229]. Changes to the demand then result from the normal operational behavior of participants within the grid. However, since these consumers are mostly not aware of their impact on the energy grid, they are considered as passive.

PARTICIPATION OF CONSUMERS IN CONVENTIONAL ENERGY GRIDS The stability of energy grids strongly relies on their capability to adjust production to an ever-changing demand. However, it has been recognized that some benefits result from controlling the demand-side within energy grids [219]. However, the available actions for consumers that allow them to have an impact on the resilience of the conventional grid are limited. Among the most prominent actions are:

- *Incentive-based control schemes*. These schemes use incentives to motivate consumers to adjust their electricity consumption based on the current situation of the energy grid. These changes aim to alleviate the burden of control entities to operate the energy grid resiliently. Among the most prominent examples for such approaches are *real-time pricing*, *time-of-use rates* and *critical peak pricing*, where the benefit for the consumer lies in reducing their electricity bill by adjusting the time when electricity is consumed. [76]. This behavior, simultaneously, alleviates the tasks of control entities by reducing the need for additional production during peak times.

- *Direct load control schemes*. Direct load control approaches are used for quickly mitigating severe demand and supply problems in the energy grid. The concept is based on disconnecting loads from the grid to reduce the overall demand, while the disconnected load experiences a blackout. This can be done by remotely controlling specific devices or notifying consumers to reduce their current demand. Small-scale consumers, like private households, are mainly not considered for such approaches, as the impact of their local resources in conventional grids is negligible. However, for industry and large-scale consumers, the scheme is considered to be more appropriate [231].

- *Prosumers*. Prosumers are consumers of electricity that are, simultaneously, capable of producing and storing electricity locally using, for instance, RESs and battery storage units [34]. This allows prosumers to supply their own demand using locally produced electricity and, if available, excess electricity can be stored for later use or can be used to support the electricity production of the energy grid as a whole. The benefit for the prosumers lies in reducing her electricity bill or even profit from selling excess electricity to the grid.

It is rather obvious that the two schemes do not represent mechanisms for *active* consumer participation to support the resilience of energy grids. For both management schemes, the consumers remains largely unaware of the situation of the grid and their own contribution to improve the overall situation. For instance, consumers that reduce their consumption based on information provided by incentive-based schemes mainly do so to avoid high electricity bills. Similarly, participants within direct load control schemes do not know how much their action contributes to the resilience of the grid.
The transition of consumers towards prosumers may passively affect operational processes in the energy grid, since local production can reduce the amount of electricity prosumers require from the grid. However, prosumers can be considered as *active* participants in the grid, where their degree of activeness depends on their choice for leveraging the locally generated electricity [94]. For instance, they can actively decide to use excess electricity to support the grid or store it locally.

OPTIONALITY OF INVOLVEMENT We want to stress that the *active* aspect of the aforementioned consumer participation lies mostly in the willingness of people to support and participate actively in processes for operating the energy grid resiliently. The presented schemes are incentivized by responsible authorities, like energy providers or the government, and people are free to decide on their participation within these schemes. Moreover, they are often provided with information about the implications their participation can have on their own situation, like changes of their electricity bill, or necessary investments for purchasing technical equipment. Similarly, the decision of consumers to conduct the necessary technical installation to become a prosumer is assumed to be a free choice of the consumer.

However, peoples' ability to make such decisions freely strongly depends on the social system in which they are living, as well as the associated norms. Theoretically, adherence to the mechanisms and technical changes presented above could be enforced (e.g., mandatory installation of remotely controllable electrical devices). Furthermore, such adherence could be made legally pursuable by establishing corresponding laws and regulations even without the consent of consumers.

Within this work we assume that people are part of democratic social system, such as liberal democracies. While this does not prevent potential changes in the energy grid from happening, which some people may be reluctant to accept, the decision towards these changes is based on a democratic process. Consequently, the decision should reflect the opinion of the majority of the people. Alternative social systems may differ in numerous aspects, like the assumptions and challenges stated in this work; however, the investigation of the thesis contributions in the context of these alternative systems is out of scope of this work.

WILLINGNESS FOR PARTICIPATION The willingness of consumers for participating in processes for supporting the energy grid is challenged in various ways. For instance, the aforementioned approaches of time-based electricity prices and direct load control either require consumers to change their behavior regarding the consumption of electricity or to allow remote access to some of their appliances. To change their electricity consumption consumers are required to actively think about the fact how they use electricity, and how to adjust their daily routines to improve their situation. The majority of people is reluctant to adjust such routines, especially if the emerging benefits are not apparent or incentivization is insufficient [90].

Other challenges that impair the willingness of people to participate emerge from allowing remote access and potential deactivation of appliances within their homes. People are hesitant to surrender control of their local appliances to private companies or their energy provider [3]. The required ICT-infrastructure exacerbates peoples' concerns by the possibility of malicious third-parties accessing private information [119].

2.4.2 *Increased Involvement of People in Smart Grids*

The transition of energy grids towards smart grids poses a tremendous task that requires technical changes but also requires people within various stages of the process. In the following, important aspects are highlighted, where people can be increasingly involved in smart grids.

ENABLING CHANGE People can have an impact on the majority of changes that are going on within our modern society. For instance, the plan of Germany to step-wise reduce the operation of nuclear and coal-based power plants [52, 64] was developed by people, then supported by political fractions, which were elected by the people within the country. Therefore, we can assume that the goals of this operation were important goals for the general population of Germany at the time of decision-making.
For the transition process towards smart grids, the need for the support of changes by the people may become increasingly important. Changes may affect numerous domains, like private households, public places and enterprises. For instance, establishing a comprehensive ICT-infrastructure requires the installation of hardware and software components within these domains. However, the decision-making within these domains varies significantly. Towards this end, the support of people is crucial either by actively supporting changes in their

personal domain (e.g., by transitioning towards a prosumer), or to accept the necessity of the changes and support processes that work towards their realization (e.g., by supporting political parties).

INCREASINGLY ACTIVE PARTICIPATION IN OPERATIONAL PROCESSES In addition to supporting and enabling changes within energy grids, these changes can provide people with capabilities for actively contributing to the operational processes within future smart grids. One of the key-enablers for this increasingly active participation is a comprehensive ICT-infrastructure that strongly connects consumer/prosumers and control authorities, like energy providers and system operators [74]. However, the transition towards smart grids is a step-wise process and technological advancements may also differ between individuals in the grid (e.g., some people may not want to install ICT in their homes, others are early-adopters of technological changes). Nonetheless, numerous possibilities for a more active participation of people can already emerge from the intermediate phases, some of which are listed in the following:

- *Information and data*. Increasingly smart devices and their interconnection using an ICT-infrastructure allows displaying and sharing a variety of information, both locally and globally. For instance, local consumption-related data can be used as a reminder for people to adjust their consumption behavior [27, 48, 75]. The effectiveness of such information dissemination can be improved by combining them with various incentive mechanisms [7, 208]. Information about incentives could also be provided and shared via the ICT-infrastructure.

- *Local Control*.The digitization of homes and the introduction of an increasing number of smart devices and appliances is ongoing[4]. Controlling numerous local appliances can be strongly supported by ICT to improve their energy-efficient operation [97, 243]. Furthermore, by supporting local control of appliances people may contribute to operational processes in the energy grid. For instance, by supporting the mitigation of demand and supply deviations [38, 46].

The energy grid has always been a socio-technical system in which people are an essential component. Some people are actively involved in processes for maintaining the continuous operation of the grid, like expert personnel conducting control and repair operations. Others, are mainly passive consumers which are less involved in direct grid control but are an important driver of developments in the grid to adjust to changing requirements and situations. The ongoing change of consumers towards prosumers and the increasing integration of ICT

4 https://de.statista.com/infografik/3105/anzahl-der-smart-home-haushalte-in-deutschland/

within the energy grid introduces several challenges but also provides opportunities for increasing the active involvement of people. Within this thesis, we focus on opportunities for a stronger consumer/prosumer integration in processes for maintaining the operation of the grid. We assume that people are crucial to leverage local resources, like RES, electric vehicles, and battery storage units effectively and that the majority of them is, in general, willing to support the energy grid, especially during hazardous situations.

2.5 STRATEGIES FOR KNOWLEDGE TRANSFER

In this section, prominent strategies for computer-based knowledge transfer are presented. First, the concept of serious games is introduced. Second, related concepts of E-learning and edutainment are presented.

2.5.0.1 *Serious Games*

The first definition of the term "serious game" close to the meaning its current use was provided by Abt [2]. In his much-cited work, he described serious games—which were not limited to computer-based education at that time—as follows:

> *"We are concerned with serious games in the sense that these games have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement. This does not mean that serious games are not, or should not be, entertaining."*

From this quote, it can be concluded that—according to Abt—the primary goal of serious games is educating people, in comparison to conventional games (e.g., video games) that are mainly developed for entertainment purposes. However, the definition of serious games remains ambiguous which leaves room for interpretation. For instance, the authors of [152] share the view of Abt and consider education as the primary component of a serious game. In contrast, Zyda [244] emphasizes that education aspects are crucial, but they must subordinate themselves to the entertainment aspects. Furthermore, he points out that serious games are not limited to education but could also be applied within contexts like training, simulation, healthcare, and strategic communication [150].

SERIOUS GAMING IN ENERGY GRIDS The concept of serious games is already applied to convey knowledge about energy grid topics. For instance, *"Balance"* [110] is a mobile puzzle game, where players solve issues about connecting part of the energy grid infrastructure and maintain their operation by adjusting the electricity production of power plants. Another example is *"Power the Grid"* [41], which is a real-time strategy game where the player needs to solve numerous challenges, ranging from maintaining the balance between demand and supply to organizing the resource consumption of power plants. The main goal of the game is to transition from a fossil-fueled energy production towards one that is based on RESs. A comparable approach is followed by the game *Energetika* [85], where the player is in charge of conducting the energy transition for an existing energy grid. The focus of the game lies on ecological and political decision-making to achieve the energy transition.

2.5.0.2 *E-learning & Edutainment*

Several definitions exist that describe electronic learning (E-learning), ranging from "learning supported by digital *electronic* tools and media" [138] to "[...] education delivered through electronic means" [135]. Common application scenarios are online seminars or virtual classes [150]. Here, electronic means can either replace or support conventional means of education. Since serious games can be such a means to support the education of people, we consider them as a subordinated category of E-learning.

Edutainment is a portmanteau of *education* and *entertainment*, and describes the general concept of learning, which is, simultaneously, entertaining. Although edutainment is predominantly used in combination with games in a computer-based context, the term can also refer to television programms and software for text and image generation, for example [80]. In contrast to serious games, edutainment often has a strong separation between learning and entertainment content (e.g. the entertaining part is seen as a reward for learning), whereas in serious games the aim is to overlap both components. As a result, serious games show characteristics that are similar to commercial computer games (e.g., a high degree of motivation), but which are rarely found in edutainment titles due to the strong emphasis on the learning component.

2.6 SUMMARY

The chapter introduced relevant definitions, basic terminology, and concepts, as well as important assumptions. This information is essential for the motivation of this thesis and to understand the contributions within the individual chapters.

An overview of common structures for complex systems was provided and corresponding important properties and demarcations were explained. The detailed structures are hierarchies, heterarchies, and holarchies. Next, this chapter provided fundamental information about energy grids, electricity production, and the electricity dissemination process within conventional energy grids. Afterward, a high-level description of smart grids is presented. Smart grids and preceding stages within the transitioning process represent the environment for contributions within later chapters of this thesis. Following the introduction of energy grids, the chapter provided a detailed explanation of the resilience concept used within this work. Towards this end, the term resilience was explained in general and, subsequently, resilience was detailed in the context of conventional energy grids. Afterward, the increasing need for resilience within smart grids was explained and numerous arguments were given related safety and security challenges that emerge from the transitioning process. These challenges and the concept of resilience are relevant aspects for motivating and understanding the contributions within the subsequent chapters of this thesis. Afterward, the chapter elaborated on the involvement of people within energy grids. The chapter provided a distinction between people that are actively involved within processes to support the energy grid, and people that are passive participants. Common participation schemes for involving people within conventional energy grids were explained. Finally, the increasing opportunities for a stronger involvement of people within smart grids was presented. The chapter concluded with a brief introduction of concepts for conveying knowledge by using digital means for education. In this context, the concepts of serious games, E-learning, and edutainment were explained.

3 HOLONIC SYSTEM MODELING AND SIMULATION

In this chapter, a semi-formal model for structuring smart energy distribution grids is introduced, which is based on the concept of holons and improves the resilient operation of energy grids during hazardous situations. Holons are a promising paradigm facilitating the incorporation of heterogeneous stakeholders into complex systems and organizing them in a system-of-system fashion. The emerging advanced energy grid structure facilitates a strong integration of those stakeholders and their local resources in processes for supporting the mitigation of demand and supply problems. Furthermore, to investigate the feasibility of the holonic energy grid structure and to support the development of corresponding control mechanisms, the discrete-time simulation environment HOLEG is introduced. Finally, the willingness of people to participate in a holonic energy grid is investigated via an online user study. The capabilities of HOLEG are used in subsequent chapters of this work to simulate and evaluate our research.

The chapter is structured as follows: Section 3.1 motivates this chapter and discusses the challenges emerging from the energy transition and the need for novel resilient energy grid structures and control approaches in brief. Section 3.2 presents related work of the application of holons in energy grids and provides insights into the importance of active participants within these grids. Furthermore, the importance of testing and system simulation in energy grids is briefly highlighted. In Section 3.3 the semi-formal holonic energy grid model is introduced. In this section, the technical requirements are stated briefly and a recursive holonic system structure is presented as a bottom-up approach for enabling prosumers to actively contribute to processes for mitigating hazardous situations. Afterward, in Section 3.4, the simulation environment HOLEG is introduced, which reflects the proposed holonic system model and acts as a testing and evaluation environment for novel control and optimization approaches. Subsequently, in Section 3.5 the results of an online survey on the willingness of prosumers to actively participate within holonic energy grids are presented. Finally, Section 3.6 concludes and summarizes the findings.

3.1 MOTIVATION

Energy grids have been recognized as critical infrastructures for decades. They maintain a continuous supply of electricity despite the increasing energy-technical demand of our modern society. In fact, the functioning of other critical infrastructures , like ICT and the water distribution network are directly dependent on the stable operation of energy grids. In order to fulfill this responsible role, conventional energy grids are driven by the electricity demand of consumers, and the flow of electricity is controlled at central locations. From this emerges a strictly top-down producer-to-consumer electricity delivery process, where large producers match the production—at any point in time—to the demand of the consumers. For years, energy grids have been undergoing drastic changes: large-scale fossil-fueled electricity producers are increasingly replaced by small-scale (distributed) RESs, like solar panels, wind turbines. Simultaneously, the strictly top-down oriented electricity delivery process gives way to concepts facilitating local electricity production [74].

From this transition, numerous challenges emerge that affect various domains within the energy grid. Among the most prominent ones is the challenge of handling the severe increase of volatility introduced by RESs. Since the operation of the majority of RESs depends on volatile environmental factors, like weather conditions (e.g., wind and solar radiance for wind turbines and solar panels), conditions can change instantaneously, drastically affecting the power output of these resources. Such deviations result in mismatches between the demand and supply for electricity in the grid and can challenge the stable operation of energy grids [193, 198]. The severity of such situations is increased further since the structure of the conventional energy grids relies on a hierarchically organized electricity dissemination process. This process requires central locations (or entities) that are responsible for controlling the large producers in order to adjust to changing situations. Especially during hazardous situations, the corresponding decision-making for mitigating problems (e.g., by using reserve capacity) is conducted at central locations within the grid. Towards this end, sophisticated technologies that support monitoring and controlling the energy grid are mainly located at large producers and control entities on higher layers in the energy grid. In comparison, lower layers of the grid, which encompass the majority of consumers, lack such technology. This shortcoming exacerbates the challenges of smoothly integrating distributed RESs, incorporating novel stakeholders, and mitigating problems locally.

PROBLEM STATEMENT Using predominantly distributed RESs for maintaining a continuous supply with electricity, may cause situations where large amounts of excess electricity, or a severe shortage of such, needs to be handled. Both situations—if not mitigated appropriately—can contribute to the destabilization of the energy grid. In order to improve the resilience of energy grids facing such situations, numerous challenges need to be resolved to mitigate deteriorating consequences. Among the most prominent ones are:

- An increasing amount of reserve capacity is required to compensate for the volatile behavior of RESs [96]. Smart grids need to provide such resources on lower layers in the grid, where access may be limited, or resources may not be controllable at all [74, 219].
- Traditional measures for problem mitigation, like rolling blackouts, may not be applicable in smart grids [22]. The separation of parts of the grid may prevent using local resources for mitigating the hazardous situation; additionally, the stability of the autonomously operating parts needs to be ensured.

THE CHALLENGE OF INTEGRATING DISTRIBUTED RESOURCES In this chapter, we improve the capabilities of smart grids to mitigate hazardous situations caused by the production excess electricity, or the absence of such, to support its resilient operation. Towards this end, the utilization of resources located on lower layers in the grid needs to be improved while considering numerous requirements for operating an increasingly distributed system. In this work, the following particular challenges are addressed:

- *Heterogeneous stakeholders*. Technical advancements and the need for an increasing amount of reserve capacity on lower layers in the grid requires a stronger integration of stakeholders that provide the corresponding resources (e.g., households with rooftop solar panels, electric vehicles (EV)). However, these stakeholders are highly heterogeneous, ranging from private households with RESs, over enterprises providing resources for load-shedding, to organizations that offer auxiliary services. Despite this heterogeneity, the individual goals and requirements of all participants need to be considered during the mitigation of hazardous situations in the grid.
- *Operation-relevant information*. The aforementioned stakeholders may consume and produce electricity, which can affect the stable operation of the energy grid. To improve the mitigation of emerging demand and supply issues, operation-relevant information (e.g., magnitudes of available production and consumption capability) of these stakeholders needs to be made available to control authorities.
- *Improved resource usage*. In conventional energy grids, strong deviations from the balance between demand and supply—if they cannot be mitigated using operating reserves—are resolved by disconnecting parts of the grid [19]. The disconnected parts then experience a blackout situations. For smart grids, such techniques

cannot be easily applied since production resources are distributed throughout the grid, which may become unusable if the respective parts are disconnected. Therefore, more fine-grained resource control is required, which prevents undesired separation of important parts and supports the autonomous operation of the disconnected segments of the grid.

CHAPTER CONTRIBUTION In this chapter we provide a semi-formal model that allows smart grids to be structured as holarchies to improve their capabilities to cope with the challenges stated above and increase their resilience in hazardous situations. In particular, the core contributions in this chapter are the following:

- A semi-formal system model—based on the concept of *holons*— is provided for representing smart grids and enhancing their abilities for integrating heterogeneous stakeholders.
- These stakeholders are then empowered to offer their local resources as so-called *flexibilities* dynamically to support balancing demand and supply deviations.
- A modeling and simulation environment is provided, which reflects the holonic system model and allows developing and testing of control and optimization algorithms in a safe environment.
- An online survey is presented, which investigates peoples' willingness to participate in processes for mitigating hazardous situations by offering local resources and analyzes peoples' main concerns.

3.2 HOLONIC SYSTEMS AND SIMULATION TOOLS

This section provides the necessary background information to fully understand the application of holonic concepts in energy grids and within this work. First, the application of holons in related work of energy grid modeling and simulation is presented to support the design-decisions for the holonic system model presented in this chapter. Second, the increasingly important role of individual stakeholders within operational processes of energy grids is motivated. Finally, existing modeling and simulation environments for smart grids and corresponding applications are presented and discussed.

3.2.1 *Application of Holons in the Energy Grid Domain*

One of the first approaches to transfer the holonic concept into the domain of energy grids was presented by Higgins et al. [102]. The authors combine an industrial standard for encapsulating function blocks (IEC 61499) and a digital communication standard for substations (IEC 61850) to form a hybrid system of self-encapsulated and communicating entities. In contrast to structuring function blocks, the use of a recursive bottom-up aggregation for the conceptual modeling of energy grids is proposed by Negeri et al. [161, 162]. Their generic modeling approach aims at grouping prosumers as holons in a holarchy and use a service-oriented architecture to enable communication and state-assessment functionalities. Another implementation of holonic properties in the context of energy grids is provided using hybrid multi-agent systems [170]. In their work, agents are used to modeling an electrical distribution grid and control the reactive power at consumer-site solar panels. Towards this end, agents are organized in a holarchy to represent different abstraction layers of a distribution grid, ranging from *substation*-level to *house*-level. The agents aim to establish an energy balance between holons by matching their reactive power requirements to conditions that are delegated from higher levels in the holarchy. Another generic control architecture that is based on the concept of holons is provided by the authors of [79]. In their work, the authors propose holons as a concept for combining heterogeneous control solutions for entities in the grid depending on their typical interaction patterns. In this context, holons are capable of negotiating trade-offs between contradicting goals of interacting entities. Moghadam & Mozayani [155] propose a hybrid multi-agent system approach for organizing the IT-infrastructure of smart grids to facilitate efficient information exchange and increase the security of the communication between entities. They apply a holonic concept to organize different software aspects depending on their use within a certain domain of energy grids. For instance, software related to outage management is integrated in a so-called *outage-management-holon*.

3.2.2 *Increased Involvement of Participants in Grid Control Processes*

RESs and novel technologies, like electric vehicles and battery storage systems of smart grids are envisioned to be located in the vicinity of consumers. This combination of consumption, storage, and local production evolves consumers into so-called prosumers and changes the role and impact of these stakeholders within the resilient operation of energy grids. In the following, the role of conventional consumers in energy grids is highlighted. Afterward, the potential impact of active prosumers in holonic energy grids is discussed briefly.

ROLES OF PARTICIPANTS IN CONVENTIONAL ENERGY GRIDS The two most prominent roles within conventional energy grids are consumers (C) and producers (P). Usually, consumers are referred to as entities that consume electricity, compared to producers, which usually represent electricity-generating participants. However, with the appearance of prosumers, which can take on both aforementioned roles, further differentiation is required to fully understand the prop-

Role	t_i	$[t_m, \ldots, t_n]$	T_{total}	Participation
Pure Conventional Consumer	C	C	C	passive
Pure Conventional Producer	P	P	P	passive/active
Net-consuming Prosumer	P/C	P/C	C	limited-active
Net-producing Prosumer	P/C	P/C	P	limited-active

Table 3.1: Time-dependent differentiation between roles in conventional energy grids. Here, parameter C denotes the cosumption of electricity and P refers to production. These roles can be differentiated for individual points in time t_i, for time-intervals $[t_m, \ldots, t_n]$, and for the total amount of time a participant interacts with the energy grid.

erties of the respective roles and their impact on conventional energy grids. Towards this end, we differentiate between four roles within conventional energy grids as shown in Table 3.1.

Pure conventional consumers are the majority of participants in conventional energy grids. Those consumers do not produce but only consume electricity at each point in time t_i for $i \in \mathbb{N}$ when they operate as a part of the energy grid (e.g., a house without local RESs). Consequently, their role remains a consumer during arbitrary time-intervals $[t_m, \ldots, t_n]$ for $m, n \in \mathbb{N}, n > m$ and for the total amount of time T_{total} while they are connected to the grid. The participation of the pure conventional consumers is *passive* since their demand needs to be matched by the producers in the grid, while the consumers are largely unaware of the feats that need to be accomplished to ensure a continuous supply with electricity.

Similarly to the consumers, *pure conventional producers* denote participants in energy grids that produce electricity (e.g., solar panel, coal power plant). When they interact with the energy grid they act as producers at each point in time, during arbitrary intervals, and for the total amount of time while they are connected. Their participation in conventional grids can be considered as either *active or passive* depending on the type of the producer. For instance, coal power plants can be controlled to actively adjust their production to match the ever-changing demand in the grid. In comparison, many solar panels or wind-turbines are producing electricity depending on the current weather conditions but their production cannot be actively adjusted. Note that nowadays the majority of RESs can automatically adjust to changing situations or their electricity production can be controlled remotely [30].

For the prosumers we distinguish between two roles, namely *net-consuming prosumers* and *net-producing prosumers*. As prosumers, they are capable of both consuming and producing electricity while they interact with the energy grid. Consequently, for specific points in time t_i they can be either consumers or producers. For instance, during midday, local solar panels may produce excess electricity and the prosumer acts as a producer in the grid. Similarly, during the evening the consumption may exceed the local production and the demand need to be matched with electricity from the grid. These role changes cannot only occur for specific points in time, but can last for time-intervals. The main difference between the two roles is the accumulated consumption or production for the total amount of time while they are interacting with the grid. Here, the net-consuming prosumer consumes more electricity than she produces and the net-producing prosumer produces more electricity than she consumes. The participation of both types of prosumers can be considered as l*limited-active*. These prosumers are contributing actively to the operation of the energy grid by using locally produced electricity to cover (parts of) their demand or provide excess electricity to the grid. However, they remain largely unaware of the overall situation of the grid and adjustments to the local production (e.g., if too much electricity is generated) are mostly preconfigured [30]. Such limitations are reasonable, as they prevent control authorities from arbitrarily limit production, which would result in monetary losses for the prosumers. However, this also limits the prosumers capabilities for making local decisions that can improve the overall situation of the energy grid.

IMPACT OF ACTIVE PROSUMERS UPON RESILIENCE IN HOLONIC GRIDS As pointed out repeatedly in this thesis, smart grids are envisioned to be highly digitized and encompass a comprehensive ICT-infrastructure that supports, for instance, bidirectional communication between participants in the grid. Using the ICT-infrastructure allows increasing the active participation of stakeholders and their impact upon energy grid resilience. Here, we distinguish between the participation of stakeholders during the mundane operation of the grid and during hazardous situations. The beneficial impact of active stakeholders in both cases is explained next.

Mundane Operation. During mundane operation it is assumed that no major disruptions occur; otherwise, it is considered as a hazardous situation. The impact of active stakeholders on the energy grid resilience during mundane operation is mainly achieved by local optimization similar to the goals of HEMSs and schemes that encourage adjustments to local energy consumption, like demand-side management. Kreutz *et al.* [129] showed that an increasing number of digitally controllable components, can improve demand-side management approaches and reduce the overall base-load that needs to be supplied by the grid. Other benefits are peak-load reduction, valley-filling and a more flexible load-shape [82, 143, 156]. Therefore, active and aware prosumers that offer local resources to support energy grid operations can contribute to the resilience of the grid by alleviating the challenge of maintaining a balance between demand and supply.

Hazardous Situation. We consider a situation to be hazardous in two main cases: firstly, if an event is anticipated, which cannot be prevented but is likely going to have a severe impact on the operation of the energy grid (e.g., storms). Secondly, if disruptions occur that are not anticipated, like failing components or attacks on the grid. Both situations can severely impact the stable operation of energy grids [31, 33, 165, 168, 177, 191, 196, 207]. In this context, active and aware stakeholders can support the mitigation of hazardous situations. On the one hand, similar to the benefits during mundane operation, e.g., a lowered peak-demand results in fewer resources that are required to compensate the situation. On the other hand, the concepts presented in Section 3.3 support the operation of autonomous subparts of energy grids as holons. In these holons, small-scale resources can have a strong impact on the balance between demand and supply since smoothing effects, which are present in large energy grids, are not as effective in smaller autonomous systems [227]. Therefore, prosumers can contribute to mitigation processes by offering additional local resources. This potential for fine-grained adaptability of demand and supply within holons, the increasing impact of prosumer resources, and the ability of prosumers to make local-decisions increases the resilience smart grids.

THE IMPORTANCE OF THE LOCAL SITUATION OF PARTICIPANTS

Actions that are conducted by stakeholders to support mitigation processes, like offering flexibilities, affect their local situation and may have negative consequences for them. For instance, while flexibilities may contribute to stabilizing the grid, their use affects the state of the underlying devices. As a consequence, these devices may not be usable by the stakeholder, devices may experience increased wear, and local resources may be consumed [242]. Such negative effects, if not mitigated or compensated properly, may yield a variety of problems. For instance, people may be reluctant to accept novel technologies or methods that cause negative effects for them. Furthermore, peoples' willingness to contribute actively within mitigation processes may be impaired if negative consequences of their participation are too severe.

To mitigate these negative effects on stakeholders, their devices, and the environment, information about the local situation of the prosumers need to be taken into account during the mitigation processes. In this work, various methods are considered to reduce or compensate the detrimental consequences of active stakeholder participation. Towards this, priority classes are considered to categorize appliances depending on their relative importance to stakeholders at specific points in time. Additionally, the specification of constraints allows incorporating information about the local situation into processes for using available resources (see Section 3.3.3). Finally, different mechanisms for compensating negative consequences, which cannot be prevented, are discussed later in this work (see Section 5.2.3).

3.2.3 *The Need for Simulation in Energy Grids*

Energy grids are critical infrastructures essential for maintaining a continuous supply of electricity for millions of consumers. Simultaneously, the ongoing energy grid transition requires developing novel system approaches and operational processes. Such developments require thorough testing and validation before they can be applied within the energy grid. Otherwise, malfunctioning behavior may occur, which can threaten the continuous operation of the grid. However, the testing of novel developments poses a severe challenge. In this section, the core challenges for testing novel developments within the domain of energy grids are explained. Subsequently, modeling and simulation are proposed as suitable methods for addressing many of the challenges of testing. Finally, existing technologies and tools that are used in academia and industry for energy grid simulation are presented.

3.2.3.1 *The Concept of Testing*

Testing aims at evaluating the operational quality of an *entity-under-test* within a defined environment or scenario. Testing can be applied to various entities ranging from individual components, over deployed mechanisms, to entire systems and environments. One of the main goals during testing is the generation of failures and faulty behavior of the entity-under-test to understand the "boundaries" of its error-free operation. Invoking failures and corresponding (problematic) consequences for the tested entity and the environment are essential for improving the entity-under-test. However, testing in the context of critical infrastructures is increasingly challenging, as failures and their corresponding consequences may impede the continuous operation of these systems. In the following, different approaches for testing and their benefits and drawbacks in the context of energy grids are presented.

TESTING IN THE ENERGY GRID The process of testing will likely produce errors and faulty system behavior. This behavior can then impede the correct functionality of operational processes of the system, which in turn may affect the stability of the energy grid. The continuous delivery of electricity is an essential service provided by the energy grid, and (partial) deterioration of the corresponding processes can result in damaged devices and connected systems, monetary losses, and can threaten human lives. Consequently, the energy grid itself is not well-suited for conducting tests since the continuous supply of electricity is of utmost importance.

TESTING IN PHYSICAL TEST-BEDS Physical test-beds are encapsulated environments that aim at representing a system, or a part of such, to investigate effects and consequences using real-world system components. Such test-beds can consist of a combination of different hard- and software components, including domain-specific special equipment. A test-bed in the domain of energy grid can be, for instance, a small-scale replication (e.g., a model city) of a distribution grid or an authentic replication of a part of an extensive system (e.g., a transformer station including special hardware used in real systems) [136]. These systems are well-suited for testing novel developments in a realistic and secure environment. However, physical test-beds suffer from two significant drawbacks: Firstly, such systems may encompass expensive system components and the continuous maintenance and operation of the test-bed can be costly. Secondly, the results generated within a test-bed may not be easily used to draw conclusions on the system as a whole. For instance, if the test-bed only represents a part of the real system, cascading effects and the corresponding consequences cannot be investigated.

TESTING IN SIMULATED ENVIRONMENTS Modeling and simulation are established techniques for testing and evaluating systems in a safe and secure environment. The required functions or the behavior of an entity- or a system-under-test are modeled and then implemented in order to be evaluated in a digital environment. In other words, a digital representation of the original is generated by modeling all required interactions [148]. In comparison to the real grid and physical test-beds, no special purpose hardware is required (except for hardware requirements of the system that runs the simulation), and the system operates within a safe and enclosed digital environment. Testing in a digital environment is accompanied by other benefits, like robust scalability compared to hardware-based systems and the possibility for compressing time (i.e., simulations do not need to run in real-time but can often be accelerated). However, the main challenge for using simulation as a technique for testing is to provide an adequate model that is capable of representing the entity-under-test, its properties, and the interdependencies and interactions with the environment. These interdependencies need to be well-defined, especially for investigating cascading effects between systems or parts of a system. For the reasons stated above, we consider modeling and simulation as the most promising technique for evaluating future energy grid developments, and we are focusing on these concepts in the remainder of this work.

3.2.3.2 *Simulation in Energy Grids*

In this section, prominent tools are presented, which are used to model and simulate physical aspects of the energy grid as well as tools that try to combine these physical aspects with concepts from ICT for representing cyber-physical systems [61, 62].

simulation of physical properties of grids The investigation of physical properties for energy grid development is ranging from simulating electromagnetic phenomena to the extensive simulation of energy grid operations [16]. The most prominent tools—at the time of writing this thesis—for supporting the evaluation of physical properties within energy grids are listed in the following.

- *APT-EMTP*. It is a commercial simulation tool for transient electromagnetic phenomena, which is capable of simulating real power system dynamics and supports the continuous monitoring of the system state [69]. This enables the tool to be widely used within the power industry for system planning and the investigation of electromagnetic aspects. However, the tool is not tailored to model and simulate energy grids as a whole.

- *PSCAD/EMTDC*. The PSCAD/EMTP simulation environment is one of the most established tools for electricity-related calculation and simulation [89]. It provides a variety of device models and allows representing large-scale electricity networks. Moreover, a large set of analysis tools is provided, which encompasses, among others, real-time visualization of electrical phenomena.

- *NEPLAN*. It is a commercial tool for modeling hierarchically structured energy grids on various levels. Towards this end, NEPLAN supports the simulation of high-voltage grids to distribution grids and provides detailed component models and a large variety of analysis functionalities [163].

- *ETAP*. The Electrical Transient Analyzer Program (ETAP) is a tool for designing, modeling, and analyzing electrical systems [68]. It is developed by ETAP/Operation Technology Inc. and claims to be the most sophisticated electrical power system software. It provides a suite of different software applications that enable designing a comprehensive hierarchical energy grid model, the simulation of the modeled system, detailed analysis functionalities, and live-monitoring capabilities.

- *PSLF*. The tool is a general-purpose tool for modeling and analyzing the energy grid on different levels [83]. It is a standalone software developed by GE and is tailored to provide strong usability and offers diverse plotting and visualization functionalities. Additionally, it supports the analysis of geographical positioning of energy grid components and the corresponding visualization using the google earth[1] application. Further benefits are detailed model-

1 https://www.google.com/intl/de_de/earth/

ing capabilities to allow fine-grained adjustments for the behavior of energy grids.

- *Power Factory*. This tool is a commercial calculation and simulation software developed by DIgSilent [53]. Similar to the NEPLAN software, it provides sophisticated modeling and analysis capabilities for the energy grids. It supports its own programming language DPL, which can be leveraged to automate tasks for the software and enables interaction with the modeled network.
- *GridLAB-D*. The GridLAB-D toolbox [37, 159] is an agent-based simulation tool for energy grids. It allows creating models of distributively organized grids and supports a variety of analysis functionalities. Additionally, the simulation time can be freely configured, supporting short-term and long-term analysis.
- *OpenDSS*. OpenDSS was developed in 1997 by Electrotek Concepts, Inc., and it is used for the modeling and analysis of electrical distribution systems [63]. It is inherently script-based and facilitates strong extensibility. However, this limits usability since users require strong programming capabilities.

SIMULATION OF CYBER-PHYSICAL GRIDS Cyber-physical power grid simulation aims to combine the simultaneous representation of physical energy grid properties and ICT-infrastructure simulation. In general, two simulation types can be differentiated for cyber-physical system simulation, namely, *integrated* simulation and *Co*-simulation approaches. The integrated simulation addresses cyber and physical aspects holistically by integrating them into a single tool. In comparison, co-simulation uses tools and techniques to simulate each domain separately and mediates between these standalone simulations. In the following, the most prominent cyber-physical simulation tools and approaches are briefly listed.

- *EPOCHS*. This time-discrete simulation framework is based on the High-Level-Architecture (HLA)-standard [111] and combines three standalone tools PSCAD/EMTDC, PSLF and the NS-2 simulator [107]. The tools are organized as a co-simulation approach and act as collaborative agents, which are synchronized to combine realistic network communications with electric power components.
- *INSPIRE*. INtegrated co-Simulation of Power and ICT-systems for Real-time Evaluation (INSPIRE) is a co-simulation tool, which is based on the HLA-standard and combines OPNET for ICT simulation with DIgSilents Power Factory for the underlying physical energy grid simulation [84]. In their work, the authors strongly focus on the reduction of transmission time between the two simulators and the corresponding time synchronization. For this, the framework uses a conservative time synchronization approach, which

guarantees that the current state of the co-simulation can be processed without the interference of the individual simulators.

- *GECO*. It is an event-driven co-simulation framework for power systems and communication networks [141]. In their work, the authors propose a scheduler that handles the events generated by the individual processes and uses a global time-scale for organizing them. This concept aims at solving the problem of synchronization window-sizes between processes, which is common in HLA-based solutions. The tools combined within this co-simulation approach are PSLF and NS-2.

- *ORNL Power Simulator*. It is a discrete-event simulator for modeling of the dynamics of electro-mechanical components [169]. Towards this end, it provides a discrete approximation for the continuous dynamics of electrical components. This event-based simulation is then combined with other standalone ICT-simulation tools to provide a cyber-physical co-simulation model. To facilitate interoperability, ORNL provides an API to incorporate additional simulators like OMNET++ or NS-2.

3.3 HOLONIC SYSTEM MODEL

In this section, a semi-formal model for representing smart grids based on the concept of holons is presented. First, the fundamental assumptions made within the development of the model are explained. Second, the general system concept, which contributes to addressing the challenges presented in Section 3.1, is introduced and the implication for energy grid resilience are discussed.

3.3.1 *Hypotheses and System Assumptions*

The overarching goal of this thesis is to increase the resilience of smart grids by improving their capabilities of dealing with the challenges of the ongoing energy grid transition and the mitigation of hazardous situations. In the following, the core hypotheses and the corresponding assumptions for modeling energy grids using the concept of holons are explained.

3.3.1.1 *Advanced Grid Infrastructure*

Numerous technical advancements can be assumed throughout the transitioning process of energy grids towards smart grids. In the following, three relevant assumptions about the energy grid infrastructure are explained, which will be assumed for the remainder of this work.

ADVANCED METERING INFRASTRUCTURE An advanced metering infrastructure is assumed to be widely deployed in smart grids. This ICT-infrastructure encompasses, among others, sensors for measuring control-relevant information, and enables the bidirectional communication between consumers/prosumers and responsible control entities in the grid (e.g., distribution system operator). For the holonic system concept that is proposed in this work, such an advanced metering infrastructure needs to support two main areas in particular: firstly, ICT needs to be widely deployed, such that the majority of the participants in the energy grid are capable of providing fine-grained information about local devices and appliances (see Section 3.3.3); secondly, the energy grid infrastructure is assumed to be capable of maintaining bidirectional communication among the participants in the grid. In particular, the exchange of commands and control-relevant information between sub-parts of the grid is required for status calculation and control decision-making.

AUTOMATED ACTUATORS Actuators can execute actions that have an impact on the physical connection of components within an energy grid. For instance, load break switches that are located at transmission lines could be used to (dis-)connected parts of the grid controlled by a local actuator. For the proposed holonic system, it is assumed that at least two types of actuators need to be present within smart grids: lower-layer switches that provide circuit breaker functionalities in the vicinity of stakeholders. These switches should be able to activate or deactivate at least small-scale resources at the prosumer locations, like the electricity consumption of a household as a whole, individual floors, and individual or groups of appliances. Such control can be achieved using smart meters and corresponding smart devices or smart sockets, whose electricity consumption can be controlled digitally [40]. On higher layers within a smart grid, actuators are required that manage the electricity exchange between different parts of the grid and enable the physical separation of such parts if required. Towards this end, it is assumed that supportive technologies, like solid-state transformers are widely deployed since they enable concepts like the bidirectional flow of electricity and separation of parts of the grid [201].

CONTROL INFRASTRUCTURE BACKUP ENERGY Smart grids have to face numerous hazardous situations accompanied by problems and failures in the energy grid infrastructure and the operational processes for supplying electricity to the consumers. Such situations may increase system destabilization and ultimately lead to (partial) blackouts caused by failing components (e.g., malfunctioning producers), or can be a consequence of severe load-shedding measures and rolling blackouts (see Section 2.3.1.2). However, in blackout states—

if not mitigated properly—the ICT infrastructure of affected areas would be non-functional. Consequently, the collection of data would be severely limited, and the possibilities for conducting remote or automated system control operations would be likewise impaired. Aligned with the assumptions stated above about the deployment of an advanced metering infrastructure, it is assumed that control-relevant components, like routers, local HEMSs and automated actuators have—at least—access to a limited amount of backup power (e.g., provided by local batteries).

3.3.1.2 *Holonic Energy Grids for Improving Resilience*

If smart grids can be designed and operated as holonic systems (see Section 2.1.3), their resilience during hazardous situations is improved mainly in two ways: firstly, the autonomous operation of sub-parts of the grid as holons support the prevention of cascading failures. Seondly the strong integration of heterogeneous stakeholders and their resources into processes for mitigating problems enhance the capabilities of the smart grid to tolerate and locally mitigate demand and supply deviations. However, one important aspect that needs to be considered for operating a holonic smart grid is the control concept that allows holons to operate according to the properties and capabilities defined in Section 3.3.2.1. The assumption of a holon control authority is explained next in more detail.

HOLON CONTROL AUTHORITY As mentioned several times in this thesis, holons are a part of a larger "whole", but also a "whole" by themselves (see Section 2.1.3). For a holon to be able to operate within both settings (i.e., operating as a subordinate if it is part of a whole, or autonomously as a whole itself) a central authority is required, which is capable of operating the holon and reflecting the holonic properties introduced in Section 3.3.2.1. Several works aim to address the related problem of maintaining a continuous electricity supply within autonomous sub-parts [144, 145, 238]. However, the responsibility of a holon control authority exceeds the task of maintaining the supply with electricity. Among the additional responsibilities are local optimizations to pursue the inherent goals of the holon, while, simultaneously, weight them against decisions that may become necessary due to delegated information from higher layers within the holarchy (e.g., reduce the local supply quality to support the stabilization of the grid as a whole). Furthermore, strong communication capabilities are required to facilitate the information exchange between holons and enable restructuring the holarchy dynamically (see split and merge operations in Section 3.3.2.1). Especially the reconfigurability of holarchies exacerbates the challenge for a designated holon control authority. Holons may merge, be separated, and participants within holons may change their affiliation. These changes can strongly increase the challenge of controlling individual holons and may require adjustments in holon control. For instance, if multiple houses operate as individual holons, a control authority needs to be present within each house to maintain its autonomous operation. If these houses decide to merge, they may form one larger neighborhood holon, which again requires a control authority. The questions of where this control authority is located and how it is selected adequately are out of scope of this work and, therefore, remain open. For the remainder of this work, it is assumed that for each holon there exists a designated control authority capable of maintaining its operation.

3.3.2 *Recursive Holonic System Model*

In this section, the holonic system model is described as a recursively organized bottom-up concept for modeling smart grids with strong integration of heterogeneous stakeholders. First, the general application of holons in the domain of energy grids is briefly explained. Second, *holon elements* are introduced as atomic elements (i.e., entities which are not further dividable into smaller controllable entities), and their essential properties are described. For the integration use of holon elements within the holonic system architecture, the section complements background information introduced in Chapter 2. Afterward, flexibilities are proposed as a concept that allows leveraging local resources to support the mitigation of hazardous events in holonic smart grids. Finally, the recursive aggregation of holons throughout different architecture layers is explained, and the benefits for the resilient operation of smart grids is emphasized.

3.3.2.1 *Holonic System Concept*

The idea of using holons as a concept for structuring systems is known for decades and was first introduced by A. Koestler in the context of social interaction in 1967 [122] (see Section 2.1.3). He emphasizes that in the context of holons the terms “part” and “whole” are ambiguous since systems (in this context biological or social systems) consists of hierarchically organized layers, where each layer encompasses *intermediary structures* of varying complexity. These structures (holons) are—depending on the way they are observed—a whole in their own right or a part of a more complex system. The system structure which emerges from organizing holons is called a *holarchy*, which is conceptualized in Figure 3.1.

Holons in a holarchy are recursively organized to form a hierarchical structure of “wholes” of increasing complexity. On the lowest layer (here: layer 0), holons are considered to be not further decomposable into intermediate parts that can represent a whole in their own right.

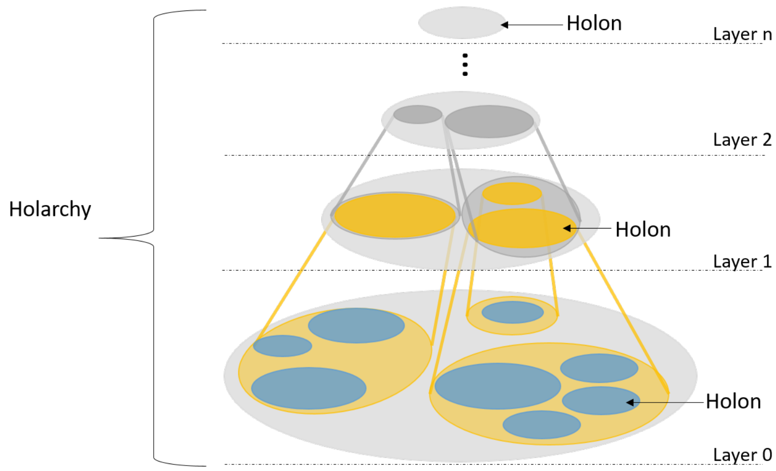

Figure 3.1: Conceptual representation of a three-level holarchy with recursively aggregated holons on different holarchy levels.

One or more holons of a lower layer can then be aggregated to form a holon of the next higher layer in the holarchy.

Numerous related work adapted the concept of holons and holarchies to apply them in the context of energy grids (see Section 3.2.1). The majority of these work uses the recursive applicability of a holonic structure to improve energy grid operations during mundane situations or in the presence of minor disturbances, which do not strongly affect the operation of the energy grid. In comparison, the holonic concept proposed in this work aims to improve the mitigation of hazardous situations that—if not resolved—would have a strong impact on the capability of the energy grid to provide a continuous supply of electricity.

Similar to prior applications of related work, the holonic system model presented in this thesis uses the recursive properties of holons for structuring the energy grid in a systems-of-systems manner. Towards this end, atomic entities are recursively aggregated and managed within holons, which act as (autonomous) sub-systems in the holarchy. These systems can again be aggregated within (higher-layer) holons. Organizing these holons and their corresponding interconnections yields holarchies, which are dynamically adaptable systems. Holons within these systems have capabilities based on logical and physical relations between the holons (e.g., the existence of power lines and load break switches, or logical connection of systems for data exchange). Such relations enable holons to interact and allow modifying the overall holarchy structure (e.g., by separating the flow of electricity between holons using load break switches). The essential functionalities and properties of holons that are required for conducting such actions are defined and explained below.

Direction	Communication Purpose
Horizontal	Negotiation
Upward	Propagation
Downward	Delegation

Table 3.2: Overview of communication categories within a holarchy and the corresponding direction of information flow.

- *Communication*. In this work, communication in a holarchy is conducted between different holons. Due to the recursive definition of holons we can distinguish between three main categories of communication depending on the *direction* in which the communication happens in the holarchy. Holons are capable of *negotiating* with other holons that are present on the same holarchy layer. Such communication can be used if the amount of information or commands received from higher layers in the holarchy is limited (e.g., due to problems on higher layers in the holarchy). In order to provide lower layer holons with information and to issue commands, holons can communicate by *delegating* between layers. High layer holons may delegate tasks for mitigating minor problems to lower layer holons, which can address the issues locally. Lastly, since communication is considered to be bidirectional within a holarchy, holons of lower layers can communicate with higher layers by *propagating* information. For instance, this type of communication is required if problems are detected on lower layers in the holarchies, but the available resources in the scope of the holon are not sufficient to mitigate the problem. In this scenario, holons can propagate information about the problem situation, which can then be resolved on a higher layer in the holarchy. The three communication categories are summarized in Table 3.2.

- *Change of affiliation*. A holon can be affiliated with a higher-layer holon (i.e., it is a part of the higher-layer holon). This affiliation can be changed dynamically such that a holon can become a part of another holon of the next higher layer within the holarchy. Such changes can result from tasks delegated by higher layers or can be initiated by holons pursuing their individual goals. The concept of holarchy layers is explained below in more detail.

- *Strive for unification*. In this work, holons are considered to possess the inherent desire to be part of a larger system. As part of a larger system, holons are willing to surrender (parts of) their autonomy and corresponding control to higher layers as long as the operations and decision-making do not *threaten* important goals of the holon (e.g., ability to sustain themselves). Due to this potentially contradicting behavior of surrendering while maintaining individual goals, holons are considered to be *Janus-faced*.

- *Janus-faced*. Derived from the two-faced image of the roman deity "Janus", holons are considered to possess two views, which strongly affect their behavior in a holarchy. Their *internal view* aims to optimize the situation towards the inherent goals of the entities encompassed within the holon (e.g., optimize local use of electricity). The *external view* is responsible for optimizing the situation according to the goals that are important for higher layers in the holarchy. Holons need to be capable of considering both views simultaneously for their decision-making.

- *Split*. A *split* of a holon denotes its separation into one or more previously encompassed holons from lower layers of its internal structure. Note that this is similar to the change of affiliation; however, if a holon is split, it forms (multiple) new holons which represent previously encompassed holons. These new holons are located at the same layer in the holarchy as the holon responsible for executing the split operation. Moreover, if the holon that initiates the split operation is located on an intermediate layer in the holarchy, the resulting holons inherit the affiliation towards higher layers since they are still a part of a holon of the next higher layer.

- *Merge*. (Multiple) holons can *merge* to form a new larger holon represented at a higher layer within the holarchy. The holons that are merged are affiliated to the newly generated holon.

holarchy layers The recursive aggregation of systems within a holarchy results in a layered system structure. More precisely, starting from the layer of atomic entities in the system, each aggregation of entities forms a new holon, which adheres to the properties defined above. By recursively applying this aggregation concept, a multi-layer architecture of systems-of-systems emerges. For example, let devices and appliances in a house be atomic entities since they—on their own—cannot provide the properties and functionalities of holons. These entities are encompassed within prosumer households, and their aggregated electricity consumption and production, therefore, dictate the overall energy profile of the house. A house (or a prosumer) has intrinsic goals like lowering the electricity bill and maintaining a sufficient supply for all appliances. These goals are addressed by managing the encompassed entities (e.g., lowering the electricity bill by using locally produced electricity and avoiding high consumption during peak times). However, these house holons need to interact with holons at the same layer and communicate with higher-layer holons (e.g., street-layer holons) to achieve the goals that are important for that higher layer. Following this principle, a holarchy emerges, where multiple houses can be aggregated as streets, which can then be aggregated as energy communities and larger systems.

The functionalities described above can affect the overall structure of the holarchy. 3.1 shows an exemplary distribution grid structured as a holarchy. The holarchy reorganizes its structure by conducting a splitting operation to separate a faulty part of the grid.

Example 3.1: Exemplary holarchy conducting a splitting operation

The exemplary grid is shown in Figure 3.2 is organized as a two-layer holarchy. Prosumers—representing the smallest possible holons in the proposed holarchy—are represented in blue. They are aggregated into layer-1 holons, whose current situation is indicated by the color-coding, where green indicates balanced holons and an increased colorization towards yellow and red indicates stronger balance deviations. One of the layer-1 holons faces stability problems due to one of its lower-layer holons disturbing the demand and supply balance (e.g., unexpected high production, strongly fluctuating consumption). The control authority resolved the situation by *splitting* the layer-1 holon and resume operating autonomously as two separate layer-1 holons. The resulting holarchy structure (right) enables stable operation for the majority of its participants. The holon with faulty behavior aims to autonomously achieve its intrinsic goals and work towards mitigating the problem situation. Meanwhile, the stable part of the grid can take measures for supporting the faulty holon and then negotiate a *merging* process to resolve the problem situation.

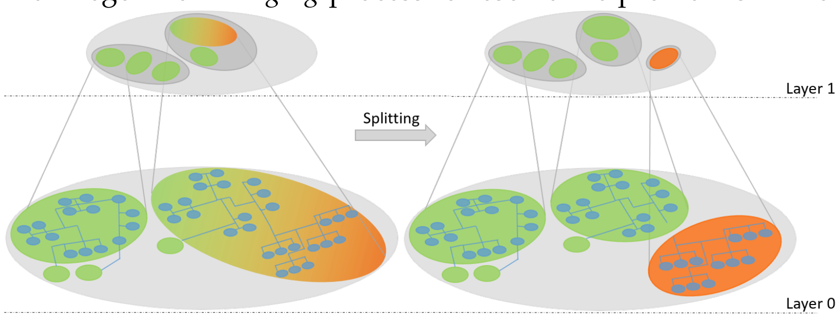

Figure 3.2: Holarchy resolving a demand supply balancing problem by separating a faulty part (orange) from the grid using a *splitting* operation. The separated holons operate autonomously to either resolve the situation internally, or by negotiating with other holons about receiving support.

3.3.2.2 *Holon Elements*

Holon elements are the atomic building blocks of the proposed holonic system model. From the perspective of the holonic system, holon elements cannot be further separated into smaller *controllable* parts (see holon properties above), which includes individual appliances (e.g., TV), parts of systems where devices cannot be controlled individually (e.g., a floor within a house), and entire systems (e.g., legacy consumer households without fine-grained ICT and actuators). Consequently, holon elements cannot delegate or propagate information.

- *Consumer*. Holon elements that consume electricity are the most common entities present in a energy grid. They can range from heavy-weight machinery in enterprises to typical appliances in households, e.g., TVs or dishwashers. As long as these devices consume more electricity than they produce, they are categorized as *consumers*.
- *Producer*. Producing holon elements provide electricity that can be consumed by other holon elements locally or can be fed into the energy grid. Holon elements that produce more electricity than they consume are categorized as *producers*, such as solar panels or fuel-based electricity generators.
- *Prosumer*. Holon elements that are categorized as *prosumers* are capable of both producing and consuming electricity such that they can represent a consumer, or producer alike. Consequently, holon elements of this category are not limited to one of the categories above but can change between them. Representatives of this category are battery storage units or EVs.

Holon elements (he) in the proposed holonic model are formally represented as four-tuples of *power magnitude, role, state* and *priority class*, which are explained below in more detail:

$$he_{i,l}^{t} = (p^{t}, r^{t}, s^{t}, c^{t})$$

Holon element $he_{i,l}^{t}$ denotes the i^{th} holon element at layer l within the holarchy. Time is measured at discrete points $t = [0, \dots T]$, where the number T on the granularity that is assigned for measurements (e.g., T = 17,280 for dividing 24 hours of a day into discrete time points of 5s). At each point in time, holon elements are in one of three mutually exclusive states $s = \{active, inactive, standby\}$, which indicate how they are currently used within the energy grid. In an active state, holon elements are currently in use and produce or consume electricity according to their electrical profile (e.g., supply requirements that define its electricity consumption or internal properties, like (dis-)charging rate and the state-of-charge of a battery) or according to environmental factors (e.g., solar radiance and resulting generated electricity). In an inactive state, holon elements do not produce or consume electricity. Holon elements in a standby state consume a small constant amount of electricity to maintain their standby state. More formally, the consumption or production of a holon element $he_{i,l}$ at time t is defined as the *power magnitude* p_i^t (i.e., current produced or consumed electricity):

$$p_i^t = \int_t^{t+1} \begin{cases} p(t)d(t) & \text{if } state(he_i) == active \\ p_c d(t) & \text{if } state(he_i) == standby \\ \emptyset d(t) & \text{if } state(he_i) == inactive \end{cases} \tag{3.1}$$

Function $p(t)$ represents the power consumption (negative values) or production (positive values) of the holon element at time t. Constant p_c represents the power consumption required to keep the holon element in a standby state. The function $state(\cdot)$ takes a holon element as input and returns its current state. Depending on the orientation of the power magnitude at time t (positive for production or negative otherwise), a holon element has a role $r = \{producer, consumer\}$ (see categories for holon elements above). If the production of a holon element exceeds its consumption, it is a producer, otherwise, it is a consumer. We emphasize that this role can change at any point in time t, especially since numerous devices and appliances are prosumers (e.g., battery storage units), the possibility for such changes need to be taken into account.

Finally, at each point in time t, holon elements are assigned to one priority class $c^t \in \mathbb{N}_0$. The purpose of this assignment is twofold: firstly, the priority class reflects the relative importance of the holon element to the responsible entity to which it belongs. For instance, a water-heater may be of high priority to a prosumer in the morning (hot water is required for showering); however, the same water-heater might be less important at midday (people might be at work and therefore do not require hot water at that time). Secondly, the priority classes are used for the flexibility concept presented in Section 3.3.3 and the decision-making within the proposed system optimization presented in Chapter 4. In both contexts, a lower priority class indicates an increased readiness of an owner to share the respective holon element or endure conflicts emerging from its use within grid control processes.

3.3.2.3 *Holons*

Holons are aggregated non-atomic entities within the proposed model. Such entities may represent individual prosumers (e.g., houses, enterprises) within the energy grid or aggregated prosumers, like *streets*, or larger parts of the grid. Holons adhere to the properties described in Section 3.3.2. In particular, they make decisions between goals important to higher layers in the grid and their own goals (e.g., a house may want to supply all appliances, but the grid as a whole needs to reduce the electricity consumption). As an aggregated entity, a holon is largely determined by its parts. For holons, these parts are lower-layer holons and the holon elements it encompasses. A holon $h^t_{j,l+1}$ is defined more formally as a seven-tuple:

$$h^t_{j,l+1} = (H^t_{j,l}, P^t_j, F^t_j, r^t_j, s^t_j, \mathrm{Flex}^t_j, HE^t_{j,l})$$

Here, $H^t_{j,l}$ denotes the holarchy that is encompassed within holon $h^t_{j,l+1}$. Parameter P^t_j reflects the corresponding power magnitude. F^t_j is the set of currently available forecasts for the holon $h^t_{j,l+1}$. The parameters r^t_j and s^t_j present the role and state of the holon at time t. Finally, Flex^t_j is the set of available flexibilities on all layers within the holon $h^t_{j,l+1}$ and $HE_{j,l}$ is the set of holon elements at layer l. In the remainder of this section, the individual parts of the formal holon representation (above) are explained in more detail.

RECURSIVE HOLARCHY $H^t_{j,l}$ represents the holarchy as a set of layer-l holons encompassed in the layer-$l+1$ holon $h^t_{j,l+1}$ at time t. More formally, the set $H^t_{j,l}$ is defined as

$$H^t_{j,l} = \begin{cases} \{h^t_{0,l}, \dots, h^t_{m,l}\} & \text{if } l > 0 \\ \emptyset & \text{otherwise} \end{cases}, \tag{3.2}$$

where $m \in \mathbb{N}_0$ denotes the number of holons that comprise layer l from the perspective of the j^{th} holon of layer $l+1$. In a holarchy, each holon can only be affiliated to one holon of the next higher layer. More formally, this definition can be represented as follows:

$$\forall H^t_{j,l}, H^t_{k,l}, \forall j \neq k : (H^t_{j,l} \cap H^t_{k,l}) = \emptyset \tag{3.3}$$

Consequently, holons that are located on the same layer within a holarchy do not share holons of the next lower layer. The recursive application of this definition ensures that a holon is always affiliated to one holon of the next higher layer.

HOLON ELEMENT SET Similar to lower layer holons, holon elements can be present at each layer within a holarchy. The set $HE^t_{j,l}$ comprises the holon elements of layer l from the perspective of the corresponding higher layer holon. The set is defined as follows:

$$HE^t_{j,l} = \begin{cases} \{he^t_{1,l}, \dots, he^t_{n,l}\} & \text{if } l \geqslant 1 \\ \emptyset & \text{otherwise} \end{cases},$$

Parameter $n \in \mathbb{N}$ denotes the number of holon elements that are encompassed within layer l from the perspective of the j^{th} holon and are affiliated to it. Similar to the disjointness requirement of holon affiliations presented above, the following property holds for all sets of holon elements:

$$\forall HE^t_{j,l}, HE^t_{k,l}, \forall j \neq k, \forall l : (HE^t_{j,l} \cap HE^t_{k,l}) = \emptyset \tag{3.4}$$

Therefore, holons at the same layer do not share holon elements.

POWER MAGNITUDE The power magnitude P^t_j reflects the electric behavior—which is the amount of electricity consumed or produced—of the j^{th} holon of layer-$l+1$ at time t . The power magnitude of holons is calculated by aggregating the corresponding information provided by encompassed holons, their holon elements, and individual holon elements in the holarchy. The power magnitude is calculated as follows:

$$P^t_j = \sum_{i=1}^{|H^t_{j,l}|} P^t_i + \sum_{k=1}^{|HE^t_{j,l}|} p^t_k$$

Here, $H^t_{j,l}$ is the set of layer-l holons encompassed in the j^{th} holon of layer $l+1$. Correspondingly, $HE^t_{j,l}$ represents the set of holon elements that are present at layer l from the perspective of the holon. The power magnitude of these holon elements is calculated as p^t_k. Accordingly, P^t_i is the calculated power magnitude of the i^{th} holon of the next lower level l.

FORECAST Holons within the proposed model are assumed to provide forecasts for their anticipated electrical behavior. More precisely, each holon provides a set of forecasts $F^t_j = \{f_i, \ldots, f_m\}$ for $i, m \in \mathbb{N}_0$ and $t < i < m$. Each forecast value f_i is derived as follows:

$$f_i = \begin{cases} P^i_j & \text{if forecast} == \top \\ \emptyset & \text{otherwise} \end{cases}$$

Each holon derives forecast values as the expected power magnitude of the holon at time i, if the holon is capable of calculating such values (i.e., forecast == $\top$). The corresponding forecast value f_i is assumed to be valid for the time interval defined by $[i, i+\epsilon]$, where ϵ depends on the granularity of points in time considered within the model.

ROLE AND STATE The role r^t_j of holon $h^t_{j,l+1}$ is defined similarly to the roles of holon elements. Since holons either operate by consuming electricity or by producing electricity at time t, they can either adopt the role of a *consumer* or *producer* respectively.

The state s^t_j of holons is more complex compared to the state of holon elements and depends (partially) on the status of each entity the holon encompasses. For holons, the proposed model differentiates between six mutually exclusive states, such that at time t, a holon can be only in only one state. More formally, the following holds for the states of holons:

$$\forall t, t' \in T : (s_j^t \neq s_j^{t'}) \implies (t \neq t')$$

Consequently, a holon remains in a dedicated state at least for the time interval of [t,t+1).

The different states comprise one *producing* state, and five states are associated with holons that are *consuming* electricity. The consumer states are *inactive, unsupplied, partially supplied, fully supplied*, and *oversupplied*. We further distinguish these states into states that are *desired* or *undesired* in the context of resilient grid operation. The different states are explained below in more detail:

- *Producing*. A desired state where the holon acts as a producer for the grid. In this state the holon's demand is covered by its locally produced electricity and, additionally, it provides excess electricity, which is transferred into the grid.
- *Inactive*. Inactive holons are treated as neutral entities in a holarchy. These holons neither produce nor consume any electricity. For a holon to be in an inactive state, all of their sub-holons and holon elements are also in an inactive state. This state is undesired as it represents a state of a holon where no flow of electricity is happening due to the deactivation of participants in the grid.
- *Unsupplied*. Holons are in an unsupplied state if the available energy is not sufficient to cover the demand of a single encompassed holon or holon element. This state is the most undesired state as it indicates an increased discrepancy between available production and required demand.
- *Partially Supplied*. A holon is partially supplied if the available electricity is sufficient to meet the demand of at least one of its holons or holon elements but is not sufficient to cover the total demand. This state is also undesired.
- *Fully Supplied*. The most desired state for a holon. If a holon is fully supplied, the available electricity is sufficient to fully cover its demand. Additionally, no excess electricity is (currently) produced that needs to be consumed or transferred to other parts of the grid.
- *Oversupplied*. A holon is in an oversupplied state if the available electricity in the grid exceeds the demand of the holon. It is assumed that the excess electricity in an oversupplied state can currently not be consumed or transferred to other parts of the grid (e.g., due to autonomous operation of the holon) and is therefore undesired.

FLEXIBILITIES The set Flex_j^t comprises the flexibilities flx_i that are available within the j^{th} holon at time t. Flexibilities represent local resources that are offered by prosumers for supporting grid control entities in the mitigation of demand and supply problems. The theoretical concept of flexibilities is presented in detail in the following section.

3.3.3 *Flexibilities - Leveraging Local Resources for Resilient Grid Operation*

Maintaining a continuous supply of electricity by balancing the demand and supply in holonic energy grids is challenging and becomes ever-more demanding during hazardous situations. In such situations, control entities aim to prevent degradation of grid operation by using various strategies, ranging from load-shifting and operating reserve power to interruptible load-management and load-shedding approaches (see Section 2.3.1.2). With the introduction of ever-more RESs the problem changes from adjusting a few large-scale producers towards coordinating numerous smaller and distributed resources. In this section, flexibilities are introduced as a concept for dynamically leveraging local resources to compensate for production and consumption deviations in holonic energy grids.

3.3.3.1 *Flexibility Concept*

Flexibilities aim to support grid control entities in processes for mitigating hazardous situations that threaten the balance between demand and supply in holonic smart grids. Towards this end, flexibilities allow prosumers to make local resources available for being used dynamically in processes for adjusting the demand and supply in holonic energy grids. Flexibilities can be offered at all layers of a holarchy where holon elements are present. These flexibilities are then aggregated for within holons and represented as their respective set Flex_j^t, which comprises all available flexibilities in the j^{th} holon at time t. A flexibility flx_i in the set Flex_j^t is more formally defined as a ten-tuple:

$$\mathrm{flx}_i^t = (p_i^t, \mathrm{ty}_i^t, \mathrm{dly}_i^t, \mathrm{dur}_i^t, \mathrm{cool}_i^t, \mathrm{cost}_i^t, \mathrm{pr}_i^t, C_{T,i}^t, C_{P,i}^t, s_i^t)$$

Here, p_i^t represents the *power* capacity (in Wattage) that is provided by the flexibility flx_i^t. The corresponding *type* of the flexibility is specified as ty_i^t. As flexibilities are based on holon elements, they encompass numerous performance parameters. Towards this end, dly_i^t denotes the *delay* time for activating the flexibility, *duration* dur_i^t specifies the amount of time for which the flexibility can provide its service and parameter cool_i^t reflects the *cool-down* duration that is required until the flexibility can be used again. The $\mathtt{cost}_i^t$ parameter represents the reimbursement for using the flexibility. Flexibilities have four time-dependent parameters, which are pr_i^t as the current *priority* of the flexibility, the sets $C_{T,i}^t$ and $C_{P,i}^t$ represent *technical* and *personal constraints* specified for the flexibility, and s_i^t denotes the current state of the flexibility. All parameters are explained in the following in more detail.

POWER (p_i^t) The *power* p_i^t denotes the capacity (Watt) of a flexibility that can be capitalized for changing the overall demand or supply within the energy grid. This information can be used to assess the impact of a flexibility in supporting a given (hazardous) situation (e.g., flexibilities with high power have a stronger impact compared to low-power ones). The power of a flexibility strongly depends on the power magnitude p^t of the underlying holon element. Moreover, the power of some holon elements is *adjustable* within a certain range, which, in turn, allows modifying the power of the flexibility. More formally, the power of a flexibility is defined as follows.

$$p_i^t = \begin{cases} p^t & \text{if } \mathtt{adjustable} == \perp, \\ \alpha \cdot p^t & \text{otherwise} \end{cases}$$

Here, *adjustable* specifies that the power magnitude of a holon element can vary in a particular range (e.g., batteries can have adjustable power in-/output). If a holon element is adjustable, the power of a flexibility can be specified within a range defined by $\alpha \in (0, 1]$ and the power magnitude p^t of the holon element. If a holon element is not adjustable, the power of the flexibility is equal to the power magnitude of the holon element.

TYPE (ty_i^t) Two main *types* ty_i^t of flexibilities are distinguished in this work, namely *positive* flexibilities and *negative* ones:

- *Positive Flexibility*. Positive flexibilities affect the energy balance of the energy grid by increasing the grid frequency. Therefore, positive flexibilities are based on resources that provide additional electricity (e.g., starting the discharge process for a local battery) or lower the current demand (e.g., stopping the charging process for a local battery).

- *Negative Flexibility*. Negative flexibilities affect the energy balance of the energy grid by decreasing the grid frequency. In this case, negative flexibilities are based on resources that lower the production in the energy grid (e.g., stopping the discharging process for a local battery), or use resources that increase the demand in the grid (e.g., starting the charging process for a battery).

The impact of both types of flexibilities on the energy grid frequency is shown as an example in Figure 3.3

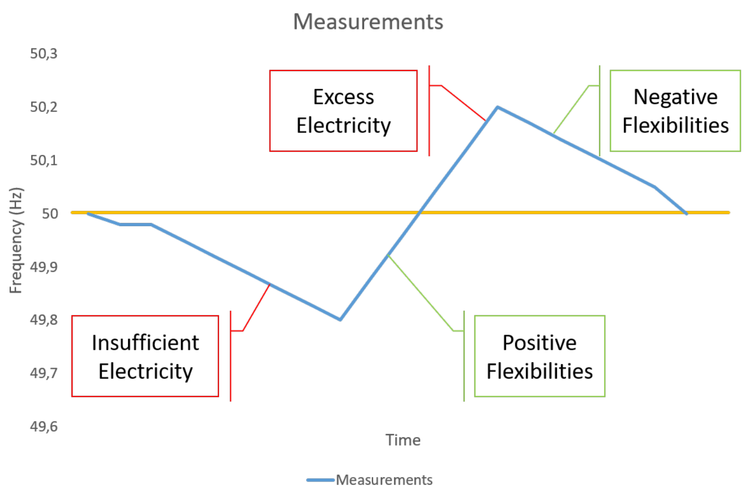

Figure 3.3: Example to show the impact of *positive* and *negative* flexibilities on the frequency of energy grids during situations where the available electricity insufficient to cover the demand, or excess electricity is available.

DELAY ($\mathtt{dly}_i^t$) Flexibilities are based on holon elements, which can be strongly heterogeneous (see Section 3.3.2.2). Consequently, flexibilities do not only vary in power but also in the time that is required until they can provide this power. Some holon elements can be able to provide their power magnitude nearly instantaneously (e.g., batteries); however, others may require some "ramp-up" time until they can provide their full power. For instance, heating devices may slowly increase their consumption until reaching their full potential. The *delay* parameter $\mathtt{dly}_i^t$ of flexibilities represents the amount of time (in seconds) that is required until a flexibility can provide its specified power. This information needs to be considered to plan the efficient use of flexibilities in situations of varying time-criticality (e.g., flexibilities with high delay may not be usable in situations where the grid frequency needs to be adjusted quickly but could be leveraged for maintaining a longer-lasting impact).

DURATION ($\mathtt{dur}_i^t$) Using flexibilities can affect their underlying holon elements, the overall situation of the prosumer who offers the flexibility, and the environment of the holon element. For instance, activating air conditioning reduces the temperature in the vicinity of the holon element but increases the electricity consumption of the house and the internal temperature of the holon element. Considering such effects, it is important to specify limits on the *duration* for using a flexibility to prevent monetary losses or damage to the devices or the environment. Parameter $\mathtt{dur}_i^t$ specifies the duration (in seconds) for which a flexibility can be used to support the grid. This duration can be affected by a variety of aspects, like technical properties of the devices or personal preferences of the prosumer.

COOL-DOWN (cool_i^t) After a flexibility was used, it may require time until it can be used again (e.g., the temperature of a water heater may need to drop below a threshold). The *cool-down* parameter cool_i^t specifies the amount of time (in seconds) until a flexibility can used again. Note that a time-based cool-down specification may be insufficient as numerous other factors may affect the usability of the flexibility, like the state-of-charge of batteries.

REIMBURSEMENT (cost_i^t) The parameter cost_i^t represents a form of *reimbursement*, which has to be paid for using a flexibility. This payment should act as both a form of incentive for prosumers to offer flexibilities and to compensate for (some of) the emerging expense resulting from their use. For example, wear and tear of the holon element or the consumption of local resources (e.g., depleting battery storage). It is assumed, for simplicity, that costs can be defined manually by the prosumers as a monetary value $\mathrm{cost}_i^t \in \mathbb{R}_0^+$. Note that this reimbursement is specific for the configuration of the flexibility and can therefore change for other flexibilities even if they are based on the same underlying holon element. Additional alternatives to monetary incentives are presented later in this work (see Section 5.2.3).

PRIORITY (pr_i^t) Each holon element is assigned to a priority class $c^t \in \mathbb{N}_0$ to indicate its relative importance to the prosumer at time t (see Section 3.3.2.2). In this work, it is assumed that each flexibility "inherits" the priority class of the underlying holon element. A high priority class of a flexibility indicates a high importance of the underlying holon element to the prosumer at time t. Consequently, we assume that it is likely that the prosumer wants to interact with the holon element. If the corresponding flexibility is then used, this may cause a decrease in user satisfaction, as the device may not be in the expected state. Likewise, flexibilities of lower priority are assumed to cause smaller decreases in prosumer satisfaction compared to flexibilities of higher priority classes and are therefore preferable for mitigating hazardous situations.

CONSTRAINTS ($C_{T,i}^t$ & $C_{P,i}^t$) *Constraints* represent both requirements and limitations for the use of flexibilities. Towards this end, constraints specify rules that need to be fulfilled for a flexibility to be usable in the first place, and to ensure the safe operation of the underlying holon element, its environment, and to take into account the preferences of the prosumers who offer the flexibilities. In this work, two categories of constraints are distinguished, namely *technical* constraints encompassed in the set $C_{T,i}^t = \{c_{T,0}, \dots, c_{T,k}\}$ and *personal* constraints that comprise the set $C_{P,i}^t = \{c_{P,0}, \dots, c_{P,l}\}$ with $k, l \in \mathbb{N}$.

- *Technical constraints.* These constraints specify technical aspects of a flexibility that need to be fulfilled; otherwise, the safe operation of the underlying holon element cannot be ensured. Consequently, technical constraints heavily depend on the peculiarities of the underlying holon element. For instance, a flexibility that is based on an individual device may rely on the device to automatically maintain "boundaries" for its safe operation (e.g., the internal temperature of a device). In comparison, other flexibilities (e.g., based on one or multiple devices connected to one actuator) may require the specification of limitations which cannot be maintained by the holon element (e.g., the devices connected to the actuator need to be actively consuming electricity for them being used as a positive flexibility). In this work, two primitive technical constraints are considered, namely *state-constraints* and *role-constraints*. State-constraints specify that a holon element must be in a specific state s^t to be used as a flexibility. The role-constraints limit the usability of a holon element for being used as a flexibility depending on its current role r^t.

An exemplary state-constraint for a flexibility flx_i^t is defined as $c_{T,0} := (param = state, exp = \{inactive, standby\}, fnc = \{equal\})$, where $param$ defines which parameter of the holon object is affected by the constraint. The parameter exp represents a set of values for the state parameter which are used as reference values in combination with the functions fnc to assess if the constraint is fulfilled (e.g., the *equal*-function checks if two parameters are equal). Checking the constraint $c_{T,0}$ can be done as follows:

$$\exists s \in exp, \exists g \in fnc : fnc(s, s_i^t) \implies check(c_{T,0}) == \top$$

The constraint is fulfilled if the state of the underlying holon element is either *inactive* or *standby*. Here function $check(\cdot)$ is an auxiliary function that takes a constraint as an input returns $true$ if the assessment of the constraint yields a positive result. Note that these constraints are very primitive, and increasingly complex constraints may be required to make holon elements usable and to ensure their safe operation in energy grids. Some *limitations* are discussed below.

- *Personal constraints*. These constraints are more ambiguous compared to technical constraints since they need to limit the use of flexibilities based on personal preferences of the prosumers offering the flexibilities, which are not necessarily based on technical specifications of the underlying holon elements or the environment. Information that is required to specify such constraints need to be provided by the prosumers or must be accessible locally (e.g., room temperature, time measurements). A primitive personal constraint can be a *priority-constraint*, which renders a flexibility usable depending on the priority class c^t of the underlying holon element. An exemplary priority-constraint for a flexibility flx_i^t is defined as

$c_{P,0} := (param = priority, exp = \{4\}, fnc = \{low, equal\})$, where $param$ defines the parameter for which the constraint is defined. Parameter exp represents a reference value that is used in combination with the functions fnc to check if the constraint is fulfilled. Checking the constraint $c_{P,0}$ can be done as follows:

$$\exists c \in exp, \exists g \in fnc : fnc(s, c_i^t) \implies check(c_{P,0}) == \top$$

The constraint is fulfilled if the priority class c_i^t of the holon object is lower or equal to priority class 4. Here, function $check(\cdot)$ is again an auxiliary function that takes a constraint as an input and returns $true$ if the assessment of the constraint yields a positive result. Similar to the technical constraints presented above, this priority-constraint is very primitive and increasingly complex constraints may be required to address the preferences of different prosumers adequately. The *limitations* of the presented primitive constraints are discussed below.

- *Limitations*. The specification of constraints can quickly become increasingly complex, depending on the underlying holon elements, the peculiarities of prosumer preference or combinations of both. In this work, the constraints are limited to primitive ones, which allows defining them (semi-) automatically based on the properties of the underlying holon elements. Furthermore, they can be verified based on this information (e.g., state-constraints, priority-constraints). However, for a more realistic representation of constraints, especially for personal constraints that may change over time, a more sophisticated model is required. Such a model needs to provide at least basic programming logic to enable the specification of parameters and functions for checking the constraints. Additionally, the model needs to provide the corresponding data from the holons, holon elements, or even third-party services that may interact with a holon, like EVs and weather forecast systems. However, such a model is considered to be out of scope of this work and is pursued in subsequent work.

Constraints are restricting the use of flexibilities mainly in two ways: firstly, if at least one constraint is not fulfilled after the configuration process of a flexibility, this flexibility cannot be offered for grid control processes. This technical limitation prevents prosumers from offering flexibilities that are not operating under safe conditions. Secondly, constraints must be repetitively checked—within reasonable time-constraints for the energy grid and the current situation—and need to remain fulfilled for the duration a flexibility is used. During mundane operation of the energy grid, time-intervals for checking the constraints may be more relaxed (e.g., every 15 seconds); however, for anticipated hazardous situations, and during the use of flexibilities, a higher frequency for checking may be required to be able to react to changing conditions and failures quickly. Especially, since constraints can be violated while a flexibility is used (e.g., temperature thresholds may be violated due to changes in weather conditions), in which case the flexibility becomes unavailable until the constraints are fulfilled again. The capacity provided by this flexibility to support the grid then needs to be compensated using other available resources. The various operational conditions of a flexibility are represented by different states s_i^t, which are explained below.

FLEXIBILITY STATE (s_i^t) A flexibility can be in one of four mutually exclusive states s_i^t at time t. These states define the availability of the flexibility for being used in processes to support the mitigation of demand and supply deviations. The states are *Not-offered, Offered, In-use* and *Cool-down*. These states and the corresponding transitions between them is shown in Figure 3.4 and is explained below.

- *Not-offered*. Initially, a flexibility needs to be configured by specifying important parameters and possible constraints. After the configuration, the flexibility remains in the *Not-offered* state until a prosumer decides to offer it. If a prosumer issues an offering command, the constraints are checked, and if all constraints are fulfilled, it transitions into the *Offered* state. Flexibilities can also transition into the *Not-offered* state when they are manually *withdrawn* from being offered, or when constraint violations occur.

- *Offered*. A flexibility in an *Offered* state fulfills its constraints and an offer command was issued. In this state, flexibilities can be leveraged for mitigating demand and supply deviations. If a control entity decides to use a flexibility, it transitions to the *In-use* state.

- *In-use*. A flexibility in this state is actively used to support the mitigation of demand and supply deviations. Flexibilities in this state provide their service (e.g., produce electricity) for the specified duration and cannot be used for other purposes. In this state, the constraints of the flexibility are checked repeatedly—with a higher frequency compared to other states—and, in case of any violations occur, the flexibility transitions into the *Not-offered* state. If the operation of the flexibility ends without constraint violations, it transitions into the *Cool-down* state if a cool-down is specified, otherwise, it transitions into the *Offered* state.

- *Cool-down*. After a flexibility was successfully used for its specified duration, no constraints were violated, and a cool-down is configured for the use of the flexibility, it transitions into the *Cool-down* state. From this state, a flexibility can transition into the *Offered* state if the specified cool-down time has passed and its requirements remain fulfilled; otherwise, if constraint violations occur the flexibility transitions into the *Not-offered* state.

A flexibility transitions between the states as mentioned above, depending on different events that can occur. Figure 3.4 shows the transitions of a flexibility between the states described above as a state chart diagram. The different events that are considered as conditions for state transitions are described below.

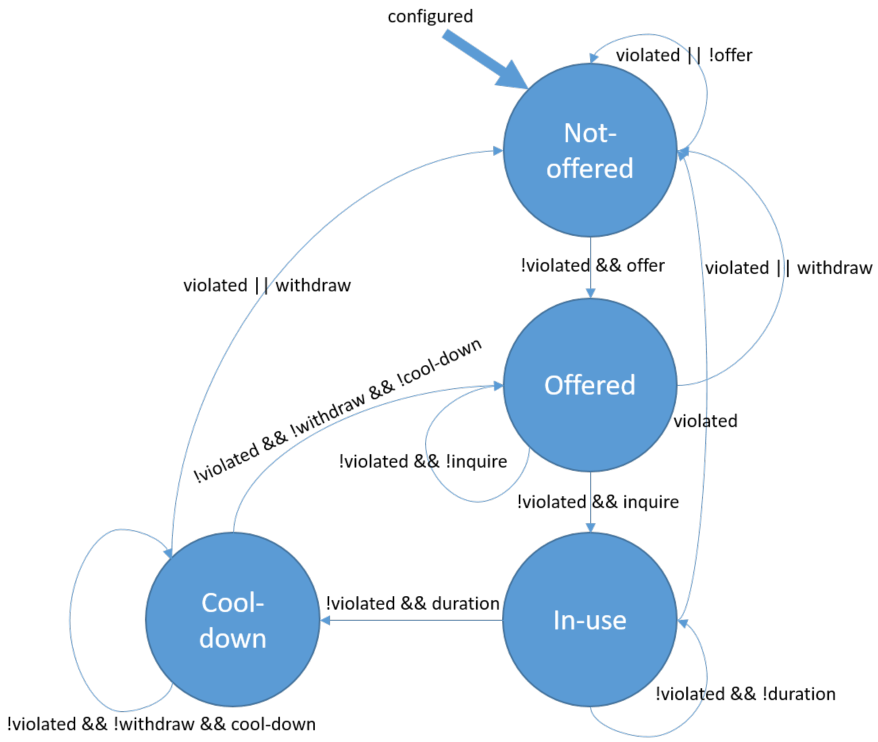

Figure 3.4: The different state transitions of a flexibility. The events that can lead to changes of states are *configured*, *offer*, *violated*, *withdraw*, *inquire*, *duration*, and *cool-down*. Combinations of these events, or their absence, allow flexiblities to transition between the different states.

- *Configured*. The *configured* event is the entry event for a flexibility after it is successfully configured by a prosumer. After the successful configuration, a flexibility transitions into the *Not-offered* state.
- *Offer*. The *offer* event denotes an attempt of the prosumer to offer a configured flexibility. If this event is triggered and no constraints are *violated* the flexibility transitions into the *Offered* state. Otherwise, it remains in the *Not-offered* state.
- *Violated*. The *violated* event indicates that at least one of the constraint checks of the flexibility failed; therefore, the flexibility can not be operated according to its specified configuration. If this event occurs, the flexibility transitions into the *Not-offered* state, regardless of its previous state.
- *Withdraw*. *Withdraw* events occur when prosumers manually withdraw their offer of a flexibility, so it can no longer be used to sup-

port the energy grid. Flexibilities can be withdrawn if a flexibility was previously offered and is currently in a state where it is not actively used to support the grid.

- *Inquire*. *Inquire* events occur if a control entity in the grid wants to use a flexibility for supporting the energy grid. If an offered flexibility is inquired and no constraints are violated occur, the flexibility transitions into the *In-use* state.
- *Duration*. The *duration* event indicates that the flexibility has been used for the intended duration.
- *Cool-down*. The *cool-down* event indicates that the flexibility successfully remained in the *Cool-down* state for the configured amount of time.

3.3.3.2 *Flexibility Integration within Holonic Smart Grids*

To use flexibilities for mitigating hazardous situations in holonic smart grids, several challenges need to be addressed regarding their integration in the holarchy and their configuration at the prosumer level. In the following, we present three important challenges for integrating flexibilities within holonic energy grids. While we do not provide technical solutions to the challenges, we highlight and discuss concepts and methods that can be leveraged to address the challenges.

RESOURCE REGISTRATION Local resources need to be made accessible to control authorities at different layers within the holarchy. At the prosumer layer, individual holon elements need to be controlled. Towards this end, holon elements must be identified at prosumer locations and made accessible (see Section 3.3.2.2). Additionally, these elements need to be prioritized to reflect their relative importance to the prosumers. Afterward, the operational parameters of the flexibilities and corresponding constraints need to be specified (see Section 3.3.3).

The identification and registration of holon elements can be done is different ways. For instance, prosumers could manually register holon elements within the local control systems by using information of data-sheets of appliances and devices. To reduce the effort of registering each device manually, devices could be identified and registered automatically. Smart devices could connect to the local control system and provide the necessary information. Likewise, smart sockets could be used to connect non-smart devices in the same way [40]. Additionally, research has shown that devices can be identified by their electrical profile and location parameters [183, 228].

The prioritization of holon elements can be conducted similarly, either by manual configuration or the local control system could learn a prioritization depending on the prosumer behavior. Research shows that user behavior recognition can be successfully applied to reduce the energy consumption within smart homes [17, 180, 197]. These techniques could be adjusted to derive holon element prioritization for individual prosumers.

(SEMI-) AUTOMATIC PARTICIPATION Once resources are accessible on a technical level for local control and control authorities within holarchies, strategies are required that specify how these resources participate within operational processes of holonic energy grids. In particular, prosumers need to be able to make local decisions regarding the participation or configuration of resources. Therefore, manual participation of prosumers needs to be supported. Additionally, strategies for *automatic* participation are required. These strategies require minimal or no manual prosumer interaction and can be applied to quickly react to emerging situations. Both kind of strategies are required to balance between the effort for prosumers to actively participate in holonic energy grids and the necessity to relinquish control through automation. Many of the required functionalities are already provided by concepts like HEMSs and energy consumption schedulers (see Section 2.3.1.2), which allow scheduling appliances at prosumer locations by facilitating digital resource control. Such approaches can be extended for supporting the concepts and methods presented in this thesis, but a prototypical implementation is considered to be out of scope of this work.

COMMUNICATION To leverage distributed resources within holonic energy grids effectively, exchanging information between prosumers and control authorities on different layers is crucial. On the one hand, participants in the grid require information about the overall grid situation and potential hazardous events. On the other hand, control authorities need to be informed about control-relevant information like sensor data and flexibilities to support them in assessing the situation and corresponding decision-making.

As described previously in this work, we differentiate between delegation, propagation, and negotiation for general communication patterns within holarchies (see Section 3.3.2.1). With the assumption of a comprehensive ICT-infrastructure being established within holonic smart grids, various concepts can be considered for realizing the aforementioned communication types [146]. However, due to the high complexity of smart grids, individual concepts are unlikely to suffice for handling the communication within holonic energy grids, especially, since the requirements for communication within may vary between layers (e.g., communication requirements within a house may different from the communication within a community). Therefore, concepts and standards are required capable of interacting seamlessly within and between different layers [18, 200, 240].

3.3.4 *Improved Problem Mitigation Capabilities*

Organizing energy grids according to the holon model proposed in this work, improves their capabilities for operating resiliently while facing hazardous situations.

Traditional approaches for mitigating demand and supply problems are based on using reserve capacity, interruptible load management, and for severe situations, the application of rolling-blackouts. Section 2.3.1.2. These approaches can improve the situation significantly but also pose a significant challenge for the energy grid.

The application of the proposed holonic model enables reorganizing energy grids quickly, depending on the current problem situation and improves the local mitigation of demand and supply problems. Towards this end, the intrinsic properties of holons (see Section 3.3.2.1) allow operating emerging sub-systems autonomously or in collaboration with other holons, despite potential disturbances on higher layers in the grid. Locally available holon elements—offered as flexibilities—support the balancing of the demand and supply within holons, reducing the need for transferring (remote) balancing power and supporting the stability during autonomous operation. 3.2 provides an exemplary showcase to highlight the improved mitigation capabilities.

> **Example 3.2: Example for showing the improved problem mitigation capabilities of holonic energy grids**
>
> Let there be a small set of holons ($h_{i,0}$) and holon elements ($he_{j,0}$) for $i, j \in \mathbb{N}_0$ representing individual houses as a part of a layer-1 holon ($h_{1,1}$), which is connected to the medium voltage (MV) grid via a transformer (MV/LW). Another layer-1 holon ($h_{2,1}$) represents the neighborhood (NH), which has an individual connection to the MV grid and is otherwise separated from ($h_{1,1}$). The layer-0 holons encompass smart devices and actuators as described in Section 3.3.1. Additionally, three EVs are present in the holon $h_{1,1}$. Figure 3.5 shows the exemplary energy grid.

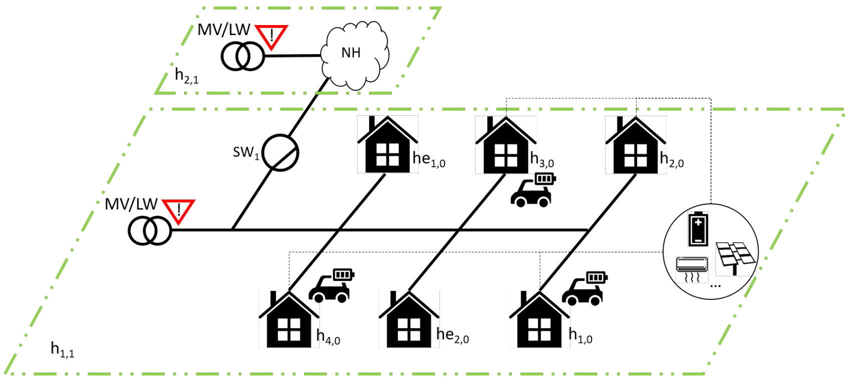

Figure 3.5: Exemplary scenario for improved problem mitigation. The holonic energy grid faces a drop in production capacity due to disturbances on higher layers in the grid.

Now let a severe problem occur in the grid, resulting in a severe drop of production in the grid that cannot be efficiently compensated by traditional operational capacity and requires rolling blackouts organized by higher layers in the grid. In this case, $h_{1,1}$ and $h_{2,1}$ would (repetitively) experience blackouts until the problem situation is resolved. As a consequence, layer-0 holons with battery storage, local production, or EVs with vehicle-to-grid technology might be able to supply themselves (partially) during this situation, but at least all holon elements on layer-0 would experience a blackout situation.

In comparison, Figure 3.6 shows a conceptual solution that can be applied to mitigate the problem situation (even if higher layers in the grid are not responsive). Here, holons $h_{1,1}$ and $h_{2,1}$ decide to *split* from the MV grid—to follow their intrinsic goals—and operate *autonomously*. Since this also disables the flow of electricity from higher layers, demand and supply need to be balanced locally. Towards this end, all participants provide positive *flexibilities* to either reduce their consumption or provide additional production. These flexibilities are then used while considering the corresponding *priorities* to balance demand and supply and to maintain prosumer satisfaction. The holons $h_{i,0}$ with $in \in \{1, 2, 3, 4\}$ and holons of the neighborhood NH reduce their consumption by using positive flexibilities of lower priority. Additionally, holons $h_{1,0}$ and $h_{1,4}$ use their EVs (low priority) to provide additional production capacity. To further improve the situation, holons $h_{1,1}$ and $h_{2,1}$ *negotiate* and decide to *merge* in order to combine their resources. Combining the actions described above allows maintaining a continuous (but reduced) supply with electricity to all participants in this part of the grid, where, otherwise, at least the holon elements at layer-0 would have experienced a complete black-out. Simultaneously, the loss of prosumer satisfaction is reduced by mainly leveraging flexibilities of lower priority and keeping holon elements of higher priority operable for the duration of the problem situation.

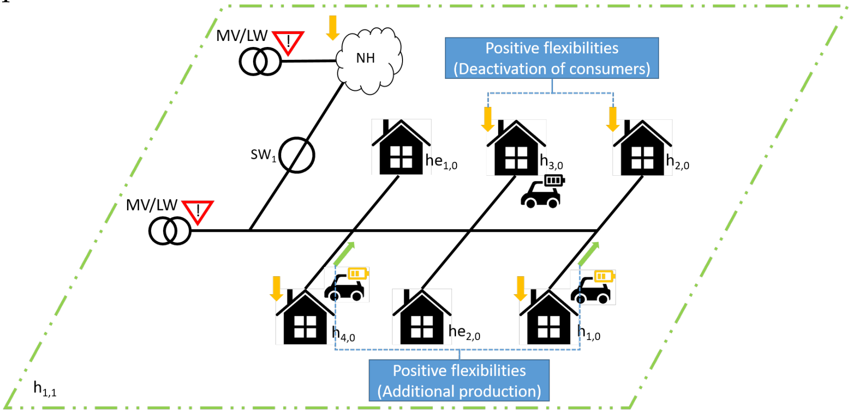

Figure 3.6: Using the reconfiguration capabilities of holons and local flexibilities to improve the problem situation compared to traditional mechanisms, like rolling black-outs.

3.4 HOLONIC SYSTEM SIMULATION

To investigate the proposed model, a testing and evaluation environment is required. As described previously in this chapter, the real grid is unavailable for testing, and test-beds for evaluating holonic concept are not available (see Section 3.2.3). In this section, first, the unsuitability of existing simulation tools for simulating our proposed holonic model is highlighted. Second, the discrete-time simulation environment HOLEG is presented, which is based on the proposed semi-formal holon model (see Section 3.3.2). Finally, the core functionalities of HOLEG for supporting the evaluation and investigation of novel optimization and control approaches is presented [59].

3.4.1 *Limitations of Existing Simulation Tools*

A broad selection of modeling and simulation tools for the energy grid exists Section 3.2.3. However, these tools are not well-suited for integrating the holonic concept and for evaluating novel system control approaches. In the following, identified requirements are presented, which are important for simulation environments to support the modeling and simulation holonic energy grids and for investigating novel control concepts. Subsequently, existing simulation tools are compared based on the aforementioned requirements, and their most important limitations in the context of holonic energy grids are briefly discussed.

REQUIREMENTS FOR HOLONIC SYSTEM SIMULATION

1) *Architecture Support*: As the energy grid transitions towards an increasingly distributed system, simulation environments need to support various architectures ranging from hierarchically organized systems to distributed ones, and hybrid approaches, like holarchies.

2) *Granularity*: Smart grids are envisioned to involve a diverse set of heterogeneous stakeholders and their resources. Since these stakeholders may become increasingly relevant for the mitigation of hazardous situations (see Section 2.4), simulation environments need to be able to integrate these stakeholders and their local resources.

3) *Scalability*: With an increasing number of stakeholders on various layers within the energy grid and a strong integration of ICT, the overall number of devices that need to be considered in the grid increases significantly. Therefore, simulation environments need to be capable of handling many devices.

4) *Extensibility*: The grid is undergoing drastic changes in the process of transitioning towards a smart grid. Towards this end, parts of the grid are extended and novel components are introduced. This development is an ongoing process, which will–if it ever finishes—continue for decades and needs to be considered by simulation environments. Towards this end, simulators need to be extensible such that adjustments to existing technologies can be made and novel technologies can be smoothly integrated.

5) *Interoperability*: The energy grid requires special hardware (e.g., equipment in transformer stations, load breakers) and is, additionally, going to be increasingly interconnected with various other energy sectors. Since such couplings are required to support the efficient use of electricity, energy grid simulators should support the interoperability with hardware, tools, and devices from various domains to investigate the impact of novel developments on real hardware, and to analyze the effects that emerge from the collaboration between different energy sectors.

6) *Usability*: A well-designed simulator with good usability improves understanding of the simulated aspects and, furthermore, supports non-IT experts from different domains in using the simulation tool (e.g., manufactures for EVs).

7) *Interactivity*: System security and safety are important properties for energy grids. In order to assess the impact and consequences of failures and attacks on the energy grid, a simulator should provide capabilities to introduce hazardous situations into the simulation process. Especially since technologies based on RESs strongly depend on volatile environmental factors like wind and solar radiation and the integration of ICT introduces the potential for cyber-

attacks, it becomes increasingly important to investigate the emerging consequences of such technologies.

8) *Time-Management*: With the transition towards increasingly distributed systems, the dynamic behavior of stakeholders within the system increases. The interdependencies between stakeholders may cause problems that appear after short periods but may also yield problems that develop slowly or are cascading through the energy grid. To address such aspects emerging from various time periods, energy grid simulation tools should support the simulation of variable time-horizons to assess short- and long-term behavior and corresponding consequences alike.

COMPARISON OF AVAILABLE SIMULATION TOOLS For investigating the holonic system concept, the available tools (see Section 3.2.3) are compared according to the requirements stated above. In the following, Tab. 3.3 show the results of this comparison. Here, ✓ indicates a requirement that is fulfilled and (✓) indicates partially fulfillment or strong potential to integrate the necessary changes without the need for conducting fundamental changes on the tool. ✗ refers to requirements that are not fulfilled, and (✗) indicates that increased effort is required, but changes could be conducted to fulfill the requirement. Most of the tools cannot fulfill one or more of the identified require-

Table 3.3: Overview of the physical aspect simulation tools and their coverage of the identified requirements for their future application in smart grid simulations.

Simulator\Requirement	1	2	3	4	5	6	7	8
APT-EMTP [69]	(✗)	(✓)	(✓)	✗	✗	✓	✗	(✗)
PSCAD/EMTDC [89]	✓	(✗)	✓	(✓)	✗	✓	✗	(✗)
NEPLAN [163]	✓	✗	✓	(✓)	✓	✓	(✓)	(✗)
ETAP [68]	✓	(✗)	✓	(✓)	(✓)	✓	(✓)	✓
PSLF [83]	(✓)	✗	✓	✓	✓	✓	(✓)	(✓)
Power Factory [53]	✓	(✗)	✓	✓	✓	✓	(✓)	✓
GridLAB-D [159]	✓	(✓)	✓	(✓)	(✗)	✗	(✓)	(✓)
OpenDSS [63]	✓	(✗)	✓	✓	(✓)	(✓)	✗	(✗)

ments, and, additionally, commercial tools cannot be adapted except by the company responsible for maintaining the tool. This further complicates the investigation of novel approaches within the energy grid. For the comparison above, we did not distinguish between commercially available tools and open-source solutions but solely focused on their properties and capabilities. The HOLEG simulation environment is explained in detail next.

3.4.2 *HOLEG Simulation Environment*

HOLEG is a discrete-time simulation environment based on the holonic energy grid model presented in this work (see Section 3.3.2). HOLEG is continuously developed as an open-source project[2]. The main purpose of this tool is to support the investigation of holonic energy grids and the development of novel grid control approaches for mitigating hazardous situations. Towards this end, HOLEG allows simulating simplified energy grids based on the holon model proposed in this work and provides capabilities to investigate, observe and evaluate approaches to support the mitigation of problems within the system. Figure 3.7 shows the graphical user interface of HOLEG with a modeled small-scale grid example. In the following, the most relevant aspects of HOLEG are presented and explained in detail.

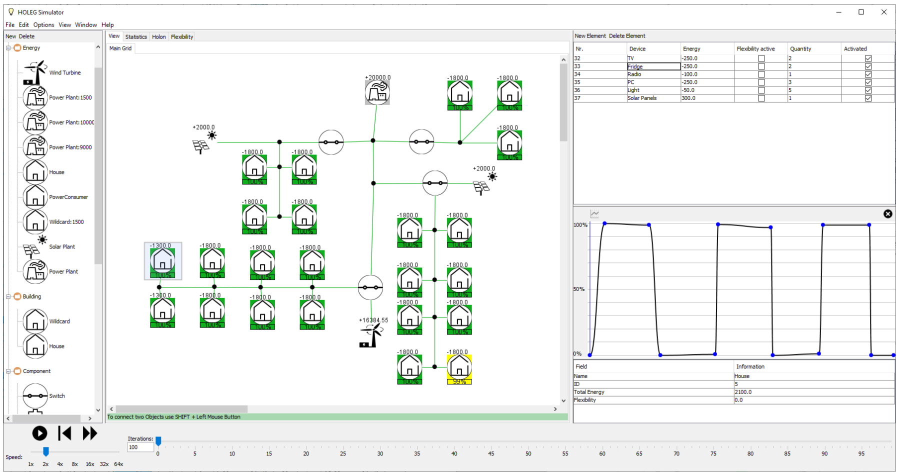

Figure 3.7: The graphical user interface of HOLEG consists of an object library (left), a central canvas for modeling grids (center) and an information area (right) for showing and modifying a variety of detailed information.

3.4.2.1 *Holon Element Representation*

HOLEG models energy grids based on the previously introduced holonic system model (see Section 3.3.2). Holon elements and their corresponding behavior in the grid can be configured according to the model presented in Section 3.3.2.2. In order to simplify the modeling process, HOLEG provides a selection of pre-configured holon elements as part of the object library (e.g., solar panel, fridge, house)

2 https://git.tk.informatik.tu-darmstadt.de/carlos.garcia/praktikum-holons

and the corresponding production and consumption information according to typical load and production profiles. Note that the object library can be easily extended. Furthermore, the production and consumption behavior of the holon elements can be modeled in detail by adjusting their power magnitude profile (see Figure 3.8). This profile defines their electrical production or consumption behavior during a specific period of time (e.g., for an hour or a day). During the simulation, devices follow their power magnitude profile and produce or consume electricity accordingly. If the profile is specified for a time period that is shorter than the overall simulation duration, the behavior is repeated until the simulation ends. For instance, for devices that show a repetitive behavior of increasing and decreasing consumption, e.g., fridges, one cycle of the behavior can be modeled (e.g., for one hour) and then be repeated for the duration of the simulation. This reduces the overall modeling effort but also allows representing repetitive effects like day-night cycles.

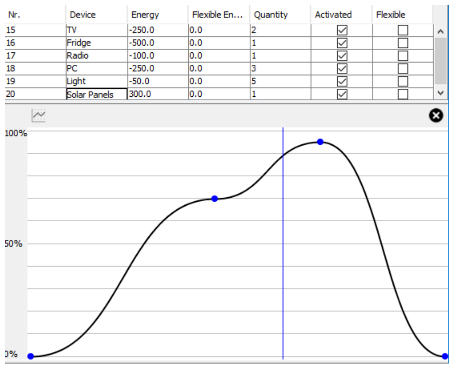

Figure 3.8: Holon element configuration panel. It enables the configuration of individual holon elements encompassed in a holon and provides detailed modeling functionalities for the electrical consumption and production of the holon elements.

Holon elements are not considered as holons, as they lack the necessary properties to operate autonomously and to sustain themselves (see Section 3.3.2.1). Therefore, either holon elements are encompassed within a holon that is responsible for managing them, or they are operating as standalone entities on a specific layer within a holarchy. Towards this end, HOLEG introduces *holon objects* to act as an intermediate representation and first aggregation layer for holon elements. These holon objects can represent both primitive holons as an initial aggregation of a set of holon elements (e.g., a house encompassing appliances) or individual holon elements (e.g., a house with a consumption profile) if they do not aggregate any holon elements.

3.4.2.2 *Holon Representation*

The representation of holons with HOLEG is using two concepts: firstly, holon objects can represent "primitive" holons on layer-0, where holon elements are aggregated to form a holon without any further encompassed holons; secondly, *group-nodes* are introduced that allow aggregating arbitrary entities on one layer to form a new holon of the next higher layer in the holarchy. For instance, after modeling several prosumers in HOLEG, a group node can be used to aggregate them as a holon that represents a street. Once a holon or holon element is encompassed in a holon at the currently visible layer, group-nodes automatically prevent that these entities can be affiliated to another holon at the same layer. The holon objects and group-nodes are used as the main building blocks for modeling participants in the energy grids and to form a holarchy.

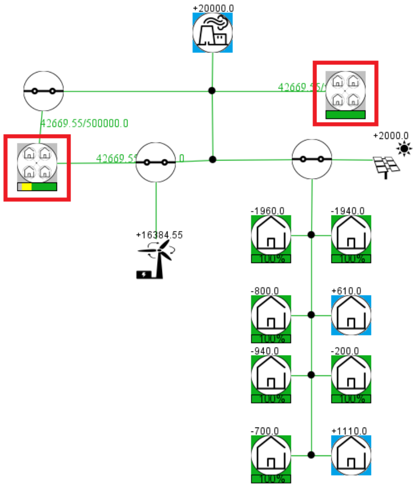

Figure 3.9: View of holarchy layer-1 in HOLEG, where two layer-1 holons are represented as group-nodes and multiple holon objects represent holon elements. The group-nodes are marked with a red rectangle and encompass numerous level-0 holons and holon elements.

Holons, in general, comprise numerous components, and the state of holons is correspondingly an aggregation of the states of their encompassed entities. In the following, the representation of these states in the HOLEG simulation environment is presented.

HOLON STATE REPRESENTATION One of the most important indicators for users of the HOLEG simulation environment to assess the current situation of the energy grid are the states of the individual holons within the holarchy. Towards this end, HOLEG implements the states that are introduced in Section 3.3.2.3 using a color-coded highlighting for holon objects and group-nodes. The currently implemented color-coding is shown in Figure 3.10.

The implemented states and corresponding colors are *producer* (blue), *unsupplied* (red), *partially supplied* (yellow), *fully supplied* (green), *over-supplied* (purple) and *inactive* (gray). All states except for the inactive and producer state, provide additional information about their status via a percentage indicator located below the icon of holon objects.

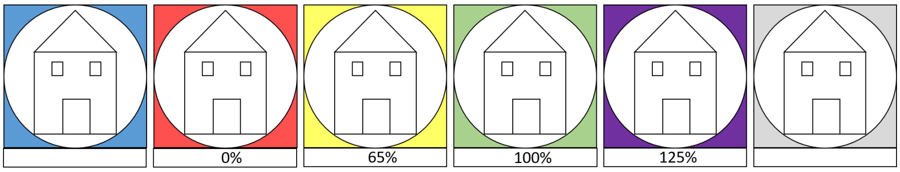

Figure 3.10: The different holon state representations are *producer* (blue), *unsupplied* (red), *partially supplied* (yellow), *fully supplied* (green), *oversupplied* (purple), and *inactive* (gray).

This indicator reflects the degree to which a holon is currently supplied within its current state. For instance, let a layer-0 holon contain five holon elements. If the available electricity is sufficient to supply one of its holon elements, the holon is in a partially supplied state (yellow), and the percentage bar indicates 20%. In this case, the partially supplied state is achieved by supplying at least one of the encompassed holon elements but not all of them. The 20% indicator is derived from the amount of available energy that is sufficient to supply one out of five of the encompassed holon elements.

For higher-layer holons that are represented as group nodes, the same requirements as specified in Section 3.3.2.3 apply, but the percentage indicator works slightly differently. Since holons of higher layers may encompass numerous holons, fine-grained information about the state of the encompassed entities can be useful to assess the severity of the situation. Towards this end, the percentage indicator shows the number of holons and their corresponding states by coloring individual fractions of the indicator bar according to the fraction of encompassed holons that are currently in this specific state. For instance, if 25% of the encompassed holons are partially supplied, 15% are producers and 60% are fully supplied, the corresponding fractions of the bar are colored in yellow, gray and green (see Figure 3.9).

FLEXIBILITY REPRESENTATION HOLEG allows holon elements to be offered as flexibilities according to the specification proposed in Section 3.3.3.1. Towards this end, holon elements can be configured and can then be offered to be used in processes for mitigating demand and supply problems in the holarchy if they are encompassed in a holon that is responsible for managing the holon element. Otherwise, the holon element is an uncontrollable part of the grid (e.g., a consumer without ICT). For holon elements that are encompassed within a holon, the configuration dialog shown in Figure 3.11 is provided within HOLEG.

Here, a holon element representing a washing machine, which is part of a layer-0 holon (represented as a holon object), is in the process of being configured as a flexibility. The *type* of the flexibility is positive, so the intention is for the holon element to be used to raise the grid frequency. The delay is derived from the holon element, which is

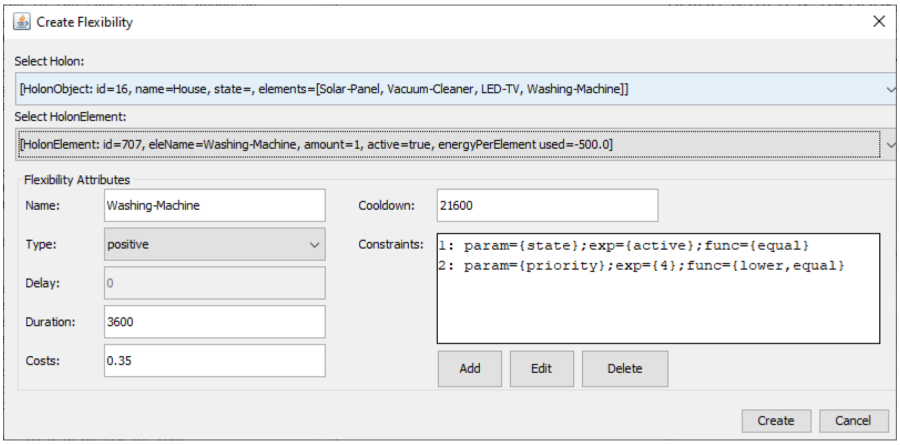

Figure 3.11: Dialog within HOLEG to configure a flexibility. A holon can be selected and one of the holon elements within the holon can be registered as a flexibility. Note that some parameters, like the *power* and *priority* are derived from the underlying holon element and cannot be specified manually.

zero. This indicates that the flexibility takes effect instantaneously after activation. The *duration* is configured to be one hour, and the costs for using the flexibility are 35 Cents. After the flexibility has been used, there is a required cool-down period of 21,600 seconds, which is six hours. Finally, two constraints are registered, which are one *state-constraint* and one *priority-constraint*. The state constraint requires the flexibility to be in an active state in order to be used for mitigating demand and supply problems. The priority constraint states that the priority of the underlying holon element needs to be equal or lower to a priority of four. Other parameters, as specified in Section 3.3.3.1, are derived automatically from the underlying holon element and are not displayed in the configuration dialog.

At the time of writing of this work, HOLEG supports the configuration of relatively primitive constraints as discussed in the constraint paragraph of section 3.3.3.1. The representation of increasingly complex constraints (e.g., based on a combination of prosumer preferences) cannot be easily done by using the flexibility configuration dialog of HOLEG but need to be programmed. Extending HOLEG with the functionality that allows the configuration of increasingly complex constraints is part of ongoing and future work.

After a flexibility is configured successfully, HOLEG allows investigating all holon elements and corresponding important information (e.g., the configuration as flexibilities and their states) using the *flexibility manager*, which is shown in Figure 3.12. The example shows a water-heater and a solar panel, which are configured as two flexibilities each. One flexibility for each of the holon elements uses a state-constraint that requires the holon element to be inactive; therefore, these flexibilities are currently violated (i.e., their state is *unavailable*). The other two flexibilities, require the holon elements to be *active*, which is currently the case, and the flexibilities are successfully offered.

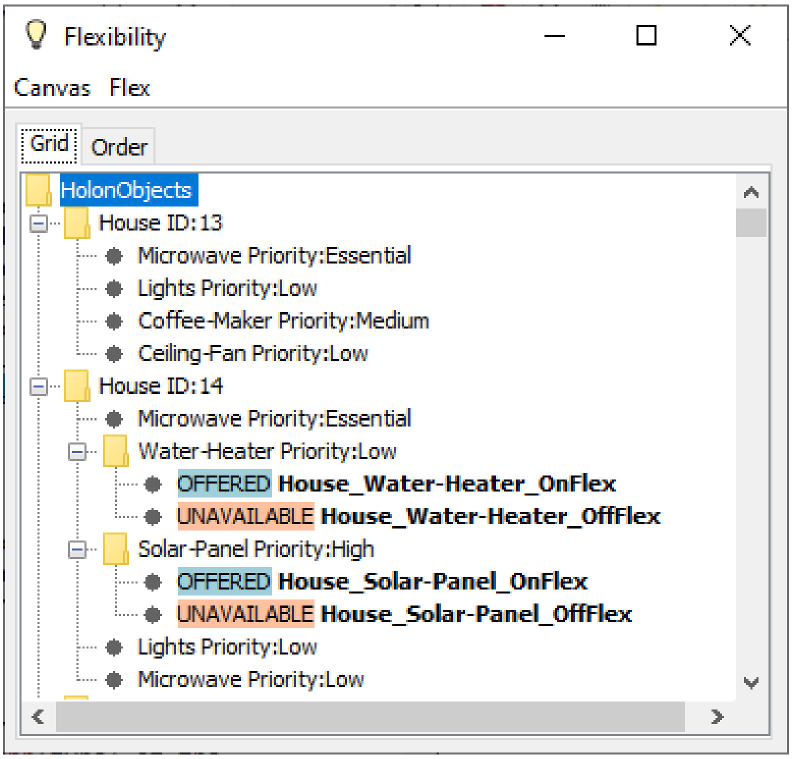

Figure 3.12: The flexibility manager of HOLEG, which shows information about all holon elements within the modeled holarchy. Among this information is the affiliation of holon elements to holons, the assigned priority classes and their configuration as flexibilities.

3.4.2.3 *HOLEG Algorithm API*

An important purpose of the HOLEG simulation environment is supporting the development of algorithms that allow controlling and optimizing the operation of holonic energy grids. Towards this end, HOLEG provides a designated algorithm application programming interface that has two main purposes: firstly, it enables access to all information of the holarchy model and the functionalities of the HOLEG simulation environment. This allows simulating numerous effects, like weather impact on electricity production and failing components in the grid. Furthermore, the process of modeling various energy grids can be simplified by using scripts to automatically generate different grid configurations and components (e.g., different houses with various holon elements), which allows adjusting the grid quickly (e.g., increasing the available number of solar panels in the grid). The application programming interface also provides access to actuators of holon elements, load breaker switches, and information about holons, which can be used to implement control and optimization algorithms for managing the simulated holonic energy grid. These algorithms can then be executed during the simulation, and their effects can be observed and analyzed.

Secondly, the application programming interface can be used as an interface to connect third-party tools and hardware to the HOLEG simulation environment and enables their interaction with the model. Using this interface, developers can use the Java programming language to implement novel control strategies and evaluate the performance of their approaches. The results of the simulation and the execution of the algorithms can be displayed within HOLEG and exported into external files for further use. A selection of algorithms that are implemented using the aforementioned interface of HOLEG are briefly explained next.

HOLON ELEMENT RANDOMIZATION The holon element randomization algorithm supports developers in generating diverse holonic energy grids. Towards this end, the algorithm can be used to select holons in a model holarchy and adjust the encompassed holon elements. A set of preconfigured holon elements is provided by HOLEG and can be loaded by the randomization algorithms. The state of the holon elements and their priority class can then be assigned probabilistically. Figure 3.13 shows the graphical user interface of the holon element randomization, where different holons can be selected, which then get modified to encompass a certain number of holon elements (here between three and seven). Furthermore, the holon elements can be assigned to priority classes, where the sliders on the right side specify the fraction of holon elements that gets assigned to a four-class priority setup (i.e., priority classes 0–3).

INFORMATION PANEL The information panel algorithm uses the HOLEG application programming interface to access a variety of information provided by the holarchy model. This information is then processed (e.g., statistical calculations) and displayed to the user. Figure 3.14 shows an excerpt of the information panel, which displays information about switches, holon elements, and priority classes in a holarchy.

HOLARCHY RECONFIGURATION Holarchy reconfiguration algorithms aim at optimizing the management of holonic energy grids by reconfiguring the holarchy, and allocating available resources (e.g., flexibilities). Figure 3.15 shows an exemplary algorithm graphical user interface of a particle swarm optimization (PSO) algorithm. The numerous parameters of the algorithm can be configured and the results are displayed on a console at the bottom of the algorithm window. This algorithm—and numerous others—is explained and compared extensively later in this work (see Chapter 4).

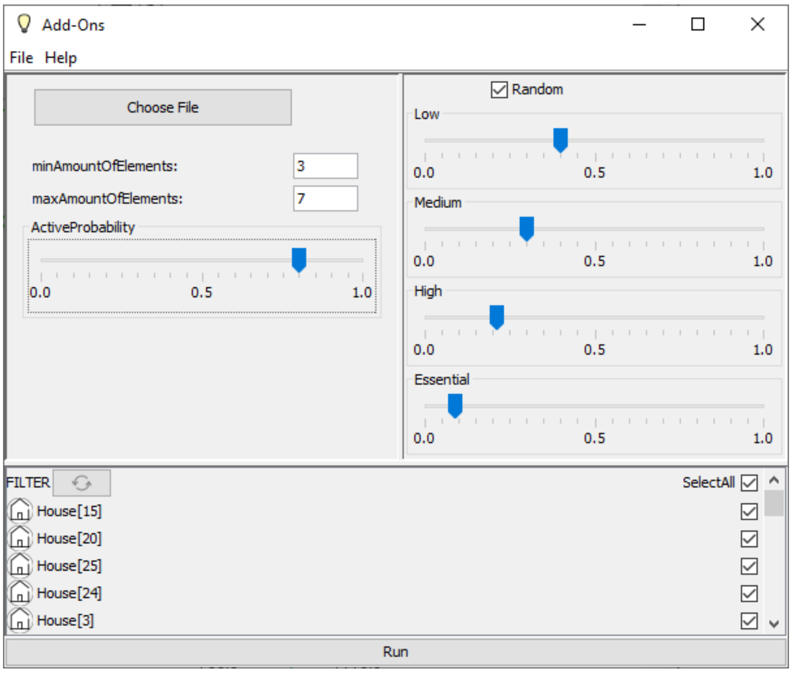

Figure 3.13: Randomization algorithm for holon elements, which allows loading preconfigured holon elements and placing them in selected holons. This supports the diversification of a holarchy, by simplifying the process of representing different houses or enterprises.

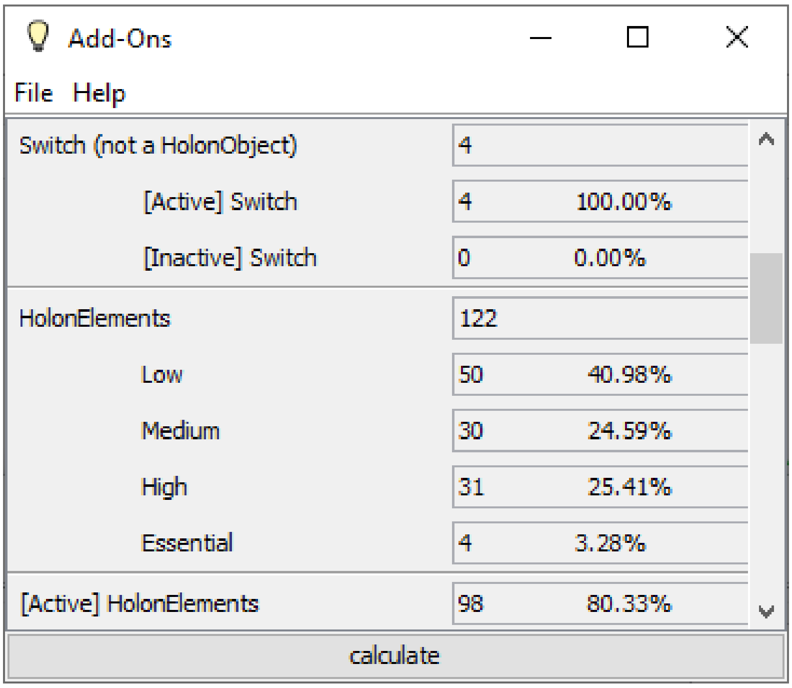

Figure 3.14: Information panel that shows various information derived from the data of the holarchy model.

3.5 EVALUATION

The concept and methods presented in this chapter strongly involve prosumers in processes for mitigating hazardous situations in holonic

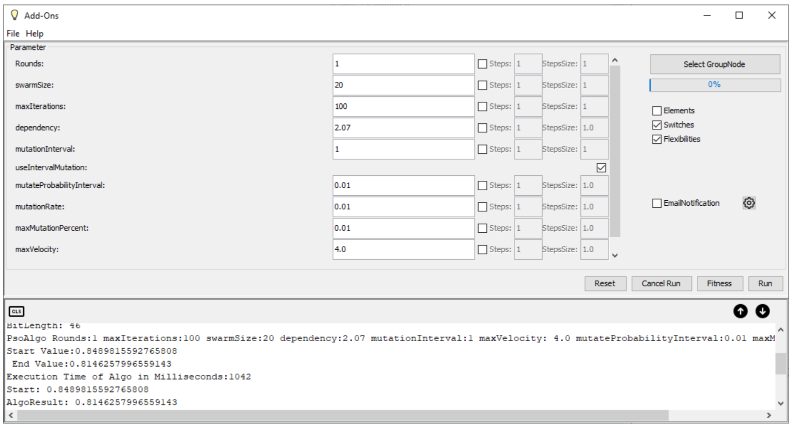

Figure 3.15: Exemplary holarchy reconfiguration algorithm that can be used to optimize the allocation of resources within the holarchy and reconfigure the holarchy structure.

energy grids. In addition to the technical challenge of implementing such a system, it is of paramount importance that people are motivated or at least do not oppose the idea of being involved in energy grid processes in the first place.

An online survey was conducted, where a concept for integrating prosumers in mitigation processes of holonic energy grids was introduced (referred to as prosumer integration framework (PIF)). The PIF allows prosumers to participate in a holonic energy grid, by offering the following core-functionalities: 1) Digital monitoring and control of local devices and appliances, 2) Prosumer notification about hazardous situations; and 3) Empowering prosumers to support mitigation processes by offering local resources as flexibilities (see Section 3.3.3). In this survey, the core functionalities of the PIF were presented to the participants using descriptions and supportive images to explain the conceptual mode of operation. Additionally, general questions were asked that aimed to assess the general knowledge of participants about the current electrical grids and their opinion on ongoing changes within the energy domain. Afterward, participants were asked to provide their opinion about the presented functionalities and about the PIF as a whole. The goal of the survey was to investigate if people perceive the PIF concept as useful to support the resilient operation of future energy grids and if they would be willing to be involved in processes for mitigating problems in the grid. Towards this end, the following hypotheses were formulated:

$H_{1.1}$ *The willingness of people to offer flexibilities differs between age-groups.*

$H_{1.2}$ *People who are already willing to actively adjust their electricity consumption show a higher willingness to offer flexibilities.*

$H_{1.3}$ *People whose use of electrical appliances is influenced by ecological aspects show a higher willingness to offer flexibilities.*

$H_{1.4}$ *People whose use of electrical appliances is influenced by economic aspects show a higher willingness to offer flexibilities.*

$H_{2.1}$ *The perceived usefulness of the* PIF *concept differs between different levels of education.*

$H_{2.2}$ *There is an effect between peoples' involvement in smart grid topics and their perceived usefulness of the* PIF *concept.*

3.5.1 *Survey Design*

The survey consists of 68 questions and is divided into five parts, namely *Welcome*, *Demographics*, *Energy Opinion*, *Core Functionalities*, and *Framework Opinion*. Two pre-tests were conducted initially to test the survey: The first one with two participants, and the second one with one participant. The survey structure is presented by Figure 3.16.

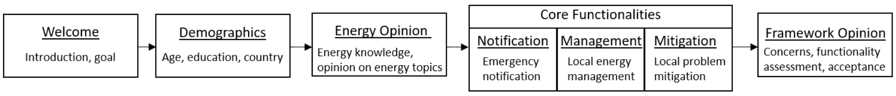

Figure 3.16: The study procedure and path for the participants

WELCOME & DEMOGRAPHICS Participants are informed about the general topic of the survey and the expected duration for participating. Furthermore, the data handling is explained, and the participants are informed about the voluntariness of the survey. Subsequently, the overall structure of the survey is introduced, and contact information is provided for addressing questions and concerns. The demographic information that is collected consists of age (chosen from different intervals), the level of education, and the country where the participant is currently living.

ENERGY OPINION The survey part for the *energy opinion* includes questions to gather data about two main aspects: first, the previous knowledge of the participants about the energy domain and ongoing transformation processes, for instance, the energy transition in Germany; second, the participants' opinion on changes that are part of the transition process towards future smart grids, like, for example, the reduction of fossil-fueled and nuclear producers and the increase of RESs. This energy-related information is collected by using 13 dichotomous choice questions.

SCENARIO & CORE FUNCTIONALITIES Before the explanations and questions about the core functionalities, the general scenario is explained to establish an understanding for the participants about the environment and situation in which the PIF operates. The explanations encompass information about the electricity production value chain and introduce the concept of *prosumers*. Subsequently, current mechanisms for handling problems of demand and supply mismatches in current energy grids are presented, and the potential role of private households within such mitigation processes is proposed. Afterward, three critical challenges are introduced, which need to be addressed to involve prosumer households into problem mitigation processes. Finally, the general purpose of the prosumer integration framework is explained, and the following parts of the survey focus on the core functionalities, which aim at addressing the previously mentioned challenges.

NOTIFICATION The notification part of the survey is mainly concerned with investigating how the emergency notification functionality of the framework is perceived by the user. For this, a concept of emergency notification for the prosumer is presented and essential steps are explained (see Figure 3.17). After the survey participants became familiar with the notification functionality, a combination of Likert-scale questions, dichotomous choice questions, and multi-selection questions were asked. The goal of this part of the survey is to investigate how participants perceive the importance of emergency notifications, their opinion on improving current technologies to also cover electricity-related problems, and what information about such problems they consider as useful for them.

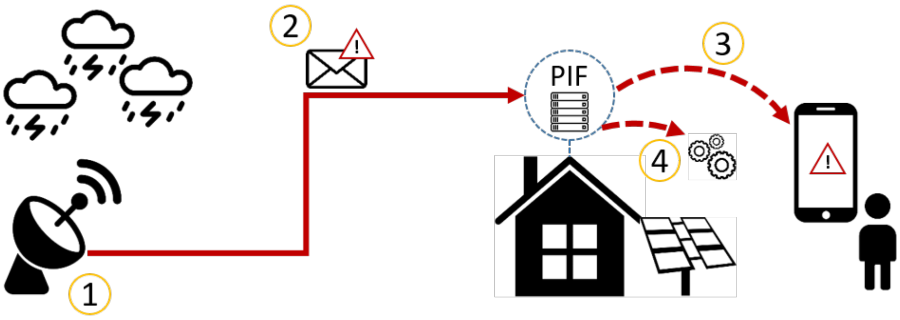

Figure 3.17: The concept of emergency notification for the prosumer integration framework.

MANAGEMENT The management section presents and explains the interaction capabilities of the prosumer integration framework to support prosumers in monitoring and managing their electricity consumption locally. The core functionality is explained using Figure 3.18. The focus of this part of the survey is to investigate the opinion of the participant about smart devices (holon elements) that can be controlled digitally, the prioritization of devices at different times, and if they perceive the unavailability of devices as a burden.

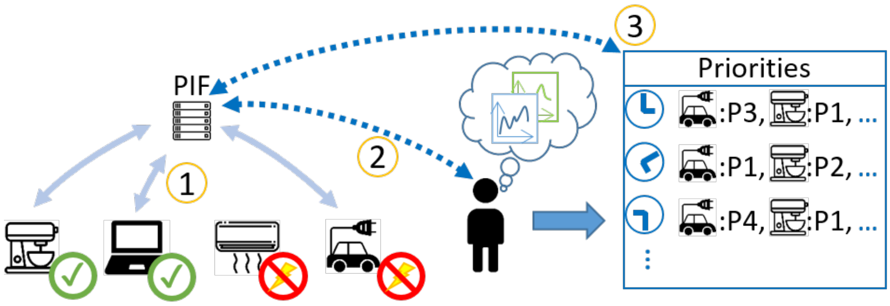

Figure 3.18: The concept of local device management and prioritization.

MITIGATION The third core functionality explains the concept of offering local resources as flexibilities (see Section 3.3.3) for supporting the mitigation of demand and supply problems using Figure 3.19. The focus of this part of the survey is to investigate the participants' willingness to participate in mitigation processes offering local resources. In particular, questions address aspects like optionality of participation within the mitigation processes and if reimbursements are expected.

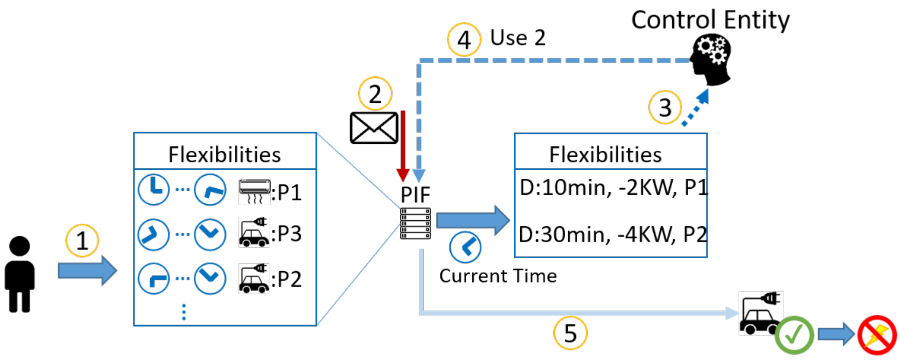

Figure 3.19: The concept of flexibility management for supporting problem mitigation.

FRAMEWORK OPINION The final part of the survey addresses general questions for assessing the opinion of participants on the different core functionalities and the framework as a whole. For instance, questions are asked about privacy concerns and the willingness of participants to accept slight increases in costs for smart devices. Additionally, open questions are asked if the participants have further concerns with the presented framework and if they would be willing to install a prosumer integration framework in their home.

PARTICIPANTS We recruited 108 participants from ten different countries by advertising the survey on social media and networks, mailing-lists, posters and by word-of-mouth. The general target group

Age / Participants		Education / Participants	
18–24	12 (11.6%)	Primary School	3 (2.9%)
25–30	35 (33.7%)	Secondary/High School	20 (19.2%)
31–40	40 (38.5%)	Vocational Education	6 (5.8%)
41–50	5 (4.8%)	University (Bachelor)	20 (19.2%)
51–65	12 (11.5%)	University (Master)	35 (33.7%)
		University (Ph.D.)	20 (19.2%)

Table 3.4: Overview of the survey participants.

was not limited. The advertisement encompassed a general description of the prosumer integration framework and that the survey was conducted to evaluate this thesis work. Participants of the survey could choose to participate in a raffle, where three Amazon vouchers (each worth 50€) were given to three random participants. For this, they needed to provide a contact e-mail address, which was stored separately from the information they provided in the survey. We excluded four participants, who only started participating in the survey but did not proceed after providing their demographic information. Consequently, N = 104 participants provided valid survey data.

3.5.2 *Quantitative Results*

In this section, the quantitative results of the survey are presented. First, the results related to peoples' willigness for active participation in energy grids are highlighted. Second, the results of the peoples' perception of the usefulness of the PIF are detailed. An overview of the survey questions and detailed results is shown in Appendix A.

3.5.2.1 *Willingness for Participation*

Various questions of the survey aimed to assess the participants' willingness to support the stable operation of the energy grid by participating actively. Firstly, questions aimed to assess participants' general opinion on active participation. Secondly, their opinion on active participation using the PIF flexibility concept was investigated.

opinion on active participation To get insights into the general opinion of the participants on becoming active, they were asked if they perceive the goal of producing their own electricity locally as a desirable goal. Results show that 79.8% (N = 104) of the participants perceive this local production as desirable and, furthermore, 73.1% (N = 104) consider the production of excess electricity

(electricity that exceeds the own demand) to support the grid as desirable. In addition, 77.9% (N = 104) of the participants stated that they would be willing to decrease their electricity consumption if required to support the stability of the energy grid and 74.0% (N = 104) would be willing to consume more electricity. These results indicate that people are willing to make adjustments to actively contribute to the stability of energy grids. Furthermore, participants consider the possibility of a stronger involvement of prosumers in processes for mitigating problems as useful (Mean = 3.98, N = 102, SD = .900). However, the question did not clarify if participants see themselves in the role of a prosumer or if they consider the stronger involvement of others (prosumers) as positive.

PARTICIPATION BY OFFERING FLEXIBILITIES After the presentation of the mitigation functionalities of the PIF, the participants stated that they can imagine supporting the energy grid by offering flexibilities in emergency cases (Mean = 4.25, N = 102, SD = .941). Furthermore, results show that participants are also willing to support the energy grid during mundane operation (Mean = 3.72, N = 102, SD = 1.057) using the flexibility concept. To further investigate aspects that can be associated with the participants' willingness to offer flexibilities, we first analyzed if there are significant differences between the age-groups ($H_{1.1}$). Afterward, we tested if participants that were initially willing to adjust their electricity consumption are more likely to offer flexibilities in mundane or emergency situations ($H_{1.2}$). Finally, we analyzed if there is an effect between participants' ecological or economic motivation for adjusting their electricity consumption and their willingness to offer flexibilities ($H_{1.3}$ and $H_{1.4}$).

To investigate $H_{1.1}$, we conducted two Kruskal-Wallis tests. Both test results showed no significant differences between age-groups for mundane grid operation ($\chi^2 = 4.76, p = .31, df = 4$) and emergency situations ($\chi^2 = 3.06, p = .55, df = 4$). Consequently, ($H_{1.1}$) cannot be supported. To analyze ($H_{1.2}$), we grouped *active* participants that are willing to make adjustments to support the stability of the grid, and *passive* ones that are not willing to make any adjustments. We then tested if there are significant differences between the active and the passive group by conducting two Mann-Whitney U tests. The results show that there are significant differences between the two groups regarding mundane operation (U = 189, p < .001) and emergency situations (U = 314, p < .05). Therefore, ($H_{1.2}$) can be supported.

> *Willigness to be active.* People that initially stated to be willing to make active adjustments are significantly more willing to support the energy grid by offering flexibilities.

Out of the participants, 59.3% (N = 108) stated that their usage behavior when handling electricity is influenced by ecologic aspects (e.g.,

CO_2 reduction) and 75.0% (N = 108) consider economic aspects. We conducted Mann-Whitney U tests to analyze $H_{1.3}$ and $H_{1.4}$. For mundane grid operation, the results show no significant difference for people that stated to be influenced by economic aspects and those who are not (U = 1029, p > .05). However, results show significant difference for peoples' support during emergency situations (U = 1026, p < .05). Consequently, ($H_{1.3}$) can only be supported for emergency situations but not for mundane operation. In contrast, the results show significant differences for people who stated that their handling of electricity is influenced by economic aspects. Here, the Mann-Whitney U tests showed significant differences for both, mundane grid operations (U = 529, p < .001) and emergency situations (U = 610, p < .001). Therefore, ($H_{1.4}$) can be supported in both cases.

Motivation. Economically motivated people are more willing to offer flexibilities compared to ecologically motivated participants.

The participation within processes for problem mitigation using flexibilities is accompanied by potential disadvantages for the participants. Those disadvantages can have a strong impact on the willingness of prosumers to participate in the first place and need to be investigated. Towards this end, participants stated that they would be only slightly burdened if some of their appliances would be deactivated during emergency situations (Mean = 3.05, N = 104 SD = 1.240). Simultaneously, results show that participants strongly prefer if disturbances resulting from offering flexibilities are kept low (Mean = 4.08, N = 102 , SD = 1.03). To compensate these disturbances to some degree participants get reimbursed if flexibilities are used to support the grid. Results show that participants would be hesitant to offer flexibilities if *no* reimbursement would be provided (Mean = 2.86, N = 102, SD = 1.26). In comparison, participants favor an *adequate* reimbursement for offering flexibilities (Mean = 3.75, N = 102, SD = 1.07); however, the results also indicate that these reimbursements do not need to generate *profit* for the participants (Mean = 2.94, N = 102, SD = 1.25).

Reduced desire for profit. The participants specified that the want to be reimbursed *adequately* for offering flexibilities. In comparison, results indicate that a *profitable* reimbursement is not required.

SHORT SUMMARY OF IMPORTANT RESULTS Results indicate that participants are mostly willing to actively contribute to the stable operation of energy grids by taking local actions. The willingness of participants to offer flexibilities does not differ significantly among age-groups, but shows significant differences between people who stated that they are willing to adjust their handling of electricity and those who are not. Furthermore, significant differences are also present for people whose electricity handling is influenced by economic aspects.

The expected reimbursements for offering flexibilities are expected to be *adequate* and do not need to generate *profit* for the participants.

3.5.2.2 *Perceived Usefulness*

In this section, the quantitative results regarding the assessment of the perceived usefulness of the PIF concept are presented. First, the results related to the general perceived usefulness of the PIF are shown. Second, results about the concerns of participants about the PIF are depicted.

USEFULNESS OF THE PIF CONCEPT To get insights into the participants' opinion on the PIF concept, they were asked if they perceive the PIF concept as a whole as useful. Furthermore, participants should indicate the perceived usefulness of the presented core-functionalities of the PIF, namely *notification*, *management*, and *mitigation*. The results are shown in Table 3.5

	Mean	N	SD
Notification	4.19	102	.97
Management	4.09	102	.97
Mitigation	4.03	102	1.09
PIF concept	4.04	102	1.04

Table 3.5: Results of the perceived usefulness of the PIF concept and the individual core-functionalities.

Overall, results indicate that all core-functionalities and the PIF as a whole are perceived as useful by the majority of participants. To further investigate these results we analyzed if there are differences between different educational levels and their perceived usefulness of the system ($H_{2.1}$). Furthermore, we investigated if there is an effect between participants' involvement in smart grid topics and their perceived usefulness of the PIF concept ($H_{2.2}$).

To investigate if there are significant differences between the education levels, we conducted a Kruskal-Wallis test. The results show that there are no significant differences ($\chi^2 = 8.19, p = .316, df = 7$). Consequently, ($H_{2.1}$) cannot be supported.

Another Mann-Whitney U test aimed to investigate ($H_{2.2}$). The results show that there are no significant differences ($U = 667$, $p > .05$) between people that are involved in smart grid topics and those who are not. Therefore, we cannot support ($H_{2.2}$).

CONCERNS ABOUT THE PIF CONCEPT The concerns of people may influence their perception of the PIF concept. Therefore, two questions about common concerns related to digitization in energy grids and one open question on additional concerns were asked: first, participants should state if they are concerned that their habits on using electrical devices may be revealed by the PIF. Second, participants were asked if they fear that unauthorized third-parties may gain access to local end devices. Afterward, participants were asked for additional concerns about the PIF concept. The results are shown in Table 3.6 and detailed comments of participants are shown in Section 3.5.3.

	Mean	N	SD	Yes	No
Reveal habits	3.84	102	1.12	-	-
Third-party access	4.12	102	1.09	-	-
Additional concerns	-	102	-	37 (36.3%)	65 (63.7%)

Table 3.6: Results of the concerns about the PIF concept.

Overall, the result show that participants are concerned about revealing habits and third-party access.

SHORT SUMMARY OF IMPORTANT RESULTS The overall PIF concept and its presented functionalities are considered useful. The usefulness of the PIF seems to be perceived differently by people with an academic education level and alternative education levels. However, these differences are not significant. The personal or private involvement in smart grid topics does not lead to significant differences in the perceived usefulness of the PIF. Participants have a variety of concerns about the PIF concept, which are presented in the next section in more detail.

3.5.3 *Qualitative Results*

The survey encompassed several (semi-)open questions to get deeper insights into the needs, concerns, and preferences of the participants. Towards this end, the following questions were asked:

Q1: *"Are there any additional settings you would like to make for configuring flexibilities?"*

Q2: *"I have the following additional concerns regarding the use of the PIF in my home."*

Q3: *"Do you have additional comments and concerns about the presented Energy Assistant and its corresponding functionalities?"*

The answers of the participants to these questions are presented next.

FLEXIBILITY CONFIGURATION Question Q1 aimed to investigate if parameters for specifying *time-of-availability* and *reimbursement* are considered as sufficient by the participants to configure flexibilities. Quantitative results indicate a weak agreement of participants that these parameters are sufficient. (Mean = 3.49, N = 101, SD = 1.10). Additionally, 16.8% of the participants commented on Q1 and the answers were assigned to two categories:

- Goal configuration
- Exception configuration

Participants seem to desire a way to specify goals aligned to specific tasks, which need to be finished until a particular point in time. As long as the task is completed until the specified deadline, people seem to be willing to offer corresponding devices as flexibilities. A sample comment given by the participants is as follows[3]:

"goal definitions; for instance, laundry should be done at a certain point in time [...] device deactivation can be arbitrary as long as the goals are fulfilled."

Comments related to exception configuration are as follows:

"special users to override the flexibilities. Having a guest at home (the whole day) should allow water heaters to work throughout the day. Such guests would be there for a few days only. Hence, I should have the feature to 'temporarily' override [...]."

"The possibility to withdraw a flexibility on short notice, due to an urgent need of the consuming device (e.g., I have to charge the car NOW due to shortage of time)."

"Option to define exceptions to the existing rules without modifying the general configurations."

The comments show that the participants want to be able to make temporary and short-notice modifications to their flexibility offers. This is also supported by quantitative results of the survey, where people were asked if they perceive the possibility of adjusting flexibilities *regularly* (e.g., daily, weekly) or at *any point in time* as useful. Results show that regular configurability is strongly desired (Mean = 4.32, N = 101, SD = .927) and there is a positive trend for making adjustments at any point in time (Mean = 3.90, N = 101, SD = 1.179).

CONCERNS FOR USING THE PIF Question Q2 extended the quantitative questions on participants' concerns about the PIF (see Section 3.5.2.2) and allowed participants to state additional concerns in an open-text format. Out of the participants, 36.6% stated additional concerns, which were categorized as follows:

- Fairness

3 The comments are translated from the original German.

- Safety guarantees
- IT Security & Data protection
- Technology compatibility & Usability
- Impairment of grid development

One major concern of participants is related to maintaining *fairness* while using the PIF. Since participation was assumed to be voluntary, people are concerned that a few individuals would be responsible for supporting the stability of the grid. Selected comments of the participants are the following:

"a few [people] carry the burden of many ignoramuses."

"[...] participation of few [people] and therefore an increased burden for the participants."

The second category of comments is related to *safety* concerns for the PIF. People seem to be concerned about the malfunctioning of the presented PIF and the digitization of their home. Selected comments of the participants of the survey are the following:

— *"Susceptibility to errors increased."*

— *"[...] Malfunctioning of control, unwanted deactivation of devices due to system failures."*

— *"What would happen in case of a failure of the PIF."*

The third category is related to participants' concerns about *data security* provided by the PIF. The most prominent concerns are about malicious third-parties (e.g., hackers) gaining access to local data and devices and privacy concerns about the data usage by energy providers. Selected comments of the participants are the following:

— *"What about hacker attacks that generate fake notifications which are then disseminated to the prosumers?."*

— *"[...] Smart home and smart devices always are pose an opportunity for hackers and other security risks [...]."*

— *"Data protection, security, no trust in the producers and/or grid operator [...]".*

— *"Generation of behavior profiles (who is at home and what is he doing)".*

Aside from security, *technology compatibility & usability* is perceived as important. Participants seem to desire standardized interfaces, such that they can purchase and combine devices from different vendors. Additionally, participants are concerned about the usability of the PIF. Selected comments of the participants are the following:

— *"As long as there is no unified interface, the threshold for acquiring [the PIF] is high (similar to the situation of electric vehicles and numerous cables for charging)".*

— *"Maintenance, workload for configurations, reminders, etc."*.

The last category is related to the *impairment of grid development*. Several participants are concerned that the expansion of the energy grid may be impaired by using the PIF. Selected comments of the participants are the following:

— *"The expansion of the grid is not pushed forward, since the PIF resolves problems via deactivation"*.

— *"The expansion of the grid would lose priority"*.

ADDITIONAL COMMENTS AND CONCERNS The final question Q3 aimed to investigate general concerns and comments of the participants regarding the PIF concept. The statements of the participants were categorized as follows:

- Intrusiveness
- Fairness
- Ease-of-use

Several participants perceive the PIF as an intrusive technology due to its capability to (remotely) control local devices and allow access to a variety of data. This seems to make participants uncomfortable and raises concerns about data protection and IT-security. Selected participant comments are the following:

— *"I'm uncomfortable regarding the security of [digitally] actionable smart devices [...] I find it hard to get used to the idea of leaving control over security-critical devices to an artificial intelligence (AI) or companies or others"*.

— *"If there are approaches less intrusive towards individuals, I would favor them over providing remote control to personal devices"*.

As already stated previously by the participants fairness concerns arise in the context of the PIF. Selected participant comments are the following:

— *"To achieve a fair PIF, either all houses require solar panels, or the individuals that have solar panels installed should receive benefits"*.

— *"The PIF is a typical case of* tragedy of the commons*. Why should I turn off my TV, just to enable a neighbor to cook? This game-theoretic dilemma needs to be compensated by some kind of mechanism, e.g., low electricity prices for one that endures the use of a flexibility"*.

SHORT SUMMARY OF IMPORTANT RESULTS Participants want to have guarantees that specific tasks/appliances are executed within a specified time-horizon, and they prefer the possibility to make exceptions from their flexibility offers. The most prominent concerns of participants' are related to maintaining fairness between participants and safety and security aspects of the PIF.

3.5.4 *Discussion & Reflection*

In this section, we discuss the results and findings of the conducted survey on peoples' willingness for participation and the perceived usefulness of the PIF concept.

In general, the willingness of people to participate in novel concepts and methods for operating energy grids is crucial in two phases: first, novel concepts need to be accepted by the majority of people; otherwise, it is unlikely that they will be implemented in the first place. Second, once a concept like the presented PIF is implemented it requires the continuous participation of people to make all the benefits available to participants and the system as a whole. However, for people to be willing to accept and participate in novel concepts, it is beneficial if they consider it to be useful.

WILLINGNESS FOR PARTICIPATION Overall the participants stated that they consider a stronger integration of prosumers into operational processes of energy grids as useful. To further investigate the participants' willingness to so, participating in the presented PIF concept, we tested four hypotheses (see Section 3.5) and the results are show in Table 3.7

		Mundane/Emergency
$H_{1.1}$	age-groups	Not supported/Not supported
$H_{1.2}$	active people	Supported/Supported
$H_{1.3}$	ecological aspects	Not supported/Supported
$H_{1.4}$	economic aspects	Supported/Supported

Table 3.7: Overview of the survey participants.

The lacking support for $H_{1.1}$ shows that there are no significant differences between age-groups for offering flexibilities during mundane operation of the grid and emergency situations. Consequently, we can assume that flexibility concept of the PIF was presented comprehensibly for all groups. Furthermore, this indicates that the willingness for contributing to energy grid resilience is not an aspect that is limited to specific age-groups, but relevant across all groups. This needs to be considered for developing novel concepts and methods for energy grids as they will likely affect people of all groups. As presented previously, peoples' willingness for offering flexibilities during emergency situations is higher (Mean = 4.25, N = 102, SD = .941) compared to mundane operations (Mean = 3.72, N = 102, SD = 1.057). Despite not being attributable to individual reasons, we assume that one important aspect that contributed to this difference lies in the people's understanding of benefits and drawbacks of the

PIF concept. While the potential negative consequences of emergency situations (e.g., blackout) were used to motivate the PIF initially, and were mentioned several times within the survey, the benefits of the PIF during mundane operation (e.g., peak-shaving and corresponding benefits for prosumers) were not mentioned directly in the survey. We assume that participants—especially ones without profound knowledge about the energy domain—lacked information to assess the PIF for mundane situations, which likely contributed to the difference.

The results for $H_{1.2}$ show that people who are willing to make local adjustments in conventional energy grids are more willing to support the grid by offering flexibilities during mundane and emergency situations. This indicates, that people are prepared to give up control—to some degree—, if they are willing to take on an active role. Therefore, measures for motivating people to become actively involved in the first place, may alleviate processes for accepting and deploying novel concepts and increase peoples' willingness for offering flexibilities. This is especially important within holonic energy grids, considering that a sufficient number of flexibilities is crucial to maintain the stable operation of (autonomous) holons.

The results regarding hypotheses $H_{1.3}$ are ambiguous. The lack of support for the hypothesis during mundane situations indicates again that explanations of the benefits of the PIF in these cases was underrepresented in the study. Similarly, alternative ways of compensation were also not discussed in the survey, but money was introduced as the established compensation method. This may have led to a lower willingness for offering flexibilities by people that are influenced mainly by ecological aspects. In comparison, $H_{1.3}$ can be supported for emergency situations. In this case, the potential consequence of a blackout likely has a stronger impact on peoples' decision to offer flexibilities compared to the impact of ecological aspects. Nonetheless, 59.3% of the participants stated to be influenced by ecological aspects. Therefore, such aspects need to be taken into account for motivating people to offer flexibilities in both mundane and emergency situations. Furthermore, ecological aspects could be leveraged to design alternative reimbursement methods (see Section 5.2.3), which may increase motivation and result in economic benefits for grid operators.

$H_{1.4}$ shows that there are significant differences between people that are influenced by economic aspects and those who are not regarding their willingness to offer flexibilities in both situations. As mentioned previously in this work, money was introduced as the method for reimbursing participants that offer flexibilities to the grid. Therefore, the economic benefits were more present within the survey, which may have caused the significant differences for people influenced by economic aspects. One interesting finding is related to the extent of expected compensation. Results show that the majority of people expect to be compensated *adequately* (e.g., sufficient to cover expenses caused by the use of the flexibility). In contrast, the results for *no* and *profitable* compensation show a slight negative trend. While the negative is expected if no compensation is provided, the results for profitable compensation is unexpected, especially, since 75% of the participants stated that they are influenced by economic aspects. This may indicate that monetary reimbursements could be efficiently supported by other types, like ones based on ecological or social aspects (see Section 5.2.3). However, it is also likely that these results are attributable to a biased self assessment. For instance, it is likely that people would accept profitable compensation if the actions required by the people are comparable and emerging drawbacks are sufficiently small.

USEFULNESS OF THE PIF One key aspect that can influence peoples' willingness to adopt novel concepts is the perceived usefulness of these concepts [49]. The results of the survey show that participants perceive the PIF as a whole and the individual core-functionalities (*notification*, *management*, and *mitigation*) as useful. To further investigate aspects that impact the perceived usefulness, we tested hypothesis $H_{2.1}$ and $H_{2.2}$. The results are shown in Table 3.8

$H_{2.1}$	educational levels	Not supported
$H_{2.2}$	private/professional involvement	Not supported

Table 3.8: Results for the hypotheses on the perceived usefulness of the PIF

The lack of support for $H_{2.1}$ indicates that the overall PIF concept was presented in such a way that it is comprehensible for all educational levels. The absence of significant differences in combination with the overall positive trends of the perceived usefulness of the PIF and its core functionalities (see Table 3.5) signals that the presented functionalities are reasonable and well-received by the participants. Similarly, the private or professional involvement in smart grid topics does not seem to have a strong effect on the perceived usefulness of the participants. These results are promising since a concept that is not perceived as useful will likely lack the support of people who should adopt it.

The notification functionality is perceived as the most useful core-functionality, followed by the management and the mitigation functionalities. The measured standard deviation increases accordingly for the three presented functionalities. These results signal that the presented functionalities that are more familiar to the participants and do not require taking on responsibility are perceived as increasingly useful.

This is reasonable, since many people are familiar with the concept of notifications, where they receive information, but are not required to act based on the information [223]. Consequently, the functionality does not add to the responsibilities of people. This makes it easier for people to assess if the functionality is beneficial for them and is therefore considered as useful. Similar to the notification functionality, the management functionality can—at least partially—be assumed as a predominantly familiar concept. On the one hand, functionalities related to monitoring the local system and displaying corresponding information are already available in energy grids [75, 224]. Moreover, monitoring also does not increase the responsibility of people. On the other hand, the concept of controlling devices digitally has been known for several years but raises multiple concerns on safety and security [120, 157]. These concerns are aggravated for functionalities that break the "safe" boundaries of private homes by enabling communication to outside networks, like the presented mitigation functionality of the PIF. Several prominent concerns, like the potential for malicious third-party access to local devices and disclosure of personal information on electricity consumption are reaffirmed by the results of the conducted survey. Consequently, it can be assumed the aforementioned concerns are at least partially responsible for the observed decrease in the perceived usefulness for the management and mitigation functionalities.

3.5.5 *Limitations*

For the survey, 108 participants were acquired; considering that billions of people are connected to energy grids, this number limits the generalizability of the survey results. Future studies should, therefore aim to include more participants.

The survey was conducted over the course of six weeks, and participants required 30–40 minutes to participate. The combination of this limited time window and the rather high time effort that was required for participating may have impeded the willingness of people to participate in the survey. This can be attributed to the extensive explanations provided for explaining the concept of the PIF, since no prototypical implementation was provided. Further study should aim to reduce the time required for participation.

The survey was distributed by advertisements on social media and networks, mailing-lists, posters, and by word-of-mouth. Consequently, the majority of participants are from Germany (87%). This impedes the generalizability of the study since countries can dramatically differ regarding the stability and supply quality of their energy grids and the corresponding experiences and concerns of people. For instance, people in countries where the energy grid malfunctions frequently may assess the severity of the situation differently compared to people who are used to a highly available energy grid. Further studies should aim to integrate equal numbers of participants from various countries, especially considering the peculiarities of their local energy grids (e.g., connected to the European grid, island grid, etc.).

The strategies for distributing the survey may also result in an initial bias of the participant group towards the content of the survey. Since the distribution was started by the author of the study, some contacts that were reached by using the previously mentioned distribution mechanisms may be socially connected with the author. Therefore, it cannot be excluded that some answers of participants are biased. Furthermore, the answers of the open questions are mostly related to computer science topics like digital safety and security. This may also depend on the participants connection to the author who works in the field of computer science.

The distribution of participants among different age-groups also limits the generalizability of the results. The majority of participants are between the age of 25 and 40 (72.2%), whereas younger and older people are underrepresented. Considering that people of different age-groups may have varying needs, concerns and technical preferences, further studies should make an effort to include younger and older people. This underrepresentation of certain age-groups for the conducted survey can limit some results regarding processes of the PIF that require user interaction.

The majority of participants are from educational groups that are related to academia (72.1%). Non-academic education, especially primary school and vocational education, are underrepresented. This limits the generalizability of the investigation of $H_{2.1}$.

The question design to assess peoples' opinion on increased involvement can be improved by providing a more clear description of the corresponding questions. For instance, the questions about the usefulness of stronger prosumer involvement do not clarify if the participant perceives herself as a prosumer in this context or if her opinion only indicates the stronger involvement of others as useful.

The focus of this survey was mainly to investigate the peoples' opinion on the usefulness of the PIF. However, the results show that numerous questions and concerns are strongly dependent on an actual technical implementation and the corresponding interaction with such a system. Further studies should consider offering various (mock-up) prototypes of the PIF.

3.6 Conclusion

The advancing energy grid transition and the increasing number of heterogeneous stakeholders challenge the stable operation of energy grids in multiple ways. Especially in interim stages of this transition, solutions that strongly involve stakeholders into the processes for stabilizing energy grids are promising approaches for maintaining a continuous supply with electricity.

In this chapter, a semi-formal model for representing smart grids structured as holarchies—a system structure based on the recursive aggregation of holons—was proposed. Holons allow integrating heterogeneous sub-systems in a systems-of-systems fashion and provide beneficial properties, like autonomy and self-sustainability of system parts. The autonomous operation of sub-parts requires mechanisms that allow separating holons physically from the main grid. The current energy grid infrastructure provides load breaker and similar technologies at some locations within the infrastructure, but for a holonic grid, the number of these locations need to be increased. Furthermore, to facilitate a quick reconfiguration of holarchies, the separation and re-connection of parts of the grid needs to be automated.

To strongly involve stakeholders in processes for stabilizing holonic energy grids a *flexibility* concept was proposed (see Section 3.3.3). The concept enables prosumers to contribute to the mitigation of demand and supply balance problems within holons by offering locally available resources for maintaining the balance between demand and supply within holons. Holons can then use these flexibilities to adjust the local production and consumption according to the severity of the problem situation.

To assess if stakeholders would be willing to take on a more responsible role within holonic energy grids, a survey was conducted. Within the survey, a conceptual interface (prosumer integration framework (PIF)) was presented, which specified home energy management systems (HEMSs) and flexibility functionalities to increase the involvement of people into operation processes of energy grids. The survey then investigated the participants' willingness for participating in holonic energy grids using these concepts and the perceived usefulness of the PIF. The results indicate that participants are willing to be more involved; however, numerous concerns remain that impede the willingness for participation. Among the most prominent ones are IT-security and privacy concerns that are induced by the requirement of increasingly digitizing peoples' homes. Another major concern is related to fairness among the participants using the PIF. To address these social challenges and to provide sufficient flexibilities for the stable operation of holonic energy grids, motivated and active people are required. Therefore, people need to understand that they—as individuals—can have an impact and may take on a share of the responsibility for the resilient operation of energy grids (see Chapter 5).

On the technical side, a challenge emerges from operating energy grids as a holarchy and leveraging a growing number of flexibilities for mitigating hazardous situations. To use these resources efficiently, complex decisions need to be made on re-structuring the holarchy and allocating flexibilities accordingly to increase the resilience of energy grids during hazardous situations and improve the situation for the involved stakeholders (see Chapter 4).

4 HOLONIC GRID ADAPTION

The previous chapter introduced a semi-formal model for improving the resilient operation of smart grids by leveraging the inherent properties of holons and enabling stakeholders to offer local resources dynamically to support processes for mitigating demand and supply balance deviations (see Chapter 3). This and the following chapter investigate solutions to challenges that emerge from structuring and operating energy grids using the presented holonic model.

This chapter addresses the joint challenge of reorganizing the holons within an energy grid structured according to the model presented in Chapter 3 and allocating flexibilities for mitigating hazardous situations. The simultaneous consideration of both aspects yields a multivariate optimization problem, which is referred to as the *Holon Problem* in this thesis. In this chapter, metaheuristic optimization is proposed as suitable class of algorithms for finding near-optimal solutions to the Holon Problem. In particular, three approaches are customized to improve the overall grid resilience and support the swift mitigation of hazardous situations caused by demand and supply mismatches.

The chapter is organized as follows: Section 4.1 motivates the chapter and introduces the general challenges in future holonic smart grids that emerge from the adaption of the holonic system structure. Section 4.2 introduces relevant background information about metaheuristic optimization used within this work and provides relevant related work. Subsequently, Section 4.3 presents the application of metaheuristics for finding near-optimal solutions to the Holon Problem. First, the Holon Problem is explained in detail and cost function for assessing the quality of solutions to the problem is proposed. Afterward, the customized metaheuristics are evaluated in a simulated scenario and the found solutions are presented and discussed. The chapter concludes with Section 4.4.

4.1 MOTIVATION

Structuring energy grids as holarchies can improve their capabilities for conducting fine-grained grid control and dynamic grid reorganization (see Section 3.3.4). Especially during hazardous events, where holonic energy grids can adapt their structure—by conducting splitting and merging operations—prosumers play a vital role in supporting the continuous supply of electricity within the individual holons. Towards this end, prosumers can offer local resources as flexibilities that can be leveraged to mitigate demand and supply mismatches (see Section 3.3.3).

However, reorganizing the holarchy and the associated specification of a resource allocation to effectively mitigate problem situations presents a complex challenge. In particular, changes in the underlying energy grid structure can strongly affect the usability of flexibilities. For instance, holons that operate autonomously can neither contribute to stabilizing other parts of the grid, nor can they benefit from resources offered by the main grid. Furthermore, flexibilities can strongly vary in their capabilities for supporting the energy grid as well as their requirements and constraints (see Section 3.3.3). Consequently, their suitability for specific problem situations and holarchy configurations may differ.

4.1.1 *Problem Statement*

This chapter addresses the challenge of finding *holarchy configurations* that improve the resilience of holonic energy grids during hazardous situations. Holarchy configurations combine topological adaptions—performed by reorganizing holons within the holarchy—and allocating available flexibilities to balance demand and supply deviations. The emerging optimization problem is, in this work, referred to as the *Holon Problem*.

More formally, the problem takes into account two sets: Firstly, a set of separation points $SW = \{sw_1, \ldots, sw_m\}$ (here: *switches*) that can be used to (dis-) connect parts of the grid and therefore adapt the topology. Secondly, the set of available flexibilities $\mathtt{Flex} = \{\mathtt{flx}_1, \ldots, \mathtt{flx}_n\}$ that are currently offered within the grid and can be used for mitigating demand and supply deviations.

The problem poses a non-trivial challenge since reconfiguring the structure of the energy grid can have contradicting effects on its stable operation: separating a part from the grid (e.g., due to malfunctioning producers) can prevent disturbing effects in the main grid but may, simultaneously, advance system destabilization, as other resources within the separated areas become unavailable. Flexibilities can be used for stabilizing demand and supply within these areas; however, to use them effectively, several aspects must be considered, like their provided power, availability, and impact on the prosumers offering the underlying resources. Moreover, the availability of flexibilities within certain areas depends on the organization of the holarchy; therefore, the reorganization of the holarchy and the allocation of flexibilities are interdependent challenges that need to be addressed together.

4.1.2 *Challenges*

Solutions to the Holon Problem aim to improve the resilience of holonic energy grids and, simultaneously, optimize the use of flexibilities and their impact on the prosumers. To prevent faults and damages to the grid these solutions need to be found quickly. Therefore, we try to find a compromise between the quality of solutions and the time that is required to find them. Towards this end, this chapter addresses the following main challenges:

- Determine measures for assessing the quality of solutions to the Holon Problem.
- Develop suitable heuristic optimization method that are capable of maximizing these quality measures.
- Investigate the performance of suitable optimization methods regarding their capability of finding solutions within restricted time-horizons.

4.1.3 *Chapter Contribution*

This chapter addresses the challenges stated above and makes the following contributions:

- Modeling the Holon Problem as a multivariate optimization problem, taking into account the operational constraints of holonic energy grids, the ecological aspects for using flexibilities and the impact of flexibility usage on the prosumers.
- Designing an objective function (here: cost function) that allows assessing the quality of solutions to the Holon Problem considering numerous optimization criteria.
- Adapting metaheuristic optimization approaches based on genetic algorithms (GAs), binary ant colony optimizations (BACOs), and binary particle swarm optimization (BPSO) to find near-optimal solutions to the Holon Problem within limited time-horizons.
- Comparing the performance of the proposed optimization approaches by solving a severe undersupply situation in a simulated holonic energy grid using the HOLEG simulation environment (see Section 3.4.2).

4.2 ADAPTING ENERGY GRIDS FOR IMPROVED RESILIENCE

Adapting the energy grid for improving its resilience either proactively during a planning phase or actively during its live operation represent well-known challenges in the domain of energy grid optimization [1, 160]. In this section, prominent challenges related to the operation of energy grids in the presence of distributed resources are presented. Furthermore, relevant related work is introduced that solves these problems using metaheuristic optimization approaches. Finally, important background information about metaheuristics and the specific optimization approaches used within this thesis is provided.

4.2.1 *Resilient Operation of the Energy Grid*

Metaheuristic optimization can support the resilient operation of energy grids in numerous ways. Prominent challenges that are solved using these optimization approaches are, for instance, forecasting production capacities of renewable energy sources (RESs), like solar and wind power [11, 179] to support balancing production and demand. One of the most prominent challenges within energy grids, which is addressed by using metaheuristic optimization, is demand-side management and the allocation of production capacity provided by distributed energy resources. In this context, numerous approaches improve the scheduling of electricity consumption of appliances to reduce peak loads in the grid, which supports the stable operation of the grid [51, 92, 143]. Metaheuristics are well-suited to handle the (often) high complexity of the challenges emerging from combining the scheduling of appliances while considering numerous optimization criteria, like user satisfaction and dynamic electricity prices. For the allocation of resources within energy grids, metaheuristics are used to find high-quality strategies for using distributed energy resources. This allows control entities tom improve the use of distributed resources and minimize transmission losses [171, 230].

4.2.2 *Metaheuristic Optimization*

Metaheuristic optimization represents a sub-field of stochastic optimization. Stochastic optimization is a class of optimization algorithms where algorithms incorporate a certain degree of randomness into their mode of operation, which allows them to find optimal (or at least near-optimal) solutions to hard problems. In this section, a brief introduction of various metaheuristics optimization algorithms is provided. Subsequently, the fundamental concepts of the optimization approaches that are adapted and used within this work are explained in detail. Afterward, a formal definition of an objective function is provided, which is used during the optimization process for assessing the quality of found solutions to the Holon Problem.

4.2.2.1 *Metaheuristics*

The term metaheuristic suggests that it defines an algorithm that is "superordinate" to "ordinary" heuristics, i.e., it selects, controls, etc. concrete heuristics. In fact, this is also suggested by Glover's original definition. The latter first coined the term in his much-cited work [86] and extended the definition in [87] to a *"master strategy that guides and modifies other heuristics to produce solutions beyond those that are normally generated in a quest for local optimality"*. It is more practical, and now more common, to use the research direction that emerged from Glover's work with the term; metaheuristics in this sense denote "families" of optimization procedures that are often inspired by processes in nature. They include Simulated Annealing, Genetic Algorithms, Ant Colony Optimization, and Particle Swarm Optimization, the last three of which are specifically considered in this thesis. They are "meta" in the sense that for the tailoring of a certain family of metaheuristics to a concrete problem not only heuristics have to be parameterized, but creative modeling has to be done and suitable functions have to be found, which results in a problem-adequate heuristic.

ANT COLONY OPTIMIZATION (ACO) Ant colony optimization (ACO) as introduced by M. Dorigo in [55] is a search and optimization approach for solving hard combinatorial problems. Towards this end, ACO optimizes paths, where each path represents a solution candidate for the problem that needs to be solved. The approach applies mechanisms, which have been observed in the behavior of ant colonies, for finding paths and specifying the movement- and following-rules of ants to find near-optimal paths (solutions). Real ants use *pheromones* to mark trails in search of a destination (e.g., between the ant colony and a food source) and as a means of communication for guiding other ants along this path, where the ant's (partly probabilistic) behavior aims at yielding higher pheromone levels on viable paths as opposed to "dead ends" (or deviations). Analogous to this biological paradigm, ACO uses artificial ants within a colony as agents that are guided by artificial pheromones. The pheromone trails are used by the ants for making probabilistic decisions to generate solutions to the problem at hand.

An ACO approach is composed of μ ants. Each ant $i \in \{1, \ldots, \mu\}$ constructs a path at a discrete point in time t as

$$\vec{p}_i(t) = \{X_1(t), \ldots, X_D(t)\},$$

where $X_j(t)$ for $j \in D$ are variables that get assigned values v_j^k of their respective domains and k indicates the k-th value of the domain. More precisely, values v_j^k represent possible path-segments at the current position in the path, which can be added to the path to form a solution (e.g., at different points of a path *crossroads* may appear, which vary in available directions to choose from). A path represents a feasible solution to the problem at hand after a value has been assigned to each variable $X_j(t)$. Let the assignment of a variable $X_j(t)$ with a value v_j^k be represented as a solution component c_{jk}. This assignment process is influenced by the artificial pheromones $\tau_{jk}(t)$, which indicate the desirability (probability) of assigning the value v_j^k to the variable $X_j(t)$. A prominent probability calculation for assigning a value and, therefore, adding c_{jk} to the solution is presented by Dorigo *et al.* [56] as follows:

$$p(c_{jk}) = \frac{[\tau_{jk}(t)]^{\alpha} \cdot [\eta(c_{jk})]^{\beta}}{\sum_{c_{jl} \in \mathcal{N}}[[\tau_{jl}(t)]^{\alpha} \cdot [\eta(c_{jl})]^{\beta}]}, \forall c_{jk} \in \mathcal{N} \tag{4.1}$$

Here, $\eta(\cdot)$ is a function that assigns a heuristic value (probability) to each solution component c_{jk}. The set $\mathcal{N}$ contains all solution components that can be added to the current solution such that the solution is still valid. Due to the inherent properties of the problem, constraints can exist, which deny the assignment of certain solution components (e.g., to solve the traveling salesman problem, a city can only be visited once). The parameters α and β influence the magnitude of the impacts of the existing pheromone trail $\tau_{jk}(t)$ and the heuristic value $\eta(c_{jk})$ on the probability for solution component c_{jk}. Here, lower values for α increase the probabilistic greediness of the algorithm, whereas lower values for β increase the impact of the pheromone level present at time t.

Initially, all pheromone levels are set to a constant τ_0. The pheromone level of each solution component is then *updated* depending on the number of traversed paths that encompass this component and are eligible for updating pheromone levels (e.g., they represent a valid solution). More formally, the *pheromone update* can be represented as follows:

$$\tau_{jk}(n+1) \leftarrow (1-\varphi)\tau_{jk}(n) + \sum_{s \in S_{up}} g(s) \tag{4.2}$$

Here, φ represents the evaporation rate that controls how quickly applied pheromones disappear from a path. The set S_{up} is the set of all solutions that contain solution component c_{jk} and are eligible for updating the pheromone levels. Function $g(\cdot)$ is an evaluation function that assesses the quality of a found solution $s \in S_{up}$ according to quality criteria specified for the problem to be solved. Therefore, the pheromone update maintains an increased pheromone level for high-quality solutions. At the same time, the evaporation procedure supports the convergence of the algorithm by reducing the likelihood for ants to generate low-quality solutions (i.e., paths that are not frequently traversed by ants).

BINARY ANT COLONY OPTIMIZATION (BACO) The concept of ACO was adapted to work in a binary setting by Kong et. al. [125] and is known as BACO. A BACO is composed of μ ants. Each ant finds paths (or solutions) $\vec{p}_i(t)$, which are encoded using a binary representation such that

$$\vec{p}_i(t) = \{x_1(t), \ldots, x_n(t)\}$$

with $x_j \in \{0, 1\}$ and n is the size of the problem space (i.e., $n \in \mathbb{N}$).

The pheromones are represented using a pheromone table $P^{2\times n}(t) = (\tau_{jk}(t))$, where $\tau_{jk}(t)$ represents the amount of pheromones for the bit j and the different possible values of the bit $k \in \{0, 1\}$ at time t. Paths are generated sequentially, where each ant constructs a complete path at each time t by selecting bits with the probability

$$p_{jk} = \frac{\tau_{jk}(t)}{\sum_{l\in\{0,1\}} \tau_{jl}(t)}, \text{for} \quad k \in \{0, 1\} \tag{4.3}$$

Note that in contrast to the probability calculation for the ACO, the binary variant is only influenced by the amount of existing pheromones since the decision-making only requires to decide between binary values. While traversing a path, an ant updates the pheromone level of the taken path with

$$\tau_{jk}(n+1) \leftarrow (1-\varphi)\tau_{jk}(n), \forall (j, k) \tag{4.4}$$

Here, $\varphi \in [0, 1]$ specifies the evaporation rate for the pheromones [125]. The process of updating pheromones increases the pheromone levels of those paths that perform best and therefore yield the highest solution quality.

To avoid early convergence towards local optima in the solutions space, which can be caused by ants that do not explore beyond these local optima, a *convergence factor* (cf) [126] is used.

$$cf = \frac{\sum_{j=1}^{n} |\tau_{j0}(t) - \tau_{j1}(t)|}{n} \tag{4.5}$$

Parameters τ_{j0}, τ_{j1} represent the pheromone levels of selecting 0 or 1 for bit j of the solution. When the BACO algorithm converges early, i.e., by cf exceeding a certain threshold (e.g., $cf \geqslant 0.9$), pheromones are reinitialized. The reinitialization process sets back all pheromone levels to their starting values τ_0 but provides an additional initial pheromone update for the current best solution.

GENETIC ALGORITHM (GA) Genetic algorithms (GAs) were first introduced by Holland [103] and are based on the concept of genetic optimization. In contrast to ACO approaches, where solutions are represented as paths that are iteratively combined from movement decisions of ants, GAs iteratively improve a *population* (set of initial solutions) using *breeding* (combination) to generate *offspring* (candidate solutions). The breeding process includes various operations that dictate the algorithms exploratory and exploitative capabilities. Exploratory capabilities aim at a high gene diversity to prevent the algorithm from converging towards local optima. In comparison, exploitative capabilities aim at keeping genes that yield individuals with high fitness in the gene pool. The operations within the breeding process are *population initialization*, *selection*, *recombination* and *mutation*.

- *Population intitialization*. A population P of *individuals* (solutions) is generated uniformly at random. Each individual is represented by a B-tuple of *genes* $\vec{p}_i^t = \{x_0^t, \ldots, x_B^t\}$, where x_j encodes information about the search-space and B comprises the number of genes in a solution. For instance, $x_j \in \{0, 1\}$ for binary problems.

- *Selection*. The selection operation is used to decide which individuals are suited for reproduction based on an evaluation of their inherent *fitness*. A variety of selection strategies exist, and selecting the best-performing one may heavily depend on the problem to be solved. Furthermore, other aspects exist that impact the execution of the algorithm, like computational constraints. Choosing a good selection strategy for the execution of the algorithm can drastically improve the performance of the algorithm [14]. In this work, a so-called tournament selection approach is used [23]. For this process, several tournament rounds are conducted, where competing individuals are selected randomly (the number depends on the *tournament size*). These selected individuals then are compared according to their respective fitness measured by an objective function and individuals with higher fitness are considered suitable breeding candidates for the next generation. The individuals with lower fitness are rejected from the breeding process or can compete in another round of the tournament selection. The tournament selection provides a good trade-off between exploration and exploitation since individuals with lower fitness can be selected for breeding if they compete against other low fitness individuals (exploration). Simultaneously, due to multiple tournament rounds, the individuals with a high fitness value are likely to compete and, therefore, have a high probability to be selected (exploitation).

- *Recombination*. After sufficient individuals are selected for the breeding process, they need to produce individuals of a subsequent generation (offspring). For this, at least two parent individuals exchange genes for producing two offspring. The recombination operation defines the strategy for the exchange of genes between parent individuals. Similar to the variety of strategies available for the selection operations, there is a multitude of strategies available for the recombination operation. The selection of a good strategy depends on the properties of the underlying problem to be solved by the GA. Among the most prominent strategies are *one-point crossover*, *two-point crossover* and *uniform crossover*. In this work, a uniform crossover is used as a recombination strategy due to its increased exploratory capabilities compared to point-crossover variants [211].

- *Mutation*. Following the steps described above for generating a population of random individuals limits the gene-pool to the genes that are present within the individuals after the population initialization. As a consequence, two major problems arise: Firstly, the GA may not be capable of escaping from local optima. Secondly, the algorithm may not be capable of finding the global optimum at all, if the global optimal gene-configuration (the best possible solution) is not a reconfiguration of the initial gene-pool. To address these problems, each individual has a chance to undergo a *mutation* operation [104]. The mutation operation (randomly) modifies the genes of individuals to introduce variations of genes into the individuals of a population (i.e., replace a few genes of the individual with random genes). With this probabilistic modification, the GA is not limited to the initial gene-pool anymore but is capable—given a sufficient number of generations and a corresponding mutation probability—to traverse the whole solution space.

PARTICLE SWARM OPTIMIZATION (PSO) Particle swarm optimizations (PSOs) are a prominent class of heuristics due to their simplicity and efficacy. They were introduced by Kennedy & Eberhart [117] and extended by Shi & Eberhart [202]. PSO finds solutions to problems by simulating the behavior of birds in a flock or insects in a swarm. This heuristic is based on the observation that a swarm, as a whole, has better exploratory capabilities than the sum of the exploratory capabilities of the swarm individuals. The exploratory capabilities of a swarm are derived from simple rules that dictate how the individuals of the swarm interact with each other.

A PSO approach consists of a finite number of particles $i \in \{1, \dots, N\}$ in a swarm of size N, which are located, at time t, in a D-dimensional search space. The search space depends on the actual problem to be solved. In this search space, particles have a current *position* $\vec{X}_i(t)$ (i.e., a solution to the problem) and a corresponding velocity $\vec{V}_i(t)$ (i.e., how fast a particle moves away from a solution). These variables are more formally defined as follows:

$$\vec{X}_i(t) = \{x_1(t), \dots, x_D(t)\} \tag{4.6}$$

$$\vec{V}_i(t) = \{v_1(t), \dots, v_D(t)\} \tag{4.7}$$

Here, $x_i(t)$ and $v_i(t)$ are variables that get assigned values that are valid for the respective solution domain of the problem to be solved (e.g., coordinates along the axis of a D-dimensional space). Initially, a set of i particles can be generated using randomized positions and velocity variables. During the optimization process, at each round, the position and velocity of the particles are updated according to Equation 4.8 and Equation 4.9.

$$\begin{aligned}\vec{V}_i(t+1) = \omega \odot \vec{V}_i(t) + \alpha_1 \cdot r_1 \odot (\vec{P}_i - \vec{X}_i(t)) \\ + \alpha_2 \cdot r_2 \odot (\vec{G} - \vec{X}_i(t))\end{aligned} \tag{4.8}$$

$$\vec{X}_i(t+1) = \vec{X}_i(t) \odot \vec{V}_i(t+1) \tag{4.9}$$

Here, the $\odot$ operator represents the multiplication of a scalar and a vector. The updated position of a particle at $\vec{X}_i(t+1)$ is only affected by the particle's velocity and previous position. However, the updated velocity $\vec{V}_i(t+1)$ is affected by three components:

- The *cognitive* component $\alpha_1 \cdot r_1 \odot (\vec{P}_i - \vec{X}_i(t))$ represents the current *knowledge* of an individual particle. It takes into account the current best position the particle has seen so far $\vec{P}_i$ (i.e., the local optimum of the particle) and its current position $\vec{X}_i(t)$. The cognitive component is based on the assumption that the search of a particle is affected by its own knowledge about the best position it has found. The parameter α_1 is a weight factor for the value r_1, which influences the strength of the current best solution on the velocity update.

- The *social* component $\alpha_2 \cdot r_2 \odot (\vec{G} - \vec{X}_i(t))$ represents the knowledge of the entire swarm. Here, $\vec{G}$ represents the overall best position found by the swarm so far, which is then weighed against the current position $\vec{X}_i(t)$. The parameters α_2 and r_2 affect the impact of the global best solution on the velocity similar to the parameters in the cognitive component.

- The *inertia* component $\omega \odot \vec{V}_i(t)$ affects the update of the velocity based on the current velocity of a particle weighted by parameter ω. Shi & Eberhart [202] showed that ω can improve convergence of the swarm by improving particle trajectories.

For improving the convergence tendencies, Clerc & Kennedy [42] showed that the control parameters α_1, α_2 (acceleration) and ω (inertia) should be dependent. This required dependency leads to a constriction of the system and prevents the explosion of the particle swarm (i.e., an uncontrolled expansion)—for details see [42]. Dependency between the aforementioned parameters is achieved as follows:

$$\omega = \frac{1}{\varphi - 1 + \sqrt{\varphi^2 - 2\varphi}} \tag{4.10}$$

$$\alpha_1 = \alpha_2 = \varphi\omega \tag{4.11}$$

Here, φ is a system dependent intermediate parameter that can be adjusted. Experimental results of Clerc & Kennedy [42] showed that $\alpha_{\{1,2\}}$ must be greater than 1. Experiments conducted by Lee *et al.* [139] suggest φ to be constrained to the interval of [2.01,2.4].

BINARY PARTICLE SWARM OPTIMIZATION (BPSO) Binary particle swarm optimization (BPSO) is a variant of PSO [118] that works with binary vectors instead of continuous values. In a BPSO approach, the position of a particle is defined as $\vec{X}(t) = \{x_1, x_2, \ldots, x_B\}$ where $x_i \in \{0, 1\}$ and B is a desired number of bits. The velocity $\vec{V}(t)$ is defined as $\vec{V}(t) = \{v_1, v_2, \ldots, v_B\}$ where v_i is a real value in the range $[0, 1]$. Each v_i represents the probability of the binary value x_i being a one ($P(x_i = 1) = v_i$). Additionally, speed is defined as the number of flipped bits.

The velocity update formula of the swarm stays the same in the BPSO as the one for the PSO. That is, from the perspective of each bit i:

$$v_i(t+1) = v_i(t) + \varphi_1 \cdot (p_i - x_i(t)) + \varphi_2 \cdot (p_{gd} - x_i(t)) \tag{4.12}$$

To constrain v_i to a value in the range $[0, 1]$, a squashing function $S : \mathcal{R} \to [0, 1]$ (such as the sigmoid function) is used. The position of a particle is redefined as

$$x_i = \begin{cases} 1, & \text{if } \rho < S(v_i) \\ 0, & \text{if } \rho \geqslant S(v_i) \end{cases} \tag{4.13}$$

Here, ρ is a random number in the range $[0, 1]$.

4.2.3 *Objective Function*

The goal of optimization is to find near-optimal solutions to a given problem. Towards this end, a quantitative measure for assessing solution candidates is required, which considers (potentially diverse) criteria related to the problem that is to be solved. Such a measure can be represented as a mathematical equation—a so-called *objective function*.

Therefore, optimization aims at improving the output value of such an objective function by providing new (and better) solutions to the problem at hand or modifying existing solution candidates. Typical improvements aim at minimizing the objective function (e.g., cost-functions), maximizing it (e.g., utility/fitness-functions), or reaching a specific value. The objective function used within this work is a multi-objective cost function based on the weighted sum method shown in Equation 4.14. The function is therefore to be minimized.

$$q = \sum_{i=0}^{k} \omega_i f_i(\cdot) = \omega_0 f_0(\cdot) + \omega_1 f_1(\cdot) + \ldots + \omega_k f_k(\cdot) \tag{4.14}$$

Here, $f_i(\cdot)$ with $i \in \mathbb{N}$ represents individual sub-functions that calculate the costs of a provided solution according to different optimization criteria. The parameters ω_i represent weight values that control the influence of individual sub-functions on the overall costs for a solution. Using weights allows prioritizing important criteria, which can be necessary depending on the properties that are desired for a specific solution. Additionally, for supporting Pareto optimal conditions, $\omega_i > 0$ and $\sum_{i=0}^{k} \omega_i = 1$ [149].

4.3 REACTIVE HOLARCHY ADAPTION

In this work, metaheuristic optimization approaches are proposed for finding near-optimal solutions to the Holon Problem (see Section 4.1.1). The adjustments that are required to use metaheuristics in this context are presented in this section. Firstly, relevant information of the Holon Problem must be made accessible for the metaheuristic algorithms; therefore, a formal problem specification is provided and a corresponding mapping is defined, which allows projecting the Holon Problem to the solution space of the metaheuristics. Secondly, a cost function is presented, which assesses the quality of solutions to the Holon Problem by calculating a cost-value based on numerous optimization criteria. In particular, the considered quality criteria comprise economic and ecological aspects as well as resilience properties for holonic energy grids. Finally, the proposed algorithms are evaluated in a large simulated holonic energy grid facing a hazardous situation.

4.3.1 *Problem Specification and Mapping*

Solving the Holon Problem using metaheuristics requires a suitable representation of the problem. In this section, the Holon Problem is explained and a mapping to the operational domain of metaheuristics is provided.

4.3.1.1 *Holon Problem Specification*

For an energy grid organized as a holarchy H the Holon Problem comprises two sub-problems that need to be solved:

- Finding *reconfigurations* (i.e., changes within the organization of holons) for the structure of the holarchy based on the available separation points (switches) in the grid.
- Finding a corresponding resource *allocation* using available flexibilities within the holarchy that support the mitigation of demand and supply deviations and improve the overall resilience within the current reconfiguration.

More precisely, solutions to the Holon Problem for a holarchy H provide structural reconfigurations by adjusting the states of switches $SW = \{sw_1, \ldots, sw_m\}$ available within the holarchy. These switches are an abstract representation of components that allow separating and combining holons (see Section 3.3.2.1). For mitigating demand and supply deviations within the holarchy reconfiguration, a solution specifies the subset of available flexibilities $Flex = \{flx_1, \ldots, flx_n\}$ within the holarchy H that needs to be allocated. For the resource allocation numerous aspects need to be considered that can affect the resilience of the grid in the presence of hazardous situations. In this context, solutions to the Holon Problem consider, among others, economic aspects, like performance characteristics of flexibilities (see Section 3.3.3), the impact of flexibilities on prosumers, and general criteria that improve the resilience of holonic energy grids (e.g., distribution of resources between holons).

4.3.1.2 *Holon Problem Mapping*

The properties of the Holon Problem and the corresponding subproblems described above yield requirements for defining a representation in the operational space of metaheuristics. The most important ones are the following:

- *Interdependence*. The *merging* and *splitting* of holons influence the electrical requirements of the holarchy. For instance, splitting operations may separate producers from consumers. As a consequence, holons with a low production increasingly depend on the availability of sufficient positive flexibilities in their vicinity. Likewise, holons with strong production capacity require more negative flexibilities to maintain stability. Conducting a splitting operation in cases where the resulting holarchy cannot be supported by the remaining flexibilities may exacerbate the problem situation. Therefore, the reconfiguration and the resource allocation problem need to be solved together.
- *Decision space*. Each part of a solution to the Holon Problem represents a *decision* within one of the sub-problems described above. More precisely, a fixed solution to the Holon Problem represents a set of assigned variables, where the values assigned to these variables represent a decision either related to the modification of the holarchy or the allocation of flexibilities.

BINARY MAPPING OF THE HOLON PROBLEM To jointly address the aforementioned subproblems and corresponding requirements, in this work, a binary representation was chosen as the decision space. This representation is intuitive for the sub-problem of *reconfiguring* the holarchy since the separation points in the holonic grid are specified as switches, which can be either closed (i.e., a connected state that is represented as 1), or open (i.e., a disconnected state that is represented as 0).

To jointly represent the two subproblems in the same decision space the allocation of available flexibilities can be represented with binary values, similarly. Here, the decision of allocating an offered flexibility can be represented as 1; otherwise, the flexibility is represented as 0 and not used for the mitigation of the current problem situation. However,this representation is less intuitive since the decision-process for allocating flexibilities requires considering several aspects. A brief discussion of the benefits and drawbacks of this binary representation is provided at the end of this section.

The joint encoding allows leveraging the binary variants of the presented metaheuristics to simultaneously operate on both sub-problems and explore and exploit their interdependencies to find near-optimal solutions. A solution to the problem can be represented as a binary k-tuple $s = (b_1, \ldots, b_n, b_{n+1}, \ldots, b_{n+m})$, where b_i is the binary representation of a flexibility or a switch. An exemplary representation of a solution to the Holon Problem is shown in Figure 4.1.

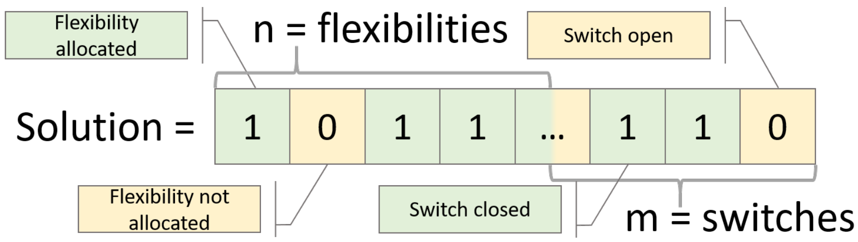

Figure 4.1: Binary encoding for solutions to the Holon Problem, where 1's represent allocated flexibilities and closed switches. Otherwise, 0's denote flexibilities that are not allocated, or switches that remain open in the current solution.

A solution to the Holon Problem is therefore of the size of 2^{n+m}, where n represents the number of flexibilities that are currently offered within the holonic energy grid, and m denotes the number of switches that can be used for reconfiguring the holarchy.

BENEFITS AND DRAWBACKS OF THE BINARY MAPPING Representing the switches and flexibility allocation as assignments of binary variables is accompanied by several benefits but also introduces drawbacks. In the following we briefly comment on prominent benefits and drawbacks that influenced the decision-making for using a binary representation.

- *Intuitive mapping for the states of switches.* As parts of the grid are either separated or connected, the state of switches represents a binary assignment. The reasoning for mapping for flexibilities to binary values follows the same argument; however, the mapping is accompanied with several drawbacks some of which are detailed below.

- *Uniformity of the decision-space*. The joint representation of the Holon Problem as binary values simplifies adjusting algorithms for solving the Holon Problem since no combined handling of different value spaces is required (e.g., discrete and continuous values).
- *Reduced decision-space*. The restriction of the decision-space to binary values can improve the process for solving the Holon Problem especially for larger problem sizes, which can emerge from situations where high numbers flexibilities are available.

Aside from the aforementioned benefits, a binary representation is accompanied by several drawbacks:

- *Loss of information*. If the allocation of flexibilities is a binary decision, fine-grained control of individual holon elements as flexibilities becomes increasingly complex. For instance, if performance parameters of a holon element are adjustable (e.g., charging rate of a battery) a binary representation of a corresponding flexibility cannot distinguish between different adjustments but an additional flexibility needs to be offered for the same holon element, which then requires interdependencies constraints between these flexibilities to prevent their simultaneous use.
- *Increased complexity for flexibility configuration*. The aforementioned loss of information leads to an increased complexity for flexibility configuration and operation at the prosumer sites. In particular, interdependencies of flexibilities need to be handled locally and constraints need to be carefully designed to enable, for instance, functionalities like the specification of goals (see Section 3.5.3) and the safe operation of devices.

4.3.2 *Holon Problem Cost Function*

In order to enable metaheuristic algorithms to optimize solutions to the Holon Problem and to make them comparable, a measure is required that allows assessing the *quality* of found solutions. Such a measure can then be used to compare solutions objectively and assess the impact of small modifications to improve the overall solution quality (see Section 4.2.3).

COST FUNCTION SPECIFICATION In this work, a cost function $f_g(\cdot)$ is proposed, which takes a *holarchy configuration* $\mathbf{H}$ (i.e., a solution to the Holon Problem) as an input and returns low values for near-optimal solutions. Correspondingly, higher values indicate that the solution is of lower quality according to the considered optimization criteria. Therefore, the penalty function is to be minimized. The function used within this work is shown in Equation 4.15.

$$\begin{aligned} f_g(\mathbf{H}) = \omega_{eb} \cdot \sigma_{eb}(f_{eb}(\mathbf{H})) + \omega_{state} \cdot \sigma_{state}(f_{state}(\mathbf{H})) \\ + \omega_{pro} \cdot \sigma_{pro}(f_{pro}(\mathbf{H})) + \omega_{perf} \cdot \sigma_{perf}(f_{perf}(\mathbf{H})) \\ + \omega_{holon} \cdot \sigma_{holon}(f_{holon}(\mathbf{H})) \end{aligned} \tag{4.15}$$

The parameters ω_i for $i \in \{eb, state, pro, perf, holon\}$ represent weight parameters in the range of [0,1] for adjusting the impact of the individual penalty sub-functions $f_i(\cdot)$. Here, the sum of all weight factors equals one. Each of the sub-functions $f_i(\cdot)$ penalizes a holarchy configuration $\mathbf{H}$ based on their quality according to different optimization criteria. To assess these criteria, the impact of the decisions that are part of a found holarchy configuration (see Section 4.3.1) is measured in the corresponding holonic energy grid and then used for calculating the penalty score within the respective sub-functions.

The following sub-functions are used within this work for assessing the quality of solutions to the Holon Problem and will be introduced and explained in details in Section 4.3.3: The penalty function $f_{eb}(\mathbf{H})$ penalizes the lack of balance between demand and supply among holons in the holarchy caused by applying $\mathbf{H}$. The function $f_{state}(\mathbf{H})$ penalizes undesired *supply states* of all the holons in the holarchy (see Section 3.3.2.3). The function $f_{pro}(\mathbf{H})$ penalizes potentially caused decreases in prosumer satisfaction depending on the priority classes of the allocated flexibilities used in $\mathbf{H}$. Function $f_{perf}(\mathbf{H})$ penalizes the holarchy configuration $\mathbf{H}$ according to numerous properties of the allocated flexibilities, which affect the economical and ecological use of the underlying resources (see Section 3.3.3). Finally, $f_{holon}(\mathbf{H})$ penalizes holons within the holarchy according to numerous properties that indicate their resilience and their capability to provide a continuous supply with electricity. The functions σ_i are squashing functions of the sigmoid family, which are explained next.

SQUASHING OF SUB-FUNCTIONS The individual sub-functions assess the solution quality according to numerous optimization parameters, which strongly differ w.r.t the range of values. For instance, performance parameters of flexibilities may be represented using small numbers (e.g., a few seconds), whereas demand and supply imbalances may be measured as several thousand Watt. To simplify the design of the individual sub-functions, we developed squashing functions σ_i of the sigmoid family that confine (and stretches) each penalty function $f_i(\cdot)$ to the interval $[0, 100)$. An additional requirement for the σ_i functions was that the sensitivity of the function can be adjusted to the peculiarities of parameter ranges of different sub-functions. For instance, if time-based performance parameters exceed a certain threshold, they should be assigned the maximum costs regardless of how much they exceed the threshold. Likewise, a threshold exists for demand and supply imbalances, but the sensitivity of σ_i needs to be adjusted accordingly (e.g., based on information on how much imbalance the grid can endure).

These properties on the one hand enable an easy comparison of results since the combination of the limitation provided by the functions σ_i and the restriction for the sum of the weights ω_i to be equal to one, provides upper bounds for the final cost value. On the other hand, functions can be quickly adjusted to changing boundaries (e.g., for comparing energy grids of different sizes). The complete form of the functions σ_i is shown in Eq. (4.16).

$$\sigma_i(x;\kappa_i) = \frac{100}{1+\exp(-\frac{10\cdot(x-\frac{\kappa_i}{2})}{\kappa_i})} - \frac{100}{1+\exp(5)}. \tag{4.16}$$

Here, $x = f_i(\mathbf{H})$ is the result of a cost sub-function. The variable κ_i is as a parameter that scales σ_i to the maximum value for which σ_i is still sensible. That is, $\sigma_i(x;\kappa_i) \approx 100$ when $x \geqslant \kappa_i$. In contrast, values x that are comparably small to κ_i result in cost scores closer or equal to zero. The function was designed in such a way that for small deviations of x) from the optimal value (i.e., zero) , the output value of the sigma function increases only slowly, but increases for stronger deviations. The graphic shown in example 4.1 presents the impact of κ on the σ_i function.

Example 4.1: An example for the σ squashing function and the κ sensitivity control

In this example the sensitivity of the function is set to $\kappa = 100$. The values for x represent the input values for the σ function. The plot below shows the output of the σ function for the x-values between 0 and 120.

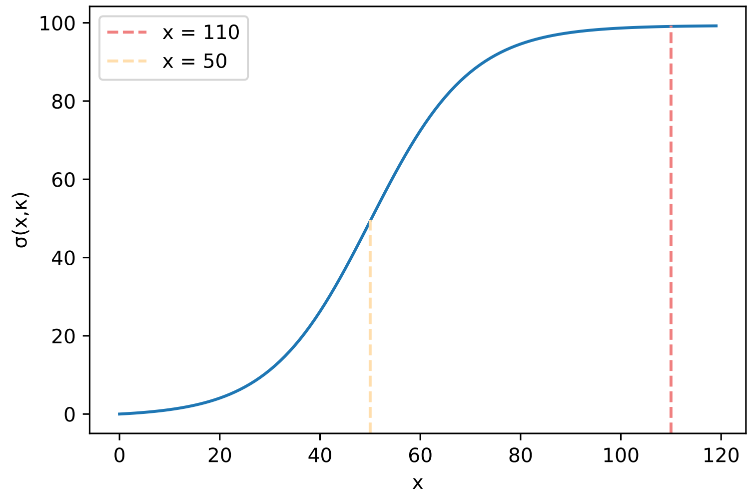

Figure 4.2: Plot of the σ function for $\kappa = 100$

If values for parameter x are close to 0, these values are squashed to values close to 0. In contrast, if the values of x reach or exceed the sensitivity threshold κ, the values are squashed close to the max value, which is indicated by the red line that shows the values for $\sigma(110, 100) \approx 99.08$. For values that range between the zero and κ, e.g., 50 = 50% of the κ value, the squashing function returns a penalty of medium severity. The orange vertical line shows the result for $\sigma(50, 100) \approx 49.33$.

4.3.3 *Optimization Criteria*

The cost function used in this work is structured as a weighted combination of multiple sub-functions and ultimately returns a cost score (see Section 4.3.2). Each of the sub-functions takes a holarchy configuration **H** (i.e., a solution to the Holon Problem) as input and penalizes it according to different optimization criteria. In this section, five sub-functions are proposed, where each function calculates a cost score based on the performance of the found solution. The optimization criteria that are considered in this work are explained in the following.

4.3.3.1 *Energy Balance Costs*

One essential criteria, which needs to be strongly considered by near-optimal solutions, is the achieved balance of demand and supply within the energy grid. This balance represents an important indicator for the resilience of the grid since a lack of balance fosters destabilization and threatens the continuous supply of electricity. Moreover, within holarchies, holons can operate autonomously while being separated from the main grid; therefore, the balance criterion needs to be assessed for each part in the holarchy.

The penalty sub-function f_{eb} penalizes a holarchy configuration $\mathbf{H}$ according to the achieved overall balance of produced and consumed electricity within the autonomous holons in the holarchy. More formally, the sub-function is represented as shown in Equation 4.17.

$$f_{eb}(\mathbf{H}) = \sum_{i=1}^{|\mathrm{holons}(\mathbf{H})|} \left| \sum_{j=1}^{|\mathrm{holon}_i|} \mathrm{prod}(ho_j^i) - \mathrm{cons}(ho_j^i) \right| \tag{4.17}$$

Here, the function $\mathrm{holons}(\cdot)$ takes a holarchy $\mathbf{H}$ as an input and returns the set of autonomous holons in the holarchy. The function f_{eb} then iterates over all holons and calculates the difference of the current demand and supply within each holon. For this, the auxiliary functions $\mathrm{cons}(\cdot)$ and $\mathrm{prod}(\cdot)$ take individual holons ho_j within the i^{th} holon as an input and return the corresponding current production and consumption of electricity. The absolute difference between production and consumption in a holon then indicates the balance achieved for this holon. High values show a lack of balance, whereas low values indicated a well-balanced holon. The sub-function f_{eb} then outputs the sum of the balance values for all holons as the final energy balance penalty for the holarchy configuration $\mathbf{H}$.

4.3.3.2 *Holon State Costs*

In the holonic model proposed in this work, six mutually exclusive states for holons are distinguished (see Section 3.3). Holons can be either in a *producer* state, or in one of five consumer states, which are *inactive*, *unsupplied*, *partially supplied*, *fully supplied*, and *oversupplied*. These states represent indicators for three main aspects related to the resilience of the holonic energy grid: the holon states (and the corresponding severity of the state) provide 1) a measure for the degree of achieved supply for all holon elements that are active within a holon; 2) an indicator for the impact of the current situation on the satisfaction of the participants in a holon (e.g., unsupplied states yield a stronger decrease of prosumer satisfaction); and 3) an indicator for the spread of allocated flexibilities (e.g., inactive holons can be caused by a strong allocation of flexibilities within the holon). To take these states into account for finding solutions to the Holon Problem, the penalty function f_{state} penalizes a holarchy $\mathbf{H}$ as shown in Equation 4.18.

$$f_{state}(\mathbf{H}) = \sum_{i=1}^{|holons(\mathbf{H})|} f_{sup}(ho_i), \tag{4.18}$$
$$f_{sup}(ho) = \begin{cases} 50 - \frac{supply(ho)}{2}, & supply(ho) \leqslant 100 \\ supply(ho) - 100, & supply(ho) > 100 \\ 0, & state(ho) == producer \end{cases}$$

Each consumer state is represented as a percentage value returned by the function $supply(\cdot)$. The function $supply(\cdot)$ takes a holon as an input and returns the degree (in percent) to which the holon can be supplied with the currently available electricity . Values below 100% represent a lack of electricity, whereas values above 100% indicate undesired surplus electricity. Consequently, inactive and unsupplied holons are considered to be 0% supplied since either no holon element can be supplied or all are were deactivated. The function f_{state} is defined such that, if $supply(ho) = 100$ (i.e., demand of the holon is fully covered) the penalty is 0. Similarly, the producer state is penalized with 0 since this state represents a fully supplied state that, additionally, provides excess electricity for its holon. For all other cases, the penalty grows linearly according to the supply state of the holon. Oversupply is penalized twice as much as undersupply states. This increased penalization is based on two assumptions: firstly, excess electricity production, which may cause the oversupply states, requires the (undesired) deactivation of RESs, which can cause fairness issues and monetary losses for the owners of the RESs; secondly, we assume that—at least during interim stages of the transitioning process towards smart grids—more positive flexibilities are available within energy grids compared to negative ones. Consequently, it may be more difficult to find sufficient flexibilities for resolving oversupply states. Furthermore, the transfer of excess electricity towards other parts of the grid can become a complex challenge if parts of the grid operate autonomously.

4.3.3.3 *Prosumer Satisfaction Costs*

As mentioned several times within this thesis, using flexibilities may cause conflicts for prosumers that want to interact with specific holon elements that are offered as flexibilities. Consequently, this may cause a decrease in prosumer satisfaction. To support the planning of holon element interaction and to allow using them within the flexibility concept, priority classes and corresponding constraints are proposed in this work (see Section 3.3.3). However, the behavior of prosumers can be affected by numerous influences and may therefore deviate from the initially assumed and scheduled use of holon elements (e.g., using the electric vehicle due to an emergency). Since these conflict cannot be fully prevented if holon elements are offered as flexibilities, we aim to mitigate the severity of the impact of the conflict using the proposed priority classes. In this work, it is assumed that conflicts affecting holon elements of higher priority have stronger impact on the prosumer satisfaction than those of lower priority. More formally, the sub-function f_{pro} is defined as Equation 4.19.

$$f_{pro}(\mathbf{H}) = \sum_{i=1}^{|flexs(\mathbf{H})|} I(state(flx_i)) \cdot (\theta^{prio(flx_i)} - 1) \tag{4.19}$$

$$I(state(flx)) = \begin{cases} 0, & \text{if flexibility } flx \text{ is "inactive"} \\ 1, & \text{if flexibility } flx \text{ is "active"} \end{cases}$$

The auxiliary function $flexs(\cdot)$ takes a holarchy configuration $\mathbf{H}$ as an input and returns the set of flexibilities that is available within the holarchy. Function f_{pro} then calculates the costs for the allocation of the available flexibilities flx_i by using the identity function $I(\cdot)$. The function returns 1 if the flexibility is allocated (active) for solving the Holon Problem; otherwise, it returns 0 (inactive). The parameter $\theta \in \mathbb{N}$ controls the costs of flexibilities according to their assigned priority classes $prio(flx_i)$: A flexibility with priority $x+1$ (i.e. $prio(\cdot) = x+1$) costs θ times more than a flexibility with priority x (i.e. $prio(\cdot) = x$). The function is designed such that flexibilities of the lowest priority class (i.e., priority class 1) are not assigned any costs. Similarly, $f_pro(\mathbf{H})$ returns 0 for all flexibilities that are not used within the current solution. Consequently, f_{pro} penalizes allocated flexibilities according to their assigned priority class.

4.3.3.4 *Flexibility Performance Costs*

Flexibilities can differ according to their performance for mitigating a problem situation since they are based on a variety of heterogeneous holon elements. For instance, flexibilities based on RESs or battery storage units should be preferred compared to flexibilities based on fossil fuel due to their ecological impact. Likewise, economic aspects are important, like the preference of long-lasting flexibilities over ones with a short duration. Such aspects need to be considered to find near-optimal holarchy configurations since a well-performing flexibility allocation supports the resilience of the energy grid in the short and long run and takes into account the preferences of the prosumers that offer them. In this work, three characteristics related to the performance of flexibilities are considered (see Section 3.3.3). The corresponding cost are calculated by sub-function f_{perf} as shown in Equation 4.20.

$$f_{perf}(\mathbf{H}) = \sum_{i=1}^{|flexs(\mathbf{H})|} [f_{del}(flx_i) + f_{cool}(flx_i) \\ + f_{dur}(flx_i)] \cdot I(state(flx_i)) \,. \tag{4.20}$$

The function f_{perf} aggregates the costs for allocated flexibilities within the current holarchy configuration (indicated by indicator function $I(\cdot)$). For each allocated flexibility the costs are derived as a linear combination of the three performance characteristics considered in this work, namely *delay*, *cool-down* and *duration* (see Section 3.3.3.1). Multiple other performance aspects exist (e.g., the provided power of flexibilities in relation to the severity of demand and supply mismatch that needs to be mitigated); however, the majority of these is already implicitly addressed within other parts of the cost function (e.g., power of flexibilities is reflected by sub-function f_{eb}, where higher power will result in greater improvements for resolving balancing problems) and would therefore cause redundant cost calculations. The three previously mentioned characteristics are derived from the properties of flexibilities as introduced in Section 3.3.3. They are more formally presented as follows:

$$\begin{aligned} f_{del}(flx) &= \frac{2\lambda_{del}}{1 + \exp(-\frac{del(flx)}{range(\kappa_{del})})} - \lambda_{del}, \\ f_{cool}(flx) &= \frac{2\lambda_{cool}}{1 + \exp(-\frac{cooldown(flx)}{range(\kappa_{cool})})} - \lambda_{cool}, \\ f_{dur}(flx) &= -\frac{2\lambda_{dur}}{1 + \exp(-\frac{duration(flx)}{range(\kappa_{dur})})} + 2\lambda_{dur}, \\ range(\kappa) &= -\frac{\kappa}{\ln(2^p - 1)}, \quad p = 0.05. \end{aligned} \tag{4.21}$$

The three functions f_{del}, f_{cool} and f_{dur} represent the cost sub-functions for delay, cool-down and duration respectively. Each function encompasses three auxiliary functions $del(\cdot)$, $cooldown(\cdot)$ and $duration(\cdot)$, which take a flexibility flx as an input and return the corresponding values for delay, cool-down and duration that are configured for the flexibility. As these parameters do not have any boundaries that restrict the value-space (e.g., a flexibility can theoretically be configured with an unconstrained delay if it never reaches its full magnitude after being activated), the corresponding functions need to be restricted. Therefore, we defined λ parameters that restrict the maximum cost value that can be returned by each of the specified functions.

The sub-functions are designed to steeply increase the returned cost value until a specified point κ, which defines the area in which the performance of a flexibility is to be distinguished w.r.t. the respective parameter. If the value of the parameter approaches or exceeds κ, the returned cost value should approach λ. The parameter

λ_j specifies the maximum penalty that is returned by sub-function f_j for $j \in \{del, cool, dur\}$. Simultaneously, the choice for each λ_j specifies the importance of respective sub-function within the overall cost calculation. For instance, if $\lambda_{del} = 100$ and $\lambda_{cool} = 50$ the bad performance of a flexibility w.r.t the delay can cost twice as much as a bad performance according to the cool-down time. The parameter κ_j is used in the auxiliary function $range(\kappa)$ (see Equation 4.21). The function $range(\cdot)$ is used to compute the value needed to set the area under the curves $\lambda_j - f_j$ between zero and κ_j for $j \in \{del, cool, dur\}$.

An example that shows the connection between the λ- and κ- parameters is shown in 4.2.

Example 4.2: Example configuration for λ and κ

Let a flexibility flx be based on a water-heater that requires 15 seconds until the internal heating elements can consume the specified power (i.e., delay = 15s). As an example, we can now specify the maximum costs that can be assigned for the performance of an individual flexibility regarding the delay as $\lambda_{del} = 80$. Consequently, we have a cost interval of 0, which is no penalty is assigned, to 80 as a maximum value. We now specify that the delay is penalized with the maximum value at $\kappa_{del} = 30$ seconds since we want to quickly resolve problems in the grid. The resulting penalty is calculated as follows:

$$f_{del}(flx) = \frac{2 \cdot 80}{1 + \exp(-\frac{15}{range(30)})} - 80 \approx 54.7$$

The use of the flexibility flx for resolving the Holon Problem would result in costs of 54.7 for its delay. Figure 4.3 shows the corresponding development of the cost function considering different values for the delay.

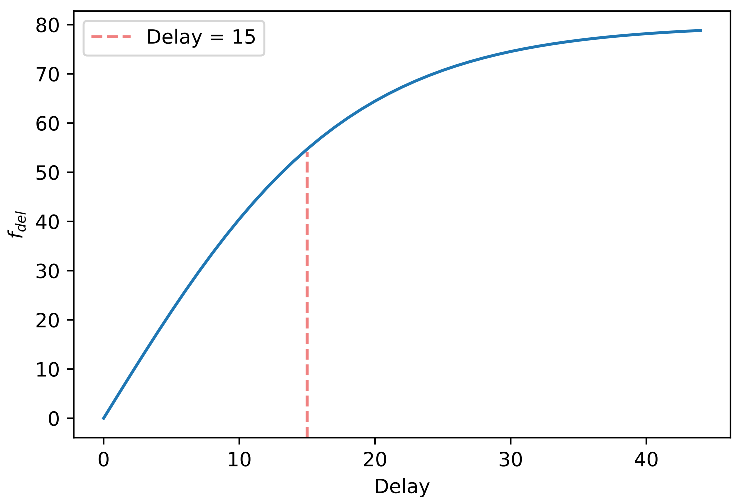

Figure 4.3: Plot of the f_{del} function for $\kappa_{del} = 30$

> If the delay gets closer to 30s the penalty will approach 80 (if delay is exact 30s the corresponding costs are 74.55) and a delay closer to 0 will yield a penalty score about 0.

4.3.3.5 *Holon Quality Costs*

The reconfiguration of the holarchy changes the inherent properties and capabilities of holons. For instance, smaller holons may require less electricity and, therefore, can sustain themselves with a lower amount of resources. In comparison, larger holons may benefit from an increasing amount of resources to resolve the problem at hand or at least compensate for faulty entities in the grid (e.g., compensating for a misbehaving producer). In order to increase the resilience of holonic energy grids, near-optimal holarchy configurations need to consider the configuration of holons such that the properties of these holons support the continuous operation of the grid. For this, a cost sub-function f_{holon} is used, which is defined as shown in Equation 4.22.

$$f_{holon}(\mathbf{H}) = \sum_{i=1}^{|holons(\mathbf{H})|} \Big[\big(f^{+}_{elem}(ho_i) + f^{-}_{elem}(ho_i)\big) + \Big(f^{+}_{flexibility}(ho_i) + f^{-}_{flexibility}(ho_i)\Big) + \big(f^{+}_{mtg}(ho_i) + f^{-}_{mtg}(ho_i)\big) \Big] \tag{4.22}$$

The auxiliary function $holons(\cdot)$ takes a holarchy configuration as an input and returns a set of encompassed holons. The cost sub-functions $f^{i}_{j}(\cdot)$ for $i \in \{+,-\}, j \in \{elem, flexibility, mtg\}$ are calculating cost values w.r.t. different resilience properties of the holons. The considered properties are the following:

- *Energy Density*. This represents the concentration (or spread) of demand and supply capacity within a holon. The costs are calculated by the functions $f^{\{+,-\}}_{elem}$.
- *Flexibility Density*. Similar to the energy density, this represents the concentration (or spread) of flexibility capacity within a holon. The costs are calculated by the functions $f^{\{+,-\}}_{flexibility}$.
- *Mitigation Capacity*. Represents the capability of a holon to cope with changes in demand and supply based on the availability of local flexibilities. The corresponding costs are calculated by the functions $f^{\{+,-\}}_{mtg}$.

The functions are explained below in more detail.

ENERGY DENSITY The sub-functions $f_{elem}^{\{+,-\}}$ return the costs for holons within the holarchy according to the inherent concentration (or spread) of production and consumption. Low values of Energy Density indicate that the production and consumption capacities are well-spread within a holon, i.e., production and consumption is equally conducted by all participants in the holon. In particular, for holons with low Energy Density it is unlikely that prosumers in the holon provide a large amount of production or consumption compared to the average. Consequently, the probability strong deviations in the demand and supply balance, due to changes, failures, or misbehaving participants is low. In contrast, if Energy Density is high, there exist prosumers in the holon that are responsible for a comparably large amount of the production or consumption and they can have a strong impact on the resilience of the holon. More formally, the Energy Density for demand and supply is defined as Equation 4.23 and Equation 4.24

$$f_{elem}^{-}(ho_i) = \sqrt{\frac{\sum_{j=1}^{|holons(ho_i)|}\left(cons(ho_j^i) - \overline{cons(ho_i)}\right)^2}{|holon_i|}} \tag{4.23}$$

$$f_{elem}^{+}(ho_i) = \sqrt{\frac{\sum_{j=1}^{|holons(ho_i)|}\left(prod(ho_j^i) - \overline{prod(ho_i)}\right)^2}{|ho_i|}} \tag{4.24}$$

Here, ho_j^i denotes the j^{th} holon encompassed in holon i. Auxiliary functions $cons(\cdot)$ and $prod(\cdot)$ return the consumption and production of a holon respectively. The functions $\overline{cons(ho_i)}$ and $\overline{prod(ho_i)}$ return the average values for the encompassed holons. The functions f_{elem}^{+-} iterate through all holons encompassed in the input holon and aggregate the standard deviations of the consumption and production of the encompassed holons. Consequently, the penalty severely increases if (multiple) entities exist whose consumption or production strongly deviate from the average consumption and production within the holon. A growing number of such entities increases the probability for more severe deviations in demand and supply if these individuals change, fail, or misbehave. Consequently, the challenge of mitigating demand and supply deviations is aggravated.

FLEXIBILITY DENSITY The sub-functions shown as Equation 4.25 and Equation 4.26 correspond to calculating a cost value for a holarchy configuration according to the concentration of flexibilities within the holons. On the one hand, the Flexibility Density has an impact on resilient grid operation similar to the Energy Density. In particular, if a large amount of flexibility potential is concentrated at a few locations within a holon, a failure or misbehavior of these locations can severely impact the resilience of a holon and strongly reduce its capability to mitigate demand and supply deviations. In contrast, if flexibilities are well-dispersed, a holon can mitigate problems more easily even if individual entities are not available. On the other hand, a high Energy Density value represents an indicator that the fair allocation of flexibilities within the holon can become problematic since the few participants that provide large amounts of flexibilities may be more involved in mitigation processes and may therefore experience drawbacks more frequently.

The functions $f^{+}_{flexibility}$ and $f^{-}_{flexibility}$ have a similar form and purpose to the functions in Equation 4.24 and Equation 4.23. However, these functions calculate the costs for unbalanced concentrations of positive and negative flexibilities within holons. The functions are defined as follows:

$$f^{+}_{flexibility}(ho_i) = \sqrt{\frac{\sum_{j=1}^{|flexs(ho_i)|}\left(pos(flx^i_j) - \overline{pos(ho_i)}\right)^2}{|ho_i|}} \tag{4.25}$$

$$f^{-}_{flexibility}(ho_i) = \sqrt{\frac{\sum_{j=1}^{|flexs(ho_i)|}\left(neg(flx^i_j) - \overline{neg(ho_i)}\right)^2}{|ho_i|}} \tag{4.26}$$

The set of flexibilities that belong to the i^{th} holon is returned by the auxiliary function $flexs(ho_i)$. The functions $pos(flx^i_j)$ and $neg(flx^i_j)$ take a flexibility and return the positive or negative power capacity that it provides to affect the demand or supply within a holon. The functions $\overline{pos(ho_i)}$ and $\overline{neg(ho_i)}$ return the average positive or negative power capacity that is provided by flexibilities in the i^{th} holon. These auxiliary functions are then used to calculate the standard deviation for the positive and negative flexibility capacity within holons.

MITIGATION CAPACITY The Mitigation Capacity refers to a holon's capacity for mitigating peak production and peak consumption situations by using locally available flexibilities. In particular, the function $f^{+}_{mtg}(\cdot)$ calculates the cost w.r.t. the lack of positive flexibility capacity, i.e., insufficient positive flexibilities to mitigate the maximum possible consumption of the holon. Similarly, the function $f^{-}_{mtg}(\cdot)$ calculates a cost value w.r.t. the lack of negative flexibility capacity, which is required for counteracting the peak production of a holon. The corresponding functions are shown in Equation 4.27 and Equation 4.28.

$$f^{+}_{mtg}(ho_i) = \lambda_{mtg} - \lambda_{mtg} \cdot \min\left(1, \frac{\sum_{j=1}^{|flexs(ho_i)|} pos(flx^i_j)}{cons_{max}(ho_i)}\right) \tag{4.27}$$

$$f^{-}_{mtg}(ho_i) = \lambda_{mtg} - \lambda_{mtg} \cdot \min\left(1, \frac{\sum_{j=1}^{|flexs(ho_i)|} neg(flx^i_j)}{prod_{max}(ho_i)}\right) \tag{4.28}$$

Here, λ_{mtg} represents the maximum cost value that can be returned by the presented functions. Each of the functions is tailored such that the costs are calculated as the degree of flexibility capacity that is missing to match the peak values for consumption or production. Once the amount of flexibility capacity exceeds the peak values, i.e., flexibility capacity is sufficient to compensate peak production or consumption, the returned costs equals zero. For instance, if the available positive flexibility covers only 20% of the peak consumption, the auxiliary function $min(\cdot)$ selects this value as it is smaller than 1. The subsequent multiplication with the maximum cost value λ_{mtg} yields the reduction of the costs value that is achieved by providing at least 20% of the desired flexibility capacity. Consequently, the final cost value represents 80% of the maximum possible penalty λ_{mtg}. In comparison, if the flexibility capacity equals or exceeds the peak consumption and production values, the function $min(\cdot)$ returns 1 which results in an overall costs of zero.

4.3.4 *Evaluation*

To evaluate the suitability of the introduced metaheuristics for solving the Holon Problem, we evaluate their performance using a simulated energy grid (hereafter denotes as network). The exemplary network is modeled using the HOLEG simulation environment (see Section 3.4.2) and represents a distribution grid facing a severe undersupply situation. The Holon Problem in this network is solved within different time-horizons to investigate the capability of the metaheuristics to find near-optimal solutions quickly and to analyze the potential trade-offs between solution quality and computation time. The time-horizons are mainly aligned to the time requirements for reserve capacity (see Section 2.3.1.2). In this section, we first describe the setup for the simulation and provide detailed information about the modeled holonic energy grid. We then present the parameter choices for both the penalty function and the individual metaheuristics. Subsequently, we present and discuss the results of the metaheuristic optimization approaches.

4.3.4.1 *Simulation Setup*

For evaluating the different metaheuristics, a variety of parameter configurations are investigated for their application in the simulated energy grid. Each run of an individual parameter configuration is executed 50 times to reduce the impact of bad random initialization. All configurations are evaluated considering three main time-horizons, which are 30s, 60s, and 10 minutes. These time-horizons are used for investigating the suitability of metaheuristics to work within time-constraints that are relevant for primary-, secondary-, and tertiary control operations (see Section 2.3.1.2). In the following, the simulated energy grid and the parameter configurations of the metaheuristics and fitness function that are used in this work are explained in detail.

NETWORK CONFIGURATION The simulated network represents a distribution grid and is modeled according to the holarchy model presented in this work (see Section 3.3). The network faces an undersupply situation, where the available production does not suffice to cover the demand. A summary of the important parameters for the network configuration is presented in Table 4.1.

Holarchy Components. The network consists of 760 layer-0 holons that are connected via connection-lines in a bus-like manner. Out of these holons, 18 represent small-scale producers that are responsible for maintaining a continuous supply of electricity within the holonic distribution grid. The remaining 742 holons are considered to be domestic prosumers within a residential area, where prosumers represent households and no industry participants are not considered.

For enabling the separation and connection of physically close parts of the network, 123 separator switches are present on connection lines within the holarchy. Initially (prior to the problem situation), all switches are closed, and the holarchy forms one large physical holon. Each layer-0 holon encompasses 3–7 holon elements, which represent typical household appliances and devices that either consume or produce electricity. In total, 3,747 active holon elements are present in the network. To represent a diverse set of active devices within the different holons of the grid and provide realistic device properties (e.g., electricity production and consumption values), the devices are chosen uniformly at random from a list of typical house appliances [45].

Appliance Prioritization. All holon elements are assigned to one of four priority classes, namely *low*, *medium*, *high*, and *essential*. It is assumed that for the considered time-horizons the appliances do not change priority classes. This is based on the assumption that users do not make adjustments with a high frequency. The assignment of holon elements to priority classes is conducted randomly, but in such a way that 40% of all devices are assigned to the low priority class, 30% are assigned to medium, 20% are assigned to high, and 10% represent essential appliances. Here, we assume that the probability for appliances that are used simultaneously in peoples' homes and, additionally, are considered to be of higher priority, is low. For instance, the majority of the devices are related to entertainment (e.g., TV) or quality of life (e.g., air conditioning). Therefore, most of the appliances are assigned to the low or medium priority class as they do not have a strong impact on well-being or financial situation of the prosumer.

Flexibility Configuration. Furthermore, a strong adoption of the flexibility concept is assumed. In particular, each prosumer offers between 0–3 of her available holon elements as flexibilities. Considering that more than five appliances are active on average, prosumers are willing to offer up to 60% of their appliances as flexibilities. In the presented network, this yields 1,570 available flexibilities. Out of those, 1,354 (86.34%) are *positive* flexibilities (i.e., flexibilities that increase the grid frequency) and 216 (13.76%) are *negative* flexibilities (i.e., flexibilities that lower the grid frequency). This significant difference between the number of positive and negative flexibilities results from the type and number of active devices that are available within the homes of prosumers. The majority of active appliances are consuming electricity. Consequently, the random assignment of flexibilities results in a higher number of active and consuming devices as flexibilities. If one of these appliances is deactivated the overall consumption decreases and, therefore, it is considered as a positive flexibility. Likewise, inactive producers that can be activated on demand and those that are active but can increase their production are considered as positive flexibilities. In contrast, the number of appliances that can be activated to consume electricity and the number of producing devices are comparably low. Furthermore, devices that are in a standby state are considered to be offline w.r.t the Holon Problem. If these devices are producers in their standby state, their activation resembles the specified behavior of a positive flexibility. Similarly, if they are a consumer in a standby state, their activation yields an increased electricity consumption and therefore represents a negative flexibility. In contrast, if these devices get fully deactivated, either their standby production or consumption only slightly decreases (i.e., the amount of electricity produced/consumed in the standby state compared to their behavior in an inactive state) and is therefore not considered in this work. The flexibilities inherit the priority classes of their underlying holon elements. From this, the following assignment of flexibilities to priority classes emerges: 756 (48.15%) flexibilities are of low priority, 501 (31.91%) of medium priority, 222 (14.14%) of high priority, and the remaining 91 (5.80%) are of essential priority.

Holon Problem Information. In order to investigate the resilience of the grid, a predicted hazardous situation is represented by a severe deviation of demand and available production. Here, the overall de-

Prosumers (layer-0 holons)	760
Separator Switches	123
Holon Elements	3,747 (100%)
Low Priority	1,858 (49.59%)
Medium Priority	1,130 (30.16%)
High Priority	517 (13.80%)
Essential Priority	224 (5.98%)
Production	1.18 MW
Consumption	2.07 MW
Difference	-886kW
Flexibilities	1,570 (100%)
Low Priority	756 (48.15%)
Medium Priority	501 (31.91%)
High Priority	222 (14.14%)
Essential Priority	91 (5.80%)
Positive Flexibilities	1,354 (86.24%)
Negative Flexibilities	216 (13.76%)

Table 4.1: Summary of the parameters for the simulated exemplary network.

mand in the exemplary grid is 2.07MW. This demand is accumulated from all appliances within all holons of the grid. The production predicted for the same time window is 1.18MW, which is not sufficient to meet the expected demand. The overall deviation is 43%, which results in the following undesired state for the holarchy: Out of 742 prosumers, 165 (22%) are predicted to be incapable to fully supply their appliances, and are therefore in a partially supplied state, 492 (66%) are capable of remaining fully supplied, and 85 (11%) act as producers due to their high capacity of local production. No prosumers are in an unsupplied or inactive state. The predicted problem situation needs to be resolved quickly as a deviation of this magnitude can have severe consequences for the overall grid stability. Furthermore, partially supplied prosumer experience a strong decrease in overall user satisfaction since devices that are expected to be running cannot be supplied.

The resources that are available to resolve the problem situation consist of 1,570 flexibilities offered by the local prosumers and 123 separator switches that are available for reconfiguring the holarchy. The emerging problem space for the corresponding Holon Problem encompasses $2^{1,693}$ possible solutions.

PARAMETERS OF THE COST FUNCTION As the weights and the function-specific parameters of the cost function strongly affect the importance and severance of the sub-functions, the selection of suitable weights and parameters is crucial for finding near-optimal solutions to the Holon Problem. The introduced cost function encompasses 18 parameters that can be divided into three sub-groups: First, five weights ω_i are responsible for regulating the impact of the individual sub-functions f_i. The weights $\omega_i \geqslant 0$ are configured such that $\sum_{i=0}^{k} \omega_i = 1, \forall i \in \{eb, state, pro, perf, holon\}$ [149] to support adjusting the impact of the sub-functions. Second, eight κ-parameters define the sensitivity of the sub-functions (see example 4.1). Finally, five internal function parameters λ are used to specify the maximum costs assigned by the individual sub-functions. Note that the choice of values for the weights and parameters heavily depends on the scenario that is used for deriving the Holon Problem and on the preferred properties of solutions to the Holon Problem. For instance, if ecological aspects of flexibilities are considered to be more important than resilience properties of holons, the weight for f_{perf} needs to be increased, and the weight for f_{holon} should be decreased. In this work, the parameters are derived from the exemplary grid that faces the problem scenario presented in Section 4.3.4.1. The choices for the weights and parameters is presented below.

Weight Values Selection. The weight values for the presented scenario are set to $\omega_{eb} = 0.3, \omega_{state} = 0.3, \omega_{pro} = 0.2, \omega_{perf} = 0.1$ and $\omega_{holon} = 0.1$. Consequently, the functions f_{eb} and f_{state} have the strongest impact on the penalization of found solutions. This decision is made based on the assumption that the main task of an energy grid, especially during a hazardous situation, is maintaining a continuous supply of electricity, such that the demand of all consumers is met. The function f_{eb} penalizes deviations from the balance between demand and supply; The function f_{state} penalizes undesired states of holons. Together, these functions represent the most important aspects to ensure a continuous supply of electricity since the balance of demand and supply is required to maintain frequency stability and desired holon states indicate that sufficient electricity is available to fulfill the needs of the consumers. Therefore, the corresponding penalty functions are both assigned the highest weight value of 0.3. We consider f_{pro} slightly less important compared to $f_{\{eb,state\}}$. The function f_{pro} penalizes actions that result in a decrease of prosumer satisfaction. Such actions (e.g., deactivation of an appliance) can generate conflicts between prosumers' intention to interact with local appliances and the use of those appliances as flexibilities for the mitigation of problems in the grid. This aspect becomes increasingly important since the resilient operation of future holonic grids during hazardous events heavily relies on prosumers providing local resources; However, maintaining prosumer satisfaction still remains slightly less important compared to ensuring the stable operation of the grid. Consequently, the weight $\omega_{\mathtt{pro}}$ is set to 0.2. Finally, both $\omega_{\mathtt{perf}}$ and $\omega_{\mathtt{holon}}$ are assigned the lowest weights of 0.1 for the given scenario. The ecological aspects of flexibilities—penalized by the sub-function $f_{\mathtt{perf}}$—are less important than maintaining stability or ensuring prosumer satisfaction since the ecological consequences resulting from further destabilization of the grid will likely outweigh the benefits derived from optimizing solutions based on the ecological use of appliances. Similarly, the weight $\omega_{\mathtt{holon}}$ is chosen since the function $f_{\mathtt{holon}}$ penalizes the generation of *bad* holons. Here, bad is defined by aspects that aim to assess the resilience of individual holons and is, therefore, concerned with the resilient long-term operation of a holarchy. More precisely, the generation of *good* holons enables the grid to operate within a hazardous situation for a longer period of time; however, the mitigation of the problem at hand is the main goal, where the quality of the individual holons is less important compared to the overall stable operation of the grid.

κ-Parameter Determination. The eight parameters κ_j for $j \in \{\mathtt{eb}, \mathtt{state}, \mathtt{pro}, \mathtt{perf}, \mathtt{holon}, \mathtt{del}, \mathtt{cool}, \mathtt{dur}\}$ define the squashing sensibility of the sigmoid function $\sigma(\cdot)$ (see example 4.2). The individual κ_j for the presented exemplary grid are set as shown in Table 4.2.

$\kappa_{\mathtt{eb}}$	$\kappa_{\mathtt{state}}$	$\kappa_{\mathtt{pro}}$	$\kappa_{\mathtt{perf}}$	$\kappa_{\mathtt{holon}}$	$\kappa_{\mathtt{del}}$	$\kappa_{\mathtt{cool}}$	$\kappa_{\mathtt{dur}}$
1,050,000	10,000	2,000	11,000	150,000	120	86,400	3,600

Table 4.2: κ parameter configuration for the exemplary grid

Random Solution Set Sampling. For deriving the specific values for $\kappa_{\{\mathtt{eb},\mathtt{state},\mathtt{pro},\mathtt{perf},\mathtt{holon}\}}$ we conducted a random set sampling of solutions to the Holon Problem and calculated the result of the individual penalty sub-functions. This process was repeated 50 times for each of the sub-functions $f_{\{\mathtt{eb},\mathtt{state},\mathtt{pro},\mathtt{perf},\mathtt{holon}\}}$. Subsequently, the final κ-value was set to the value that caused the most severe deviation from the average penalty value returned by the respective sub-functions. For instance, 1,050,000Watt was observed to be the largest deviation during the sampling process for sub-function $f_{\mathtt{eb}}$. Consequently, parameter $\kappa_{\mathtt{eb}}$ was set to 1,050,000. More intuitively, the κ-values represent indicators for the largest penalties that fall under 95% of penalties returned by the respective sub-functions and are, therefore, considered as a sensibility threshold for the squashing function. This process is used to derive the values for $\kappa_{\mathtt{state},\mathtt{pro},\mathtt{perf},\mathtt{holon}}$.

Expert Knowledge. In contrast, the values for $\kappa\{\mathtt{del}, \mathtt{cool}, \mathtt{dur}\}$ are not derived by stochastic random sampling but are based on peculiarities of the exemplary grid. Here, $\kappa_{\mathtt{del}}$ is set to 120 based on the time-horizon (in seconds) that is considered to be a reasonable maximum time for assessing the unresponsiveness of flexibilities within this work. Parameter $\kappa_{\mathtt{cool}}$ is set as $60^2 \cdot 24 = 86,400$, which represents the seconds of a day. This value is based on the assumption that the maximum cool-down of a flexibility after it was successfully used is one day. Finally, κ_{dur} is set to represent a one hour time window as $60^2 = 3600$. This value is based on the time a flexibility is assumed to be actively used for supporting the mitigation of problems. This assumption is based on two aspects: firstly, we assume that the problem scenario needs to be mitigated quickly but the solution to the Holon Problem needs to be applied only for a limited amount of time during the problem situation. Such a time limitation is reasonable as problem situations can change quickly. During this time, different flexibilities should be used to limit the burden that needs to be endured by individuals. Second, if the problem is expected to last for a longer period of time (e.g., malfunctioning of a power plant), control entities need to plan for providing additional resources that do not rely on the offers provided by the prosumers (e.g., backup power plants). The initial mitigation of the situation can still be managed by using flexibilities but during this period of time, other, more stable solutions need to be found.

Internal Parameter Determination. The internal function parameters are λ_j for $j \in \{\mathrm{del}, \mathrm{cool}, \mathrm{dur}, \mathrm{mtg}\}$, which specify the maximum penalty that is assigned by the individual sub-functions and θ. An overview of their value assignments for the exemplary grid is presented in Table 4.3.

λ_{del}	λ_{cool}	λ_{dur}	λ_{mtg}	θ
10	10	10	1,000	3

Table 4.3: λ and θ parameter configuration for the exemplary grid.

For the exemplary grid used in this evaluation the parameters were set to $\lambda_{\mathrm{del}} = \lambda_{\mathrm{cool}} = \lambda_{\mathrm{dur}} = 10$. This choice was made empirically and supports the floating-point stability of the calculations within the cost function. The corresponding sub-functions $f_{\{\mathrm{del,cool,dur}\}}$ of f_{perf} (see Equation 4.20) would not benefit from larger parameter choices as the values are squashed later. However, smaller choices for $\lambda_{\{\mathrm{del,cool,dur}\}}$ would result in small floating-point numbers lowering the overall sensitivity. Parameter λ_{mtg} is set to $1,000$. This parameter choice aims at balancing the values of f_{mtg} with the cost values calculated by f_{elem} and $f_{\mathrm{flexibility}}$. The parameter θ is set to 3. This parameter setting results in a threefold increase of the penalty value for using flexibilities of higher priority classes. For instance, using a flexibility of priority class *x+1* is assigned a penalty 3 times as high as the penalty for priority class *x*. In all conducted experiments, this value yielded the best results.

PARAMETERS OF THE ALGORITHMS Metaheuristics rely on a variety of parameters, where each one may have a strong impact on the algorithms' performance and the quality of the found solutions. Therefore, selecting suitable parameter sets depending on the environment, and peculiarities of the problem at hand is crucial. As the investigation of all parameter permutations is not feasible, we used the following steps to determine suitable parameter settings:

1) Conduct a binary search with a large step-size to specify parameter intervals for which each metaheuristic performs well during ten test runs within the exemplary network.

2) Conduct a binary search within the previously identified intervals using a smaller step-size to reduce the interval sizes.

3) Optimize individuals parameters by fixing other parameters at reasonable but non-optimized values (known through prior experiments and suggested by related work).

4) Fine-grained optimization of non-fixed parameters using small step-sizes to identify the optimal values within the given intervals.

5) Ensure comparability of parameter selections by choosing parameter configurations that yield a comparable computational complexity for the different metaheuristics (i.e., keep the number of particles/ants/individuals and iterations/generations at comparable values such that the overall number of operations that need to be executed by each algorithm is similar).

The resulting parameter configurations that are used for evaluating the metaheuristic approaches are presented in Table 4.4 for the BPSO, Table 4.5 for the GA and Table 4.6 for the BACO.

T_h[s]	P [#]	I [#]	φ	V_{max}	Pr_m
30s	20	100	2.07	9	0.0001
60s	15	275	2.07	9	0.0002
10min	80	500	2.07	9	0.0003

Table 4.4: Selected well-performing parameter configurations used for evaluating the BPSO approach.

Here T_h is the time-horizon that indicates the time available for finding solutions to the Holon Problem. The investigated time-horizons are $30, 60$ seconds to investigate the capabilities for finding solutions quickly, and about 10 minutes for a more unconstrained operation. P denotes the number of particles used within a swarm, and I is the number of iterations for which the swarm was allowed to traverse the search-space. Parameter φ represents the dependency parameter and is constrained to the suggested interval of [2.01,2.4] (see Section 4.2.2.1

and the work of [139]). Parameter V_{max} denotes the maximum velocity a particle can have. Finally, Pr_m controls the probability for mutations taking place within the solutions found by particles. Each bit within a solution found by the algorithm has a chance of Pr_m to mutate.

T_h[s]	P [#]	G [#]	Pr_c	Pr_m
30s	20	100	0.2	0.0006
60s	10	400	0.6	0.0006
10min	300	135	0.3	0.0006

Table 4.5: Selected well-performing parameter configurations used for evaluating the GA approach.

The time-horizon for solving the Holon Problem is again denoted by T_h. The size of a population within the GA is represented as P, and the number of calculated generations is G. Parameter Pr_c represents the probability used for the recombination operation. In this work, the uniform-crossover strategy is used for recombination. Hereby, offspring is generated by starting off with identical copies of the parent individuals and then traversing all genes. During the traversal process, each gene of one copy has the probability of Pr_c to be swapped with the gene located at the same position within the other copy. The probability for mutations happening for individual bits is denoted by Pr_m.

T_h[s]	A [#]	G [#]	φ	R_p
30s	10	200	0.45	0.99
60s	15	270	0.3	0.99
10min	70	600	0.4	0.99

Table 4.6: Selected well-performing parameter configurations used for evaluating the BACO approach.

The time-horizon for solving the Holon Problem is again denoted by T_h. The number of ants is presented as A, and the calculated generations are indicated by G. Parameter φ is the evaporation-factor for the pheromones, and R_p represents the threshold for the pheromone reset.

4.3.4.2 *Algorithms for Baseline Comparison*

In addition to the comparison of the metaheuristic approaches among themselves, we provide two baseline algorithms that are aligned to load-shedding approaches conducted as emergency measures within energy grids (see Section 2.3.1.2). The two algorithms are *RandomShedding* (RS) and *BestShedding* (BS) and are explained next in more detail.

RANDOMIZED LOAD-SHEDDING ON LOWER LAYERS The RS algorithm makes "beneficial" load-shedding decisions starting at the lowest layers within a holarchy. For instance, if switches for separating parts of the network exist in the vicinity of consumers (e.g., as part of a load-shedding contract with enterprises), these parts of the grid are shed first. Afterward, higher-layers switches are taken into account, which may result in more severe separations of the grid (e.g., disconnecting parts of the medium voltage grid layer). A decision is considered to be beneficial if the calculated costs of the holarchy configuration resulting from the decision are lower compared to the holarchy configuration where the decision is not made. Furthermore, the order in which the components on the different layers are considered within the decision-making are randomized to improve the exploration of the solution space of the algorithm. The pseudo-code representation of the algorithm is shown by Algorithm 4.1.

```
input  : A (binary) holarchy configuration H
output: A reconfigurated holarchy H'

H' ← H;
layerlists ← getComponentsSortedByLayer(H);
layerlists ← randomizeIndices(layerlists);
foreach layer ← layerlists do
    foreach Component c ← layer do
        if cost(H'.set(!c)) < cost(H') then
            H' ← H'.set(!c);
        else
            H'.set(c);
        end
    end
end
return H'
```

Algorithm 4.1: The *RandomShedding* algorithm, which makes randomized improvements to an initial holarchy configuration, starting at the lowest layer of the holarchy.

OPTIMIZED GLOBAL LOAD-SHEDDING The *BestShedding* Algorithm, similarly to the RS algorithm makes "beneficial" decisions within a given holarchy configuration **H** to improve the overall situation. In contrast to the RS algorithm, the BS algorithm aims to find the best possible changes that can be made within the holarchy configuration in a round-based manner. Towards this end, the algorithm iterates through the components of **H** and calculates if adjustments to each individual components decrease the cost of the resulting holarchy configuration. Once all components are traversed, the algorithm make the one adjustment that yields the most significant decrease in costs. Afterward, the modified holarchy configuration is used to repeat the process until no further improvements can be achieved.

```
input  : A (binary) holarchy configuration H
output: A reconfigurated holarchy H'
H' ← H;
for i ← 0 to size(H') do
    Index j ← getBestIndex(H');
    if j ≠ Null then
        Component c ←getComponent(H',j);
        H' ← H'.set(!c,j);
    else
        break;
    end
end
return H'
```

Algorithm 4.2: The *BestShedding* algorithm, which makes the best possible improvements by making one change within a holarchy configuration that reduces the overall costs. This process is repeated until no changes would result in a further cost reduction.

MODES OF OPERATION The two presented load-shedding algorithms can base their load-shedding decisions of different components of the holarchy configuration. In this work, we consider two different modes of operation for both algorithms, where each mode considers a different type of components for making load-shedding decisions. The *Switch* mode considers the separator switches of the holarchy configuration as components for load-shedding. This mode is aligned to the concept of rolling-blackouts (see Section 2.3.1.2), where parts of the grid are separated from the main grid. The second mode is called *SmartMeter* mode and considers the smart meters as components for making load-shedding decision. This mode is based on the assumption, that future smart meters may provide functionalities to separate the consumer/prosumer from the grid. This represents a more fine-grained load-shedding approach, but increases the problem size significantly since more participants can be considered for the decision-making compared to the problem size in the Switch mode. Flexibilities are not considered within the modes as they would increase the problem size again significantly, which would result in a high computation time. Consequently, the algorithms would not be usable within reasonable time-horizons. Both algorithms are evaluated in both modes of operation.

4.3.4.3 *Results*

The results of the performance of the three meta-heuristics for solving the Holon Problem are presented in Table 4.7. All configurations were executed 50 times within the exemplary grid facing the situation described in Section 4.3.4.1.

T_h[s]	Algorithm	T_e[s]	Costs	Unsupplied [%]	Partially supplied [%]	Fully supplied [%]	Oversupplied [%]	Producer [%]	Inactive [%]	Flexibilities [#]	Holons [#]
-	Init	-	57.8	0%	22.2%	66.3%	0%	11.5%	0.0%	0	1
30s	BACO	29.0	26.5	0.0%	10.7%	75.6%	0.0%	13.7%	0.0%	377	1.7
30s	GA	29.5	41.6	0.3%	15.9%	70.8%	0.0%	13.0%	0.0%	175	1.6
30s	BPSO	29.1	24.7	0.0%	11.0%	74.7%	0.0%	14.3%	0.0%	316	1.1
60s	BACO	59.1	19.8	0.0%	8.9%	76.3%	0.0%	14.8%	0.0%	373	1.2
60s	GA	59.1	33.8	0.0%	13.5%	72.8%	0.0%	13.7%	0.0%	202	1.2
60s	BPSO	60.0	12.4	0.0%	6.0%	78.3%	0.0%	15.7%	0.0%	394	1.0
10min	BACO	611.1	11.5	0.0%	4.7%	79.3%	0.0%	16.0%	0.0%	434	1.0
10min	GA	588.8	16.5	0.0%	7.8%	77.1%	0.0%	15.1%	0.0%	289	1.0
10min	BPSO	610.5	6.9	0.0%	4.5%	79.7%	0.0%	15.8%	0.0%	344	1.0
-	RS (Switch)	1.5	-	21.3%	33.4%	33.5%	0.3%	11.5%	0.0%	-	43.9
-	RS (SmartMeter)	9.9	-	38.2%	0.0%	50.5%	0.0%	11.3%	0.0%	-	1.0
-	BS (Switch)	92.9	-	11.4%	20.9%	54.4%	1.8%	11.5%	0.0%	-	32.0
-	BS (SmartMeter)	2201	-	21.1%	0.0%	67.4%	0.0%	11.5%	0.0%	-	1.0

Table 4.7: The average results of 50 repetitions for the BPSO, the BACO approach and the GA approach for the 30s and 60s and ten minutes time-horizon. Additionally, the results of the RandomShedding and BestShedding algorithms are presented considering switches and smart meters as components for making shedding-decisions.

Here, T_h is the time-horizon for the execution, which specifies the upper bound the algorithms need to achieve. *Algorithm* denotes the applied metaheuristic or load-shedding approach. Parameter T_e shows the average execution time that is achieved by each algorithm and the parameter *Costs* shows the average achieved cost value. The parameters *Unsupplied*, *Partially Supplied*, *Fully Supplied*, *Oversupplied*, *Producer*, and *Inactive* show the average percentage of prosumers that remained in one of the respective holon states. Finally, *Flexibilities* shows the average number of flexibilities that were used for within the found solutions, and *Holons* shows the average number of physical holons into which the holarchy was separated for mitigating the problem.

INITIAL PROBLEM SCENARIO The initial problem scenario is assigned a cost value of 57.8. For the predicted problem situation, no prosumer is in an unsupplied state (0%) since the whole grid is connected and the 18 producers in the grid provide electricity to all participants; however, 165 of the prosumers (22.2%) are predicted to be only partially supplied and can therefore not fully supply all appliance which they want to run. Furthermore, this situation is severe since this high number of partially supplied states does not only cause a strong decrease in user satisfaction but, if the situation is not mitigated properly, may cause further destabilization of the system, which can lead to a blackout. However, in theory, the majority of the prosumers—that is 492 (66.3%)—can be fully supplied with the predicted available electricity. Furthermore, no holons are oversupplied

(0%) and 85 prosumers (11.5%) provide excess electricity to the grid and act as producers. No prosumers are inactive, and initially, no flexibilities are actively used to support the grid. The overall holarchy is organized as a single physical holon forming one large distribution grid.

30-SECOND TIME-HORIZON With the chosen parameter configurations for 30s scenario (see Section 4.3.4.1) all three metaheuristics improve the problem situation within the required time-horizon and are required to conduct a similar number of calculations within their optimization process. The BPSO approach performs best, by achieving an average cost value of 24.7 compared to 26.5 for the BACO approach and 41.6 for the GA. The time required by the different approaches for finding solutions to the Holon Problem only varies slightly, where the BACO approach requires 29.0 seconds on average, followed by the BPSO approach taking 29.1 seconds and the GA approach, which is marginally slower by taking 29.5 seconds on average. The average performance of all three approaches is shown in Figure 4.4.

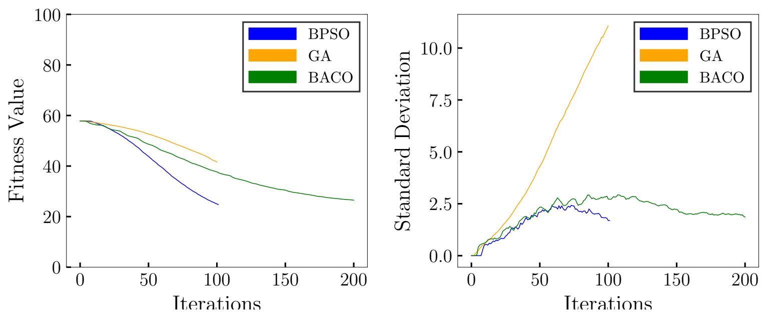

Figure 4.4: Average costs achieved by the metaheuristics in the 30s time-constraint scenario (left) and the corresponding standard deviation (right).

The left graph shows the average penalty achieved by the metaheuristics during the corresponding number of iterations. The parameter configurations for the BPSO approach and the GA only use 100 iterations but a higher number of particles and individuals. In comparison, the GA approach uses more iterations but very few ants to achieve a similar computational complexity. With these parameter configurations, the BACO approach and the BPSO strongly improve the problem situation (initial cost value of 57.8), whereas the GA performs noticeably worse. The graph displays the corresponding standard deviation of the achieved cost values during the 50 repetitions on the right side. For the BACO approach and the BPSO approach, the standard deviation slowly increases at first and then decreases again. This behavior is intended since, during the exploratory phase at the beginning of the search, solutions can improve quickly and can therefore vary strongly. Consequently, the standard deviation increases. Afterward, when the conducted search converges towards a near-optimal solution, the differences between the found solutions become smaller, and thus, the standard deviation decreases. However, for the GA approach, this is not the case, and the standard deviation continuously increases in the scope of the conducted iterations. The reason for this increase becomes apparent by analyzing the performance of the metaheuristics for each of the 50 repetitions. The results for the performance of the algorithms is shown in Figure 4.5, where each graph shows the improvement of the average cost value for one repetition.

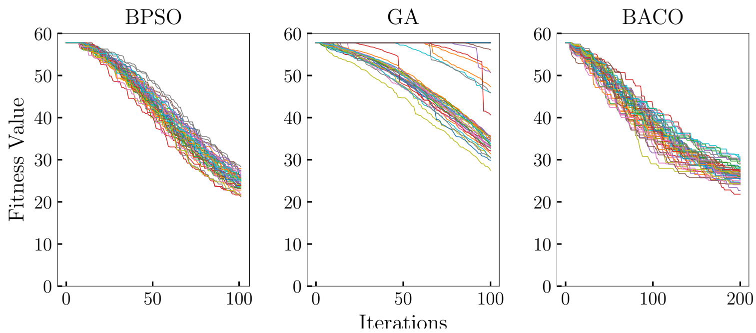

Figure 4.5: Cost values achieved by the metaheuristics during 50 repetitions for the 30s time-horizon.

For all repetitions, the BACO approach and the BPSO approach improve the found solutions and reduce the achieved cost values iteratively. Consequently, the average cost value and the standard deviation decrease as the quality of solutions increases. In comparison, the cost value of solutions found by the GA approach strongly vary for the individual repetitions. For the majority of the repetitions, the penalty decreases steadily, but for individual ones, the achieved cost optimization is low or not present at all. As a consequence, the average cost value is high compared to the BACO and BPSO approach. In particular, the standard deviation increases as the difference between successfully optimized cost values and the ones where optimization failed increases.

Inconsistent Results. The large differences between the costs for the solutions found by the GA indicate that the chosen parameter configuration is not well-suited for solving the Holon Problem in the 30s time-horizon. Consequently, the applicability of the GA in such a situation is limited since the probability for finding local optima of low quality is high.

The solutions found by the BACO and BPSO approach yield no unsupplied states for all prosumers in the grid. In contrast, GA performs slightly worse by causing 0.3% of the prosumers to become unsupplied on average. Despite this seemingly low number of unsupplied participants, this means that more than two prosumers in the grid experience a blackout. Consequently, they would be incapable of using any appliances, which may cause a strong decrease in user satisfaction or can could threaten the well-being of people.

Partial Blackouts. Despite slight improvements for some partially supplied prosumers, the results of the GA cause complete blackouts for several others.

Nonetheless, all three approaches manage to reduce the number of partially supplied prosumers from an initial 22.2% to 10.7% by the BACO approach, 11.0% by the BPSO approach, and 15.9% by the GA. All approaches increase the number of fully supplied prosumers from an initial 66.3% to 70.8 achieved by the GA, 74.7% for the BPSO approach, and the BACO approach performs best with 75.6%. Furthermore, all three approaches prevent oversupplied and inactive prosumers. For mitigating the problem situation, the GA uses 175 flexibilities, compared to the BPSO approach which uses 316, and the BACO approach which uses 377 flexibilities. The majority of flexibilities deactivate active appliances. An overview of the number of used flexibilities from different priority classes used for mitigating the problem situation is shown in Table 4.8. All three approaches predominantly use flexibilities of low or medium priority.

Algorithm	⌊Total⌉	Essential	High	Medium	Low
BACO	377 (100%)	8.42 (2.2%)	43.12 (11.4%)	124.64 (33.1%)	200.96 (53.3%)
GA	175 (100%)	4.88 (2.8%)	19.36 (11.1%)	56.46 (32.3%)	94.44 (53.8%)
BPSO	316 (100%)	6.16 (1.9%)	36.12 (11.4%)	106.72 (33.8%)	167.16 (52.9%)

Table 4.8: Priority classes of the used flexibilities for solving the Holon Problem within the 30s time-horizon. Here, the priority classes are denoted as *Essential*, *High*, *Medium*, and *Low*. Variable *Total* represents the rounded number of flexibilities used.

For some prosumers in the grid, the use of flexibilities causes a change in their status from a consuming state towards a producing state where their local production exceeds their local demand, and the excess electricity is transferred into the grid. On average, the three approaches increase the number of producers from an initial 11.5% to 13.0% for the GA, to 13.7% for the BACO, and the BPSO increases the number of producers to 14.3%.

State Changes. All approaches successfully prevented oversupplied and inactive states by limiting the number of allocated flexibilities to not exceed the demand and supply deviation and distribute the allocation among the prosumers.

For reconfiguring the holarchy, all approaches decided to mainly maintain one or two large holons. The BACO approach and the GA split the holarchy into 1.7 and 1.6 holons on average. In comparison, the BPSO approach split the grid into 1.1 holons on average.

60-SECOND TIME-HORIZON For the 60s time-horizon, the results are similar to the ones for the 30s time-horizon. The BPSO approach performs best again and achieves an average cost value of 12.4. In comparison, the BACO approach achieves an average penalty of 19.8, and the GA only manages to reduce the penalty to 33.8. The time required by the different approaches only varies slightly, where the BACO approach and the GA both require 59.1 seconds on average, followed by the BPSO approach taking 60 seconds on average. The average performance of all three approaches is shown in Figure 4.6.

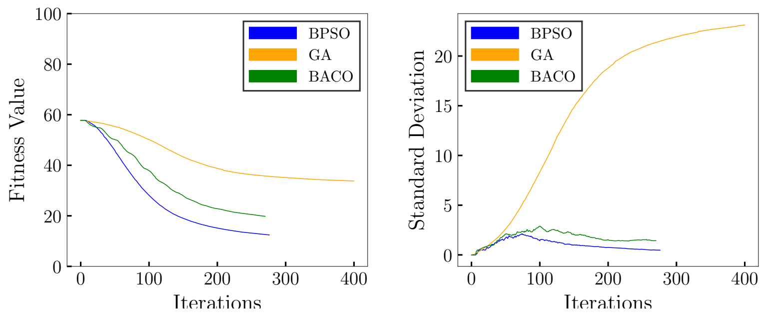

Figure 4.6: Average costs achieved by the metaheuristics in the 60s time-horizon scenario (left) and the corresponding standard deviation (right).

The parameter configurations for the BPSO and the BACO approach only use 275 and 270 iterations respectively but rely on a higher number of particles (15) and ants (15). In comparison, the GA approach uses 400 generations but a small population (10). With these parameter configurations (see Section 4.3.4.1), the BACO approach and the BPSO strongly improve the situation in the grid, whereas the GA performs again noticeably worse. The GA approach shows a steeply increasing standard deviation, similar to the behavior in the 30s scenario. The reason for this is the same as before, where some repetitions yield good cost optimizations, but individual ones do not improve the situation and therefore cause large differences for the achieved cost values. The results of the 50 repetitions for the three algorithms are shown in Figure 4.7.

While the BACO approach and the BPSO approach improve their solutions, the results of the GA approach are still inconsistent. As a consequence, the average achieved penalty score again is high compared to the BACO, and BPSO approach.

The solutions found by all three metaheuristics prevent unsupplied states for all prosumers in the grid. The achieved reduction

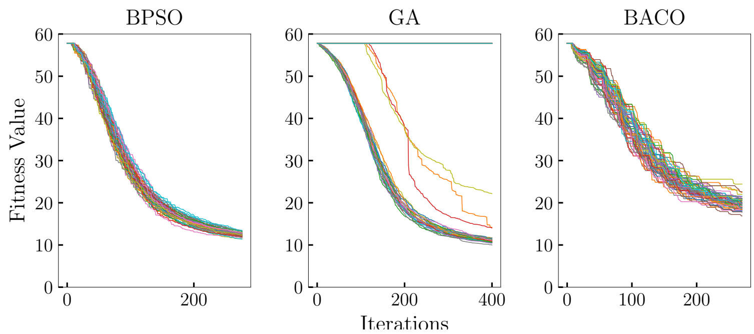

Figure 4.7: Cost scores achieved by the metaheuristics during 50 repetitions for the 60s time-horizon.

in the number of partially supplied prosumers differs noticeably between the three approaches. All three approaches improve their performance compared to the 30s time-horizon, where the BACO approach achieves 8.9% (improvement of 1.8%), the GA achieves 13.5% (improvement of 2.4%) and the BPSO approach performs best with 6.0% (improvement of 5.0%) of partially supplied prosumers. The number of fully supplied prosumers increases, where the GA manages 70.8%, the BACO achieves 76.3%, and the BPSO approach performs best with 78.3%. Furthermore, all three approaches prevent oversupplied and inactive prosumers.

Prevention of Severe States. All metaheuristics prevent severe states, such as unsupplied, inactive, and oversupplied for all participants in the 60s scenario.

For mitigating the problem situation, the GA again uses a low number of flexibilities compared to the BPSO approach, and the BACO approach. The GA uses 202 flexibilities, the BACO approach uses 373, and the BPSO uses 394 for mitigating the problem situation. An overview of the number of used flexibilities is shown in Table 4.9. All three approaches mainly use low or medium priority flexibilities to reduce the penalty for decreasing user satisfaction.

Algorithm	⌊Total⌉	Essential	High	Medium	Low
BACO	373 (100%)	6.12 (1.6%)	39.52 (10.6%)	120.52 (32.4%)	206.6 (55.4%)
GA	202 (100%)	1.44 (0.7%)	13.36 (6.6%)	66.32 (32.7%)	121.3 (60.0%)
BPSO	394 (100%)	1.06 (0.2%)	31.72 (8.0%)	128.66 (32.7%)	232.88 (59.1%)

Table 4.9: The flexibilities used for solving the Holon Problem within the 60s time-horizon.

The number of prosumers in the exemplary grid that change their status from a consuming state to a producing state increase slightly.

On average, the three approaches increase the producers from an initial 11.5% to 13.7% for the GA, to 14.8% for the BACO, and the BPSO increases the number of producers to 15.7%.

For reconfiguring the holarchy, all approaches decided to mainly maintain one or two large holons. This results in an average split of the holarchy into 1.2 holons by the BACO approach and the GA, whereas the BPSO approach maintains a single holon on average.

10 MINUTE TIME-HORIZON The evaluation for the 10-minute time-horizon investigates the suitability of the metaheuristics for situations of relaxed time-constraints (i.e., situations where more time is available to provide a solution to a problem).

For the 10min time-horizon, the well-performing parameter configurations are different from the ones used within the 30s and 60s time-horizon scenarios. While the BACO and BPSO approach increase both the number of particles/ants and the number of iterations, the GA strongly increases the size of its population but decreases the number of generations (see Table 4.5).

The BPSO approach performs best and further reduces the cost value of 6.9 (12.4 in the 60s scenario). The BACO approach performs slightly worse, achieving a cost value of 11.5 (previously 19.8), and the GA manages to reduce the cost value to 16.5 (previously 33.8). The time required by the different approaches for finding solutions to the Holon Problem is 611.1s for the BACO approach, 610.5s for the BPSO approach, and the GA requires 588.8s. The average performance of all three approaches is shown in Figure 4.8.

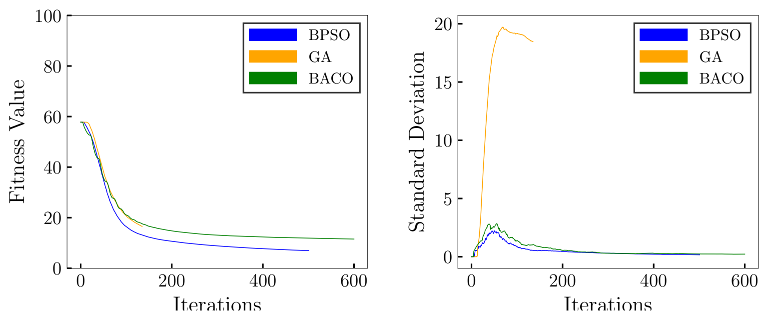

Figure 4.8: Average costs achieved by the metaheuristics in the 10 time-horizon scenario (left) and the corresponding standard deviation (right)

The BACO and the BPSO approach strongly improve the problem situation (initial cost value of 57.8), and the GA manages to improve its performance noticeably compared to the performance for the 30s and 60s time-horizon scenarios. In particular, for the BACO and the BPSO approach, the standard deviation is quickly converging towards zero. In contrast, the GA approach shows a steep increase in the standard deviation but manages to decrease it during the execution of the algorithm. This can be expected, since the large size of the initial population represents a variety of different solutions, which will likely yield in large differences w.r.t the cost values. Nonetheless, the standard deviation is still high and the convergence is slow compared to the other metaheuristics. The results of the 50 repetitions for the three algorithms is shown in Figure 4.9.

Large Initial Population for the GA. The strong increase in the initial population size drastically improves the algorithms cost optimization and shows a decreasing standard deviation.

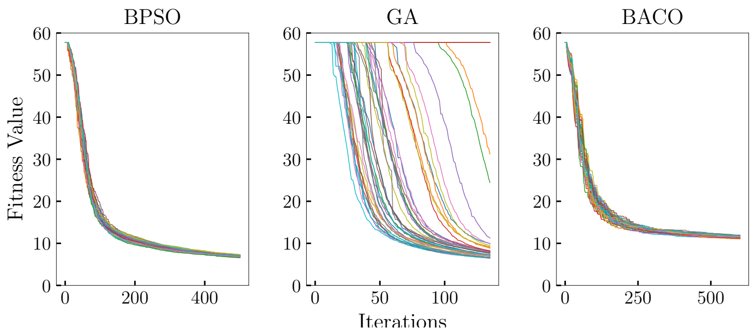

Figure 4.9: Cost scores achieved by the metaheuristics during 50 repetitions for the 10min time-horizon.

The solutions found by all three metaheuristics prevent unsupplied, oversupplied, and inactive states for all prosumers in the grid. All approaches strongly reduce the amount of partially supplied prosumers to 7.8% for the GA, to 4.7% for the BACO, and 4.5% for the BPSO. The number of fully supplied prosumers again increases, where the GA manages 77.1%, the BACO achieves 79.3% and the BPSO approach performs best with 79.7%. The number of flexibilities used for mitigating the problem situation still differs strongly between the three approaches. The GA uses 289 flexibilities, the BPSO approach uses 344 and the BACO approach uses 434 flexibilities (see Table 4.10). All three approaches mainly use low or medium priority flexibilities to reduce the penalty for decreasing user satisfaction.

Algorithm	⌊Total⌉	Essential	High	Medium	Low
BACO	434 (100%)	0.12 (0.0%)	24.02 (5.5%)	140.2 (32.3%)	270.14 (62.2%)
GA	289 (100%)	0.3 (0.1%)	13.94 (4.9%)	88.26 (30.6%)	186.18 (64.4%)
BPSO	344 (100%)	0.0 (0.0%)	13.2 (3.8%)	105.94 (30.8%)	224.82 (65.4%)

Table 4.10: The used flexibilities for solving the Holon Problem within the 10 min time-horizon.

The number of prosumers in the grid, that change their status from a consuming state to a producing state increase slightly. On average, the three approaches increase the number of producers from an initial 11.5% to 15.1% for the GA, to 15.8% for the BPSO, and the BACO increases the number of producers to 16.0%. For reconfiguring the holarchy, all approaches decided to maintain one large holon.

PERFORMANCE OF THE LOAD-SHEDDING ALGORITHMS Both algorithms are capable of improving the initial problem situation by maintaining the balance between demand and supply for individual parts of the grid. Since the algorithms do not rely on the flexibilitiy concept but conduct load-shedding, the areas of the grid that are shed experience—as expected—either a blackout or a situation of severe undersupply. The achieved cost-values for load-shedding algorithms are omitted, since they used an adjusted cost-function, which prevents a direct comparison between the scores of the metaheuristics and the ones achieved by the load-shedding approaches. This adjustment is necessary, since the flexibility concept, which is considered in the cost-function used by the metaheuristics, is not used by the load-shedding approaches. However, the remaining parameters of the solution can be compared.

For the Switch mode, the RS algorithms is capable of finding solutions in 1.5 seconds and the RS algorithm requires 92.9 seconds. Both algorithms increase the amount of unsupplied states to 21.3% for the RS algorithm and 11.4% for the BS approach. Furthermore, the RS appraoch also increases the number of partially supplied states to 33.4%, whereas the BS approach reduces them to 20.9%. The number of fully supplied states achieved by the RS approach is 33.5% and the BS achieves 54.4%. Both algorithms produce a low number of oversupplied states, where RS achieves 0.3% and BS achieves 1.8%. Finally, the number of producers remains the same and no inactive states are caused. Both algorithms separate the grid in a large number of holons, where the RS approach generates 43.9 holons on average and RS generates 32.0 holons. Note that within the holonic energy grid the shedded parts are considered as holons, therefore, this high number is expected.

For the SmartMeter mode, both algorithms are notably slower, with the RS algorithms taking 9.9 seconds on average and the BS algorithm requiring 2201 seconds. This increase is expected since 760 layer-0 holons need to be considered within this mode compared to 123 switches in the Switch mode. Both algorithms increase the number of unsupplied states, where RS achieves 38.2% and BS achieves 21.1%. Both approaches fully prevent partially supplied, oversupplied, and inactive states. Furthermore, the RS approach achieves 50.5% fully supplied states and the BS approach achieves 67.4%. Both approaches maintain one large holon as they only deactivate individual participants.

> *Load-Shedding.* The RS approach finds solutions extremely quick, but the solutions result in 38.2%–54.7% of undesired states. In comparison, the RS approach is much slower but the solutions result in (only) 21.1%–32.3% of undesired states

.

One interesting finding is the difference in the emerging holarchy between the RS and BS approach. While the RS approach mainly maintaings one larger holon that has minimal demand and supply deviations, the BS approach results in numerous smaller but also balanced holons. For instance, for the best solution found by both algorithms, each one generates a holarchy with 32 holons. Out of these, the RS approach maintains a balance between demand and supply for two holons, where one comprises 322 layer-0 holons and one 29 layer-0 holons. In comparison, the solution of the BS approach yields 13 holons with balanced demand and supply and the size of these holons ranges from 29 to 58 layer-0 holons.

4.3.4.4 *Result Discussion*

Two out of three of the evaluated metaheuristics improve the overall energy grid situation consistently and efficiently optimize the cost of found solutions to the Holon Problem. An overview of the corresponding average cost values and corresponding number of used flexibilities is presented in Figure 4.10. As introduced at the beginning of this chapter, solutions to the Holon Problem should be found quickly (i.e., within restricted time-horizons) and these solutions should maximize several quality measures (see Section 4.1.1). In the following, the presented results are discussed.

COST OPTIMIZATION IN THE 30S AND 60S SCENARIO Our results show that all presented metaheuristics are capable of solving the Holon Problem within both strict time constraints (30s and 60s) and more relaxed time constraints (10 minutes), and improve the overall problem situation. Especially for the 30s and 60s time-horizon scenarios, the BACO approach and the BPSO approach strongly improve the energy balance of the grid and the supply states of the individual prosumers. Moreover, while being capable of adhering to these strict time constraints, the achieved cost value is consistent, which shows that the high quality of found solutions does not depend on a “lucky” initialization of the algorithms but is the results of a continuous optimization process.

> *Quick Optimization.* The results indicate that the BACO and BPSO are both well-suited to solve the Holon Problem under strict time constraints, greatly improving the initial problem situation.

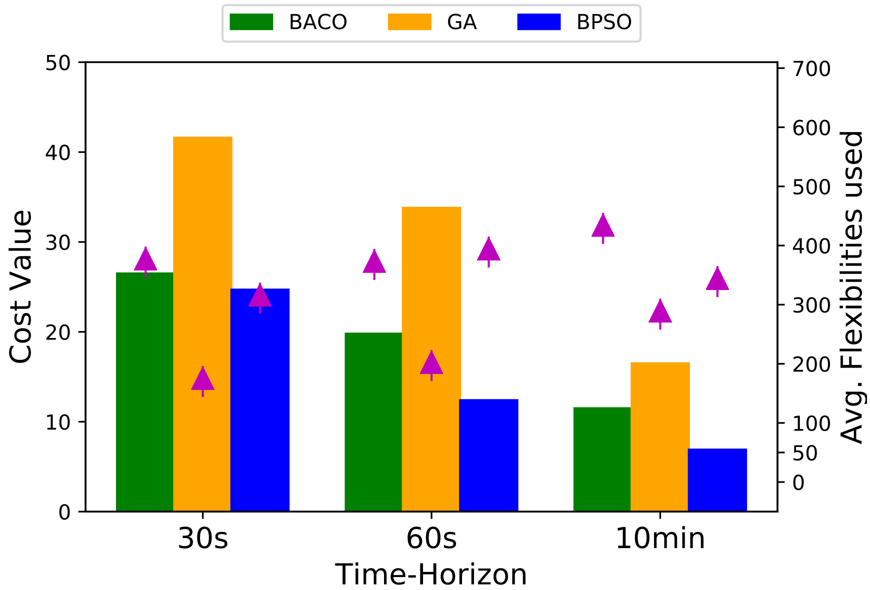

Figure 4.10: Evaluation for the different meta-heuristics and their parameter setups. The bars represent the average achieved penalty scores for the three time-horizon scenarios. BACO is indicated as green, GA as orange and BPSO as blue. The triangular markers (magenta) denote the average number of used flexibilities.

In comparison, the GA approach performs noticeably worse on average in both the 30s and 60s time-horizon scenarios. Despite the algorithm being able to find individual solutions of similar quality as the other metaheuristics, it does not find these solutions consistently. This is shown by the achieved high average cost value and the correspondingly high standard deviation. Consequently, with the selected parameter configurations for the GA, the approach is not well-suited for solving the Holon Problem within strict time constraints.

Unsuitability of the GA. For the scenarios with a restricted time-horizon, the GA is not able to consistently find near-optimal solutions and is therefore considered unsuitable for solving the Holon Problem in these scenarios.

However, this comparably low performance can likely be attributed to the selected parameter configurations. Firstly, the presented GA approach relies on more parameters that the BACO and BPSO approaches. Some of these parameter selections are not investigated in detail in this thesis but are selected due to recommendations of related work. For instance, changing the crossover technique from uniform to point-crossover or adjusting the mutation rate to increase the exploratory capabilities of the algorithm may improve its performance for the Holon Problem. Secondly, the results show that the GA finds better solutions to the Holon Problem if the initial populations size is increased.

The initially chosen low population size in combination with the general mode of operation for the GA may be a bad combination for the Holon Problem. In particular, a low population size strongly limits the variety of available genes that can be recombined for optimizing solutions. For the 30s scenario the GA started with 20 individuals and for the 60s scenario with only 10. Consequently, this represents a strong limitation for the gene-pool and reduces the possibility to generate near-optimal solutions in a solution space of the size of 2^{1693}. Further evaluations are required to investigate if these effect can be compensated with a severely higher mutation rate to increase exploration and a fine-grained analyses of parameter configurations that balance the population size and number of generations.

COST OPTIMIZATION IN THE 10MIN SCENARIO For the 10 minutes time horizon, all the performance of all investigated approaches is more aligned, and the GA manages to strongly improve its performance. Nonetheless, the problem of inconsistent result quality of the solutions found by the GA remains. However, solutions to the Holon Problem aim to prevent further destabilization and improve the overall situations for the participants in the grid. The inconsistent results of the GA with the investigated parameter selection renders this approach unusable for solving the Holon Problem with strict time constraints, and we also do not recommend it for being used within more relaxed time constraints. Several related works show, that GAs are generally well-suited for finding solutions to binary problems; therefore, it can be assumed that the bad performance is a result of poor choices for selected parameters or strategies for the algorithm in the context of the Holon Problem. Suggestions for resolving this issue for future evaluations are the following: conduct a higher number of repetitions during the binary parameter search to improve the selection process for parameter configurations of the algorithm. This may yield a more consistent and better performance of the GA as the parameters are chosen more carefully with respect to the properties of the Holon Problem. Furthermore, the suitability of different strategies needs to be investigated regarding their applicability for the properties of the Holon Problem (e.g., the order of the binary values representing switches and flexibilities).

OPTIMIZATION OF THE PROSUMER SITUATION The situation of prosumers is predominantly affected by the allocation of flexibilities for counteracting demand and supply deviations in the holarchy. The situation of prosumers is then indicated by the achieved supply states. As previously described, all three approaches are capable of improving the overall supply states for the prosumers in the grid by lowering the number of partially supplied ones and increasing the number of fully supplied ones and producer states. However, the number of flexibilities used for achieving this varies depending on the used metaheuristic. The GA uses a noticeably lower number of flexibilities for mitigating the problem but also provides a comparably high cost solutions. Especially for the 30s and 60s time-horizon scenario, the GA uses up to 50% fewer flexibilities compared to the BACO and BPSO approach. While this reduced use of flexibilities has several benefits, like a reduction in costs for using the flexibilities and a reduction of experienced conflicts for prosumers due to the use of flexibilities, the number of flexibilties used by the GA leads to solutions that cannot adequately mitigate the problem situation. Since the main goal is the mitigation of the problem using flexibilities, this trade-off between costs and quality is not acceptable.

Figure 4.10 shows that the GA and BACO approach can improve their result quality within the different time-horizon scenarios by using more flexibilities, efficiently trading-off improved problem mitigation for a higher probability of decreasing user satisfaction. The results presented in Table 4.8, Table 4.9, and Table 4.10 show that despite the varying number of used flexibilities, the share among used flexibilities of different priority classes is quite similar for all three metaheuristics. The majority of used flexibilities are of low and medium priority (over 85%) and only a few flexibilities of the high and essential priority classes are used. Consequently, the probability of decreasing user satisfaction is successfully lowered by all three metaheuristics. Nonetheless, using more flexibilities increases the probability of reducing the prosumer satisfaction since more prosumers and their devices become involved. However, the majority of used flexibilities are of lower priority, and their use yields a noticeable increase in the quality of the found solutions. Therefore, the decision to use an increasing number of flexibilities from lower priority classes is considered beneficial for the mitigation of the problem situation.

Flexibility Use. The BACO and BPSO approaches are the only ones to provide solutions that do not use *essential* flexibilities for solving the Holon Problem in the 10min scenario. A low number of essential flexibilities is used within the 30s and 60s scenarios.

While the GA and BACO approach tend to use more flexibilities within the 60s and 10-minute scenarios, for the BPSO this number only increases from the 30s to the 60s scenario but decreases between the 60s and the 10-minute scenario. Despite this decrease, the average achieved result quality of the BPSO further increases. This indicates that the BPSO in contrast to the GA and BACO approaches is capable of efficiently optimizing also the aspects that are considered of lower importance within the proposed penalty functions (e.g., ecological aspects and holon quality). Most likely, the BPSO manages to select the best-performing flexibilities, which may result in a lower number of overall flexibilities required for the mitigation of the problem, which in turn improves prosumer satisfaction.

> *Impact of Solutions on the Prosumers* The BPSO approach manages to reduce the number of used flexibilities while minimizing the cost values of the solutions for the 10min scenario. In contrast, the GA and BACO improved their solution quality by increasing the number of used flexibilities.

Overall, the BACO and BPSO approaches are capable of providing near-optimal solutions to the Holon Problem while considering numerous resilience and efficiency criteria. Furthermore, the solutions found by both algorithms efficiently use flexibilities to mitigate the problem situation and strongly reduce the negative impacts on prosumers.

COMPARISON OF METAHEURISTICS AND LOAD-SHEDDING While the two types of algorithms are not directly comparable using the cost scores, the results presented in Table 4.7 highlight several benefits of the metaheuristics in combination with the flexibility concept proposed in this work. Due to the metaheuristics' capability to consider the reconfiguration of the holarchy structure and the allocation of flexibilities simultaneously, they are capable to prevent a degradation of the states of the participants and can even improve the situations drastically. Moreover, the metaheuristic approaches already achieve strong improvements within the 60s time-horizon. In comparison, many holons experience state degradation or even blackouts if load shedding is applied, which may threaten the safety of people in the affected areas, or at least result in a strong decrease of the satisfaction of people. While, the load-shedding algorithms could take flexibilities into account to make improved decisions, the problem size would increase significantly. Consequently, the computation time for the presented load-shedding approaches would increase drastically (already indicated by the 2201 seconds required for the BS approach in the SmartMeter mode), which would limit their applicability.

> *Metaheuristics for Problem Mitigation* While the load-shedding approaches are quick and efficient for stabilizing individual parts of the grid, metaheuristics—in combination with flexibilities—can improve the situation for all participants, at the costs of some limitations for the use of individual appliances within prosumer homes.

One additional benefit of the metaheuristic optimization in combination with flexibilities is the degree of fairness achieved. The results show that inactive states are prevented by the metaheuristics and the majority of flexibilities used for mitigating the problem situations are of lower or medium priority. Therefore, it can be assumed that the negative impact on participants during the mitigation of the hazardous situation is comparably low. In contrast, especially for the BS approach, participants with a high electricity demand have a higher probability to be disconnected from the grid and experience a blackout since their separation yields a strong decrease in the cost function.

4.3.4.5 *Deployment Hurdles and Limitations*

The application of metaheuristics within holonic energy grids for solving problems like the presented Holon Problem, requires overcoming numerous challenges. Furthermore, several limitiatons apply for the evaluation conducted in this thesis. In the following, important challenges for applying metaheuristics within holonic energy grids are highlighted and limitations are presented.

CHALLENGES FOR APPLYING METAHEURISTICS IN ENERGY GRIDS Solving the Holon Problem presented in this chapter heavily relies on the availability of a sufficient number of flexibilities that can contribute to the mitigation of the problem. However, the availability of flexibilities relies on various aspects, like technological advancements to enable a smooth integration of resources but also on the acceptance of the concept by prosumers and their motivation to participate (see Chapter 5). However, our results show that near-optimal solutions can already be found by using a fraction (about 22% for the BPSO approach) of the flexibilities within the exemplary grid, which indicates that fewer flexibilities may already be sufficient to improve the resilience of holonic energy grids.

Another challenge is based on the number of switches (i.e., components that allow separating parts of the grid), which is assumed to be fairly high within this work to enable numerous options for recombining parts of the grid. For existing energy grids—especially in interim stages of the energy transition—, fewer separation switches may be available and, therefore, the possibilities for recombining parts of the grid may be strongly limited. While the problem of placing switches in conventional energy grids is addressed in related works [32, 81], further investigation is required to analyze the placement of switches in the context of holonic energy grids and assess the applicability of the holonic concept with a lower number of switches.

LIMITIATIONS OF THE EVALUATION The behavior of prosumers and potential conflicts between using appliances and offering them as flexibilities is only considered implicitly in the conducted simulation. Future simulations need to take into account typical interaction models for users and their local appliances. It is important to consider variations in user behavior since corresponding interactions with devices can alter the priorities of these devices significantly and therefore may affect the availability of flexibilities. Furthermore, such changes in priority may strongly affect the severity of the impact of conflicts caused by the flexibility concept. Therefore, quantitative measures are required to adequately specify the amount of user dissatisfaction that is generated by conflicts resulting from the application of solutions to the Holon Problem, taking into account various prosumer behavior.

The *costs* for using flexibilities need to be considered in detail. In this thesis, flexibilities are introduced such that prosumers can specify the amount of (monetary) reimbursement that is required for using a flexibility (see Section 3.3.3). The proposed cost function needs to be extended to take these costs into account to ultimately allow comparing the accumulated costs for using flexibilities with other supportive actions, like maintaining small-scale backup producers. Furthermore, other types of reimbursements need to be considered and investigated as alternatives to traditional monetary reimbursements (see Section 5.2.3).

The properties of the energy distribution grid used within this work are simplified for the conducted simulation. For instance, the Holon Problem is specified as a binary optimization problem, which introduces some limitations (see Section 4.3.1.2). More precisely, decisions for separating or combining specific parts of the grid, which are part of solutions to the Holon Problem, strongly rely on the physical properties of these parts. In particular, separating parts of the grid requires the sub-parts to be capable of maintaining their electrical frequency to prevent the safe operation of sub-part. Such frequency stabilization may require specialized hardware components that may not be available in all sub-parts. Furthermore, the connection of two independent sub-parts needs to adhere to numerous requirements before they can actually be connected on a physical level. Consequently, these requirements need to be verified before solutions to the Holon Problem are applied within an energy grid. This verification process may render specific solutions to the Holon Problem unusable and may result in additional re-runs for the search process.

4.4 CONCLUSION

In this chapter, the joint challenge of reorganizing holonic energy grids and allocating flexibilities for mitigating demand and supply deviations was addressed (i.e., the Holon Problem).

For solving the Holon Problem, it was modeled as a multivariate optimization problem. Afterward, we designed a cost-function that allows assessing the quality of soltuions to the optimization problem considering numerous optimization criteria. In order to find these solutions, metaheuristic optimization approaches were investigated as they are well-known for operating in large problem-spaces and for dealing with uncertainties and incomplete information about the problem to be solved. Towards this end, a binary mapping between the domain of the Holon Problem and the problem space of the metaheuristics was developed. The different metaheuristics were then evaluated and compared within a simulated holonic energy grid facing a hazardous situation using the HOLEG simulation environment (see Section 3.4.2).

The results show that metaheuristic approaches are well-suited to find solutions to the Holon Problem and support the mitigation of hazardous situations within holonic energy grids. The proposed problem formulation and the corresponding cost function allowed for successful optimization of the solutions according to the presented optimization criteria. In particular, the cost function enabled the algorithms to find solutions that balance the mitigation of the problem situations the ecologic use of resources, and the negative impacts on prosumers. Taking into account the impact on prosumers is crucial to motivate people to accept and participate in novel concepts (e.g., flexibilities) that increase their involvement in mitigation processes (see Chapter 5).

Furthermore, near-optimal solutions can be found quickly within strict time-horizons and solution quality can be further improved within more relaxed time-horizons. This versatility of the investigated metaheuristics shows their applicability in situations where time is limited and solutions must be sufficiently good to provide authorities with more time to resolve the problem (e.g., for quickly mitigating problems due to failing components).

However, various challenges remain for the application of metaheuristics in holonic energy grids. For instance, the proposed optimization mechanisms are based on a central authority that has comprehensive information on the available flexibilities and underlying grid topology. This limits the interoperability between different holarchies that are not affiliated to the same higher-layer holon. Therefore, future work needs to investigate the distributed optimization of the Holon Problem and a corresponding combination of found solutions. Furthermore, the strong integration of information and communication technology (ICT) and the availability of sufficient separation points (switches) within the energy grid are important aspects. Especially the availability of separation points at different locations in the energy grid requires further investigation, which is out of the scope of this thesis.

5 IMPROVED ENERGY GRID RESILIENCE THROUGH PROSUMER AWARENESS AND ACTION

The two previous chapters first introduced a semi-formal model for structuring energy grids as holarchies and supporting their resilient operation by leveraging the inherent properties of holons and local resources provided by prosumers (see Chapter 3). Afterward, the joint challenge of organizing the holons within a holarchy and allocating their local resources to efficiently mitigate hazardous situations, like strong demand and supply deviations, is addressed in Chapter 4.

While the previous chapters dealt with predominantly technical challenges and corresponding solutions in holonic energy grids, social challenges were only mentioned in passing and were insufficiently substantiated. However, people have a strong influence on both the implementation of the technical solutions presented and their effectiveness. In particular, the *willingness* of people to become actively involved in operational processes of energy grids is a fundamental prerequisite for resilient holonic energy grids, as they were presented in this thesis.

In this chapter, we make the assumption that increasing people's knowledge about important energy grid topics will increase their willingness to actively participate and enable them to contribute to the resilience of the grid. In particular, such knowledge can aid people in becoming more aware and finding answers to questions, like "why is my participation important?", "how can I contribute?", and "what actions can I take?". Throughout this chapter, we provide answers to these questions and discuss how increased knowledge about energy grid topics aids people in the process. Towards this end, we first explain how the high *availability* of conventional energy grids and the predominantly *passive* role of consumers are—at least—partially responsible for the lack of energy grid knowledge of people. Afterward, we discuss the potential benefits of increased knowledge on the awareness of people and their actions during the four phases of system resilience (see Section 2.3.1). We then highlight the importance of *motivation* for increasing peoples' willingness for participation and present *monetary* and *non-monetary* strategies for motivating people. Finally, we introduce and evaluate a serious-game prototype for conveying knowledge about energy grid topics.

The chapter is organized as follows: Section 5.1 motivates the importance of people for facilitating a successful transition towards a holonic energy grid. First, the challenge of involving people in energy grids is introduced. Afterward, the contributions of this chapter are presented. Section 5.2 discusses peoples' lack of knowledge on the resilient operation of energy grids and presents benefits emerging from increasing such knowledge. Subsequently, the importance of motivating people is highlighted and monetary and non-monetary strategies for motivating people are presented. Section 5.3 introduces a prototypical serious game approach as a technique to convey knowledge about energy grid topics to people. The serious game is evaluated in Section 5.4. Finally, the chapter concludes in Section 5.5.

5.1 THE HUMAN AS AN ESSENTIAL FACTOR FOR A SUCCESSFUL SMART GRID TRANSITION

The ubiquitous availability of electricity is one of the key enablers for the advancements of our modern society, yet the way in which it is delivered to consumers is, for the majority of people, a black-box affair. The flick of a switch suffices to illuminate rooms and, if it does not, usually a sequence of troubleshooting actions are conducted to investigate if it is a local technical issue (e.g., defect light bulbs), or if the problem is of a larger scale. However, for both cases, consumers in the energy grid are, willingly or unwillingly, largely unaware of the feats which are accomplished to maintain a continuous supply of electricity. They are participating and affecting the energy grid but are mainly *passive* participants.

Recent advances, driven by various factors, have begun to lead us towards increasingly distributed energy grids. A growing number of electric vehicless (EVs) not only roam the roads but are capable to provide electricity to the grid and the number of RESs is increasing. While these technologies have apparent benefits to the layperson (e.g., charging a car with locally produced electricity), they bring their own share of challenges: electricity production becomes increasingly volatile since RESs predominantly depend on the weather, which can be hard to predict. Furthermore, local producers within the energy grid may cause bidirectional electricity flows (i.e., excess electricity of lower layers that cannot be consumed or stored flows towards higher layers in the grid). As a consequence, the heretofore hidden processes for delivering electricity and balancing the demand and supply within the energy grid become increasingly challenging on a technical side and even less straightforward.

However, the concepts and methods proposed in this thesis strongly depend on the *active* participation of consumers and prosumers. What this means, and what it needs, is a more aware, active set of prosumers and consumers. Additionally, increased acceptance is required on the parts that

- we are in a transition period in which the conventional overwhelmingly stable grid is being slowly replaced by an increasingly distributed smart grid. Moreover, this grid may require local management and, in the interim, perhaps provides less overall stability;

- the stability of the grid is a function of how previously passive consumers and prosumers behave in smart grids;
- notions of resilience, instead of stability, need to be considered to help mitigate and manage hazardous situations.

Much of this is understood at a technical level, but energy grids are no longer solely technical systems. There is a need to appreciate the 'socio-'parts of the socio-technical energy grid. This means that there is a host of non-technical challenges that have to be understood and addressed for future energy grids to be resilient and beneficial to the people that participate in such a system. This includes aspects of education, awareness, activism, and incentivization for all concerned.

PROBLEM STATEMENT Enabling consumers and prosumers to be more aware and to take on a more active role within the resilient operation of holonic energy grids is a challenging task. The majority of people have a relatively limited understanding of the need for resilience within the energy domain [174, 213], as the stable operation of conventional grids mainly concerns a minimal number of experts that are responsible for maintaining and managing the grid. However, with the ongoing transition of the grid and the accompanying changes for all entities involved, a lack of awareness and a high degree of passivity can have detrimental effects on energy grids. Two prominent impact domains are the following:

- *Acceptance*: As we have highlighted multiple times in this work, providing technical solutions alone is not sufficient to guarantee a successful transition towards smart energy grids. *Acceptance of novel technologies* by the participants within energy grids is required [130]. Key enablers that need to provide this support are consumers and prosumers within the energy grid. If this support is lacking, it is doubtful that novel developments, like the application of holonic structures to energy grids, and the strong involvement of prosumers, will be realized. This lack of advancements ultimately can impede the transition of the energy grid towards an increasingly ecological smart grid. Furthermore, participants need to accept that their active participation within *novel concepts and methods* is important to enable a resilient operation of the grid. Especially, if the effectiveness of concepts and methods—like the ones presented in this work—predominantly depend on the voluntary participation of people.
- *Responsibility*: With the acceptance of technological advancements and the fact that prosumers will be increasingly involved in operational processes of the grid, the impact of prosumers on the stable

operation of the grid grows. Consequently, the responsibility of all participants for maintaining the resilient operation of the energy grid increases as well. This means, that the behavior of people—e.g., electricity consumption, provision of flexibilities, etc.—must live up to this responsibility. We believe that people who accept this increased responsibility are more willing to make altruistic decisions that can further improve the resilience of the grid during all phases of resilience (see Section 2.3.1.1) [194]. For instance, people may decide to use alternative non-electric ways of heating or cooking and offer these appliances as additional flexibilities or lower their priority level.

CHALLENGES In this work, it is assumed that a prerequisite for increasing the *awareness* of people and supporting them in taking on an active and *responsible* role in holonic energy grids, is *knowledge* about the energy domain, its challenges, and operational processes for resilient operation. This knowledge can support them in answering the aforementioned questions on why their participation is important, how they can contribute, and what actions they can take. While the impact of knowledge by itself on encouraging people towards changing their behavior is a much-discussed topic [216], it has been shown that knowledge can increase peoples' awareness for energy-related problems [226]. From this we derive the following challenges.

- How to effectively increase peoples knowledge about energy grid topics so that they become more aware and better able to take on their future active role?
- How can people be motivated to increase their knowledge about energy grid topics and their willingness to contribute to energy grid resilience?

CHAPTER CONTRIBUTIONS This chapter addresses the challenge of conveying energy grid knowledge about challenges, ongoing changes, and operational processes to people. The main goal in this chapter is to increase peoples' understanding of the energy domain, to foster awareness and motivate them to take on an active and responsible role within future energy grids.

Towards this end, we highlight the importance of knowledge about the energy domain and discuss why people currently lack profound domain knowledge. We present the potential impact of increasingly aware and responsible people on the four phases of resilience considered in this thesis (see Section 2.3.1.1), namely *anticipation*, *adaption*, *mitigation*, and *recovery*. Since knowledge by itself is likely insufficient for motivating people to become increasingly active, we elaborate on *monetary* and *non-monetary* methods for motivating people. Finally, a prototypical serious-game approach is presented and evaluated as a means of conveying energy-related knowledge to people.

5.2 WHY PEOPLE SHOULD CARE FOR A RESILIENT ENERGY GRID

The energy grid is an infrastructure that provides an essential service (i.e., the continuous supply of electricity), thus, enabling life as we know it as a modern society. Maintaining this continuous supply with electricity should therefore be of major concern for all participants involved. In 2019, households in the European Union were responsible for 26.3% of the overall final energy consumption [72]. This represents an amount of energy, which—at the core—is affected by the local decision-making of people living in these households. As a consequence, households represent a group of stakeholders that can have a strong impact on the grid's capability for providing electricity and operating resiliently. Especially if the transition of the energy grid and emerging technological advancements (e.g., holonic grid structure, prosumer-owned RESs, an increasing number of EVs) are taken into account, the severity of the potential impact individuals can have on the operation of the grid increases strongly [115].

Therefore, this section discusses why people should be concerned and motivated about taking on a more active role in supporting the resilient operation of energy grids. First, this section provides reasons why the majority of people lacks comprehensive understanding of the energy grid resilience and operational processes. Afterward, the potential benefits of increasing the peoples' knowledge about energy grid topics and the potential impact within the four phases of resilience is discussed. Finally, means for motivating people are provided and explained.

5.2.1 *Lack of Understanding of Energy Grid Resilience*

The need for resilience in the domain of conventional energy grids is a topic that mainly concerns a very limited number of experts, who are responsible for operating and managing the grid. These experts need profound knowledge about the operational processes of the grid. In contrast, the majority of laypersons have a rather limited understanding of the need for resilience within the energy domain [174, 213]. There may be various reasons for this lack of understanding, but three main aspects are emphasized in this section, which are at least partially responsible. In the following, the high degree of *availability* provided by energy grids the *passivity* of consumers, and the *lack of incentivization* are presented as important reasons for peoples' limited understanding of the energy domain:

- *Availability*. From the perspective of consumers, electricity seems to be ubiquitous and continuously available. The majority of people do have continuous access to electricity without any noticeable limitations on how electricity is consumed or on the amount of electricity that is consumed (e.g., people can freely connect or disconnect appliances to their local electrical sockets) [90, 204]. The Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (BNetzA) in Germany states that the average time consumers experienced power outages in 2018 was only 13.91 minutes [25].

In conventional energy grids, this high degree of availability is achieved by a combination of measures: nuclear- and fossil-fueled producers provide large amounts of electricity. The steady production provided by these producers in combination with high-quality forecast mechanisms and decades of experience in adjusting the production according to the behavior of consumers, allows control entities to closely match the production to the demand in the grid. Additional measures, like maintaining reserve capacity, component redundancy, and load-shedding mechanisms (see Section 2.3.1.2), further improve the stability of the grid and increase its overall availability. All these mechanisms aim at maintaining a continuous supply of electricity in the energy grid, where—if at all—only small parts experience actual service deterioration. If severe disturbances occur, those were likely caused by external influences (e.g., extreme weather conditions damaging connection lines and separating parts from the main grid, forecast errors) [26].

However, this high degree of availability can lead to a deceptive feeling of a safe and secure energy grid, where electricity is continuously available regardless of the actions of the individual and if incidents occur, they are not remembered by the majority of people for long [28]. Based on this perception, people do not experience any need to improve their understanding of the challenges and feats within energy grids, and the ongoing energy transition.

- *Passivity*. In conventional energy grids, the majority of consumers is not required to make any active decisions that alleviate the tasks of producers to match the production to the demand (some exceptions may exist for large industrial consumers). Consequently, information that is required to support control processes, like, for instance, state information of the grid, historical data, and weather forecasts, mainly support the control-decisions of producers. In comparison, consumers are, willingly or unwillingly, largely unaware of the current situation in the grid (except for differentiating between severe situations like blackouts and normal operation), which strongly limits their capabilities for making decisions that may support the resilient operation of the grid. Therefore, consumers are rather passive and there is neither a need for them to have profound knowledge about the impact of their actions on the situation of the grid nor is there a need to understand operational processes.

- *Lack of Incentivization*. Peoples' lack of understanding of energy grid topics can also be attributed to the lack of incentivization provided by entities that are responsible for maintaining a continuous supply with electricity, like the energy provider. Since energy providers are profit-oriented, a reduction in the electricity consumption of the consumers can directly lead to monetary losses [203]. This situation is aggravated by the lack of innovative business models that are suitable for the ongoing transition towards smart grids [43, 147]. As a consequence, adjustments to the energy consumption are not directly incentivized, which leaves the continuously increasing costs for electricity[1] as a reason for people to adjust their consumption.

5.2.2 *Impacting Energy Grid Resilience by Educating People*

Earlier in this chapter, the lack of knowledge about energy grid topics was discussed. In the following, we highlight the benefits of increased domain knowledge for the *energy grid transition*, peoples' *energy management*, their *preparedness*, and *decision-making* within the four phases of resilience considered in this work (see Section 2.3.1.1).

THE NECESSITY FOR CHANGES IN ENERGY GRIDS The energy grid is already undergoing severe changes ranging from infrastructure (e.g., large-scale producers give way to distributed RESs) to operational processes (e.g., increasing demand-side management). However, it is commonly agreed that this transition is not a one-time effort but a step-wise process that requires adjustments and advancements in numerous domains. Among the most prominent ones are politics and legislation, which need to adapt to the peculiarities of an increasingly distributed energy grid with strong involvement of heterogeneous stakeholders; industrial processes may require changes to improve their efficiency and suitability for supporting the ecologic goals of the energy grid. For instance, industrial processes need become more ecological and energy efficient, and interdependencies between these processes and the energy grid need to be increasingly exploited (e.g., steam generated as a side-product of, for instance, aluminum melting, can be used to power small-scale generators) [173].

In general, more participants within energy grids need to understand that their contribution to the transitioning process—or at least their acceptance of changes—is a prerequisite for a successful transition towards smart grids; otherwise, smart grids will not be able to reach their full potential if necessary changes are not supported by the majority of participants.

Increasing the knowledge of all participants about energy grid topics, especially, about emerging challenges, operational processes, and

1 https://strom-report.de/strompreise/strompreisentwicklung/

the roles and impact of individuals within the system, can support the transition process in several ways. For example, knowledge about the challenges and necessity of the energy grid transition may can increase the awareness of people and enable them to take actions that support this process. In particular, understanding the benefits of local electricity production and its potential impact on energy grid resilience can motivate people invest into local RESs. Furthermore, if people know more about the energy domain they can use this knowledge to improve their assessment of energy-related political decisions and technical advancements, which can alleviate the acceptance (or rejection) of technological changes and political decisions (e.g., smart meter roll-out, reduction of nuclear- and coal-based power production) [124].

IMPROVING PERSONAL ENERGY MANAGEMENT The majority of consumers are unaware of the feats that need to be accomplished to maintain the continuous operation of the energy grid and also of the effects and impact of their local energy management on the operation of the grid (see Section 5.2.1). Despite this—willing or unwilling—lack of awareness, ongoing technical advancements yield an increasing potential of prosumers to impact the stable operation of the energy grid. For instance, electric heat pumps, battery storage units, and EVs require managing large amounts of electricity locally, which exacerbates the task of control entities to operate the energy grid resiliently [10, 15].

Therefore, improving the local energy management of participants can have strong beneficial effects for the resilient operation of the grid. For instance, smart scheduling of high-consuming appliances, like the charging of EVs, can reduce the overall peak consumption within the grid [178]. Likewise, these high-consuming resources could be used for mitigating the impact of excess electricity in the grid (e.g., if a prosumer configures the EV as a corresponding flexibility Section 3.3.3). However, to benefit from these local resources, active and aware prosumers are required that understand the importance of making these resources available.

Current approaches that aim at enabling participants to improve their local energy management are not widely accepted and have only been of limited success (see Section 2.3.1.2). Therefore, additional measures for motivating people are required that do not solely rely on conventional monetary incentives (e.g., reduction of electricity bill) but also take into account means of intrinsic motivation of the participants (see Section 5.2.3) to facilitate changes in energy management [215].

INCREASINGLY PREPARED PARTICIPANTS Peoples' capability to *be resilient* can impact the resilience of future energy grids. More precisely, if people take on a responsible role within operational processes of the grid, any disruptions and problems that can affect peoples' ability to fulfill their role can have detrimental consequences for the resilience of the entire system. In other words, resilient people are required for a resilient energy grid.

Increasing the knowledge of people on energy grid topics can improve their ability to assess the *severity* of a problem situation. For instance, expert personnel is capable of making informed decisions in hazardous situations since they accumulated knowledge and experience that allows them to assess the situation. Acknowledged aspects that enable experts to act accordingly are, among others, a strong understanding of how processes work in their domain of expertise and the corresponding profound domain knowledge [186]. While a comparable knowledge-increase for laypersons in energy grids is unrealistic, we stress that increased knowledge can contribute to both the handling of the situation by the layperson and the resilient operation of the grid. For instance, people who understand the fundamental concepts of blackouts in energy grids, their most common causes, and the established operational routines for mitigating the situation (e.g., restarting impacted areas) can contribute to the resilience of the energy grid in numerous ways: first, people can—during a blackout situation—conduct supportive actions or, at least, avoid actions that exacerbate the situation (e.g., rapidly switching on appliances to check for the availability of electricity); second, people may remain increasingly calm during a blackout situation, if they understand how the situation affects them locally and what processes are in place for restarting parts of the energy grid. Consequently, fewer people may conduct actions that can impede system restoration, like calling service hotlines frequently and further depleting the resources of participants responsible for restoring the electricity supply.

ACTIVELY SUPPORTING RESILIENT GRID OPERATION Increasing the knowledge of people may not only enhance their ability to assess a problem situation and improve their situation handling, but can also enable them to contribute to the resilience of the grid. As introduced in Section 2.3.1 resilience—in this work—is considered within four different phases of a hazardous situation, namely *anticipation*, *adaption*, *mitigation*, and *recovery*. The impact of increasingly knowledgeable people within these four phases is explained next.

- *Anticipation*. The benefits for the resilience of the grid during the anticipation phase are predominantly based on the previously described improvements for participant preparedness. People who understand that the grid is not entirely fail-safe, can make preparations to endure hazardous situations more easily (e.g., storing drinking water, maintain backup electricity in the local battery storage system) [29], which can alleviate the stress on personnel that is responsible for mitigating the situation (e.g., lower stress on emergency hotlines).

- *Adaption*. Once people are increasingly prepared to endure hazardous situations, they can be involved in preemptive actions for improving the handling of the upcoming problem situation and the subsequent recovery. Within a holonic energy grid—as it is presented in this thesis—people can schedule the electricity consumption of their local appliances to reduce the overall load in the grid during the hazardous situation. This reduces the overall amount of electricity that needs to be provided by the producers which can increase their capability to react to changes in the demand and supply balance. Furthermore, people can decide to change the priorities of local appliances and to offer additional appliances as flexibilities (see Section 3.3.3.1) to contribute additional resources for the mitigation of the problem situation.

- *Mitigation*. During the *mitigation* phase prosumers can contribute to the resilience of the energy grid by actively taking actions that exceed the scope of contribution that were configured during the anticipation phase. If participants are increasingly prepared to endure a hazardous situation and their knowledge about energy grid topics is increased, they can make better decisions that consider their role within the holonic energy grid and take into account their local situation. For instance, if a hazardous situation is more severe than anticipated, people could make tough decisions for supporting the mitigation of the problem at hand, like deciding—at their own risk—to offer all appliances in their homes as low-priority flexibilities. As a consequence, all appliances are used within the problem mitigation process with an higher probability, which may render them unusable for the prosumers. Reasons for such an altruistic decision-making may be supported by the availability of non-electric alternatives (as part of measures taken by the prosumer to be increasingly prepared) to the respective electric appliance (e.g., fireplace and blankets as an alternative way of heating). However, to be able to make such a decision, numerous aspects need to be understood by the prosumers: first, the importance of their participation in mitigation processes; second, the severity of the problem situation and the corresponding necessity of their participation; and third, the fact that they—as an individual—can have an impact on supporting the mitigation of the problem at hand.

- *Recovery*. In this phase, many of the previous benefits of knowledgeable and aware users also apply (see anticipation phase). Depending on the damage the hazardous situation has done, the recovery processes may take an increasing amount of time and are often required to be conducted as a step-wise process. For instance, if blackouts occurred, partial restarts of smaller sectors may be conducted. Once these sectors can be stably supplied with electricity, further sectors are included. Especially during such step-wise recovery processes, well-informed people may remain calm due to their conducted preparations and the knowledge about ongoing processes compared to people who lack the respective knowledge. This again may alleviate the work of personnel responsible for conducting the recovery processes as fewer people may impede their work.

5.2.3 *Motivating People to Participate in Resilient Grid Operation*

The concepts and methods presented in this work require active and aware people willing to participate and contribute to the resilient operation of energy grids. Towards this end, we emphasized that increased knowledge about important energy grid topics can have beneficial effects on peoples' willingness for participation and the overall resilience of the grid (see Section 5.2.2). However, such participation may have several drawbacks for involved prosumers, which—if not compensated adequately—can have detrimental effects on their willingness to participate and contribute. For instance, monetary investments may be required to facilitate the technological changes that enable them to become active, like installing RESs, and local ICT. Other adverse effects can result from the active participation within concepts for mitigating hazardous situations, like the unavailability of appliances that are currently used as flexibilities.

The adverse effects described above can reduce the motivation and willingness of participants to accept such concepts and discourage them from participating in the first place. Furthermore, even if people are willing to participate, the repetitive experience of drawbacks—without an adequate compensation—can impede their motivation for continuous participation. However, since not all negative aspects can be avoided, especially during emergency situations, *incentives* are required that alleviate the burden on the participants and motivate them to participate and contribute to the resilient operation of the energy grid. Research has shown that *monetary* incentives (e.g., financial reward), *non-monetary* incentives (e.g., performance feedback) as well as their combination can have strong effects on motivating people [175, 212]. In the following, monetary and non-monetary classes of incentives are presented, and their applicability within energy grids is discussed.

5.2.3.1 *Monetary Incentivization*

The concept of monetary incentivization as a means for effectively motivating people is investigated for decades [140, 154, 188]. The increase in motivation is mainly derived from the fact that money can be exchanged for goods, services, or privileges [123]. Consequently, monetary incentives can be implemented in many different ways, like payments, prizes, and vacations [151]. The goal of such approaches is to guide a participant towards a particular behavior by offering a reward. Despite the ongoing discussion about the usefulness of such approaches, they are used frequently for motivating people in our modern society (e.g., lump-sum bonuses [220]).

Monetary incentivization is the most commonly applied concept for reimbursing peoples' participation in measures to improve the resilient operation of energy grids. For instance, state financial incentives are used to motivate the deployment of solar panels [192]. Likewise, demand-side management approaches predominantly use monetary incentives as one of the core optimization criteria [82, 129, 134, 143]. However, it has been shown that monetary incentivization approaches—if they are applied individually—are only of limited success for motivating participants within energy grids. In particular, adequate business cases are not established yet and, thus, the benefits are insufficient to attract a large number of participants [219]. Likewise, the magnitude of these incentives are insufficient to compensate the detrimental effects on peoples' daily routines for consuming electricity [48, 90].

5.2.3.2 *Non-monetary Incentivization*

Monetary incentives for guiding the behavior and actions of people are widely used. Additionally, several means for incentivization exist that are not associated with monetary rewards but are based on concepts like, feedback and (social) recognition [60, 175, 212, 214]. For instance, people can be informed about their performance within a scenario and provided with information to improve themselves. Furthermore, their engagement can be recognized generally (e.g., employee of the month programs), or their achievements can be acknowledged on a more social level by praise and compliments [100]. Research has shown that non-monetary incentives—especially if social recognition is involved—can have strong motivational effects that can exceed the effects of monetary ones [175, 212]. Furthermore, the costs for applying non-monetary incentivization is minimal compared to monetary ones. However, non-monetary incentivization is yet not widely applied within energy grids. In the following, we briefly explain non-monetary incentivization approaches based on *information provision*, *nudging*, and *gamification* in the context of energy grids.

INFORMATION PROVISION As described previously, providing information to participants about their performance can be an effective way to increase their motivation and performance. In the context of energy grids, several related work aimed to encourage behavioral changes in participants by providing them with information about their local handling of energy [27, 75, 167, 195]. For instance, people were provided with real-time information about their ongoing energy consumption using in-house displays [78, 98]. Others showed more high-level information related to CO_2 emission and climate change [210]. One general take-away from this research denotes that information provision—by itself—does not suffice to motivate people but needs to be combined with other means to become effective [21, 101].

NUDGING Nudging represents a technique for affecting the behavior of people by making small "adjustments" (so-called *nudges*) on the presentation of choices for people in a specific context. Moreover, the presentation is designed in such a way that it does not limit these choices but encourages people to make choices that are preferred in a specific context [225]. Towards this end, nudges target automatic cognitive processes and the outcome of the decision-making should yield benefits for the entity that is presenting the choices and/or the people making them. For instance, nudging has been successfully applied in the field of nutrition [131], or to encourage the generation of stronger passwords [184].

In the domain of energy grids research has shown that nudging can be successfully applied to guide people to reduce their overall electricity consumption [13, 190]. On an energy provider level, Pichert & Katsikopoulos [176] showed that if RESs are selected as the default energy source, people tend to prefer this option over cheaper non-renewable alternatives. Consequently, nudging represents a promising approach for supporting people in participating within the resilient operation of energy grids.

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 [50]. As people play games due to their intrinsic motivation, gamification aims at leveraging this motivation for improving the performance of people in a pragmatic context [99, 217]. Literature shows that gamification has been successfully applied in various domains, like mobile education, redesigning of business processes, and cybersecurity [77, 127, 221]. In the domain of energy grids, gamification is successfully used to achieve reductions in peak demand and costs for infrastructure operators [5, 88, 113, 114].

In practice, commonly applied game mechanics are, among others, scoring systems, levels, and achievements. For instance, [88] proposed a prototypical demand dispatch system for energy grids, which allows participants to communicate variable consumption periods for local appliances to control authorities. Authorities can leverage these variable consumption times to optimize the operation of the grid's electricty production by re-scheduling the consumption directly or negotiate changes. For decisions of the participants that improve the overall demand dispatch operations (e.g., by providing larger time-intervals during which appliances can be scheduled) they are rewarded with *Earth Saver Points*. These points can then exchanged by the prosumer to earn titles in the context of the application (e.g., Eco Hero).

Overall, gamification represents a promising technique to increase the motivation and involvement of grid participants within actions to improve the resilience of energy grid operations. However, numerous challenges need to be overcome to apply the concept successfully, like preventing information overload for prosumers and designing intuitive user interfaces that foster engagement of the participant with the gamification concept [95].

5.2.4 *Knowledge and Motivation as Key Aspects for Active and Aware Participants in Energy Grids*

Until this point in the chapter, we have provided reasons why it can be assumed that the knowledge of the majority of participants in energy grids is limited. Furthermore, we highlighted several benefits for energy grid resilience that can emerge from an increased energy domain knowledge of people in the grid. We are aware that such an increase of knowledge—by itself—is likely not sufficient to encourage people to become more active participants and take on an increasingly responsible role. Therefore, we presented monetary and non-monetary means that can be leveraged for incentivizing them and increase their motivation. However, the question remains how people can be educated about energy grid topics. This is no mean feat, since there is a great deal that is assumed or taken for granted at present. Furthermore, it is unlikely that education is going to be a speedy process: some information is technical, some is irrelevant to different kind of participants in the grid, and learning is a predominantly curiosity-driven process. To provide an entertaining way for people to learn about energy grid topics and to motivate them to become increasingly active participants in the grid, in the following we present a serious game prototype.

5.3 ENERGY GRID KNOWLEDGE TRANSFER USING SERIOUS GAMES

In this section, we present a prototypical serious game (in the following referred to as "Griducate") as a motivating and exciting technique for conveying knowledge about energy grid topics. First, the learning content of Griducate—at time of writing of this thesis—is presented. Afterward, the general concept of Griducate is introduced and the individual *mechanics*, *dynamics*, and *aesthetics* of the game are briefly explained. More detailed background information about serious games and related learning concepts are provided in Section 2.5.

5.3.1 *Initial Learning Content*

In this chapter, it was mentioned several times that people are largely unaware of the feats that need to be accomplished to maintain a continuous supply with electricity in conventional energy grids. Furthermore, these processes may become even more ambiguous as energy grids transition towards smart grids. Therefore, it was decided that the initial learning content for the Griducate prototype should encompass fundamental information related to those feats. In particular, the initial learning content is divided into four categories, namely *infrastructure*, *stakeholders*, *operation*, and *energy transition*, which are explained next in more detail. Note that these categories need to be extended and new categories must be integrated during the further development of Griducate.

- *Infrastructure.* Content in this category aims to educate people about important components and challenges related to the energy grid infrastructure. The current implementation of Griducate encompasses information about the different *voltage layers*, their properties, interdependencies, and important hardware, like *transformers* and their role within the grid infrastructure.
- *Stakeholders.* This category comprises information about stakeholders involved in the operational processes of energy grids. The current implementation of Griducate provides information about numerous *conventional producers* (e.g., nuclear and coal power plants) and *RESs* (e.g., solar panels and wind turbines) as well as *consumers* and *prosumers*.
- *Operation.* The operation category is concerned with information about the operational processes within energy grids. At the time of writing of this thesis, Griducate informs people about the challenge of maintaining a stable *grid frequency* in the presence of everchanging demand and potential consequences. Furthermore, information on the impact of *volatile RESs* and their peculiarities are provided (e.g., location-based efficiency, day-night-cycle impact, etc.).
- *Energy transition.* In this category, several changes and corresponding challenges of the energy transition are addressed. For instance, information on the *environmental impact* of coal and nuclear power plants is provided. Furthermore, challenges for RESs and changing roles of consumers towards prosumers is presented. Additionally, the benefits of *energy storages* are introduced.

5.3.2 *General Concept of Griducate*

Based on the previously introduced categories of desired learning contents, a prototypical serious game was developed using the Unity development environment[2]. The overall theme of Griducate is based on the goal of maintaining the stable operation of an energy grid that is supplied completely by renewable energy sources. This goal needs to be achieved by adjusting initially fossil-fuelled energy grids to incorporate sufficient RESs while managing limited financial resources and the satisfaction of stakeholders involved in this transitioning process. Figure 5.1 shows the general view of a player within the Griducate game.

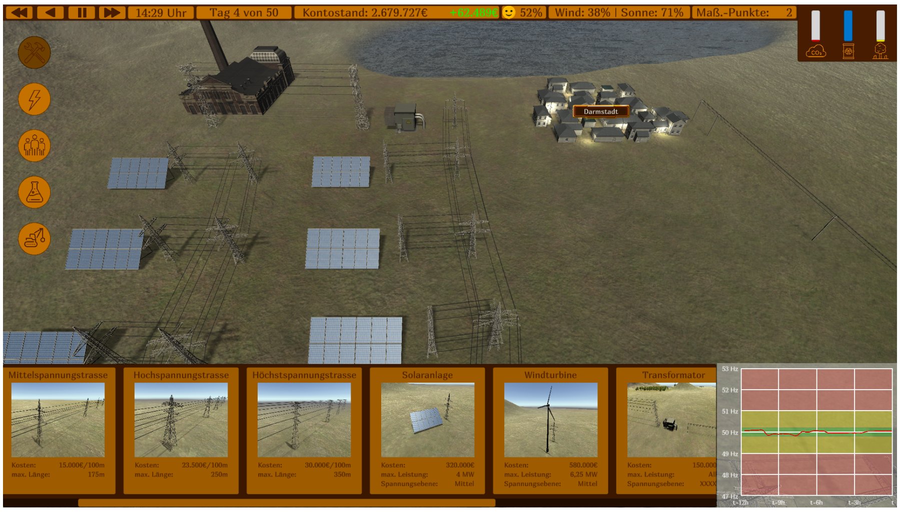

Figure 5.1: General view of Griducate from the perspective of a player.

The fundamental game concept of Griducate is based on the MDA framework proposed by Hunicke *et al.* [109], who divide game design into three areas, namely *mechanics*, *dynamics*, and *aesthetics*.

- *Mechanics.* Technical components of the game that comprise the handling and representation of data and corresponding algorithms.
- *Dynamics.* Emerging behavior of the mechanics as a consequence of input generated by the player.
- *Aesthetics.* Desirable emotional responses of the player as a consequence of interacting with the game.

The most important aspects of Griducate and their affiliation to the areas described above are presented next.

GRIDUCATE MECHANICS The game mechanics describe components of Griducate that enable actions, define in-game behaviors, and offer control functionalities. In Table 5.1 the most important mechanics that are required to support dynamics, aesthetics and learning contents in Griducate are concisely enumerated.

2 https://unity.com/de

Category	Mechanic	Information
Infrastructure	Component placement	Place, delete, and adjust components like electric poles, cables, etc.
	Rules and limitation for placements	Check for limitations like voltage level or terrain placement limitations.
	Topology detection	Detection of sub-grids and topology validity checking.
Stakeholders	Electricity production	Power plant and RESs behaviors, P-regulated production control [121].
	Electricity consumption	City-level consumption, load-curve adjustments of citizens, private RESs.
	Citizen Satisfaction	Satisfaction score calculation.
Operation	Grid frequency control	Frequency calculation, algorithms for stabilization.
	Energy storage control	Battery storage behavior (e.g., (dis-)charging behavior).
	Environmental influences	Day-night cycle, weather model and behavior.
Energy transition	Research and development	R&D system for grid improvements and stakeholder interactions.
	Environmental impact	fossil-fuel impact on the environment, waste generation.

Table 5.1: The core-mechanics implemented in Griducate at the time of writing of this thesis.

GRIDUCATE DYNAMICS The dynamics are based on the previously described mechanics and allow generating the desired aesthetics of the game. The most important dynamics are briefly described next.

The current main dynamic of Griducate is based on building arbitrary energy grids by using financial resources. Players can place energy grid components, like power plants, RESs, energy storage, and different types of transmission lines and electric poles in the environment. The correct combination of these components yield a functioning energy grid, which then needs to be maintained to operate in a stable manner. In particular, the grid frequency of each energy grid needs to be kept at 50Hz, which requires maintaining sufficient production resources in the presence of ever-changing demand and external influences, like changes of the weather or day and night cycles. Furthermore, to achieve a good high-score at the end of the game, the satisfaction of citizens is important. Decisions of the player can impact the satisfaction of the citizens, like high prices for electricity or placing coal power plants near a city. Players can conduct information campaigns to educate citizens about the importance of changes and increase their acceptance. Finally, players need to manage their finances by balancing electricity production costs and electricity prizes for citizens.

GRIDUCATE AESTHETICS As introduced above, aesthetics describe the desired emotional reactions of resulting from interacting with the game. The main aesthetics for Griducate, according to the classification of Hunicke *et al.* [109], are *challenge* and *discovery*.

To make Griducate *challenging* for players, the following game objective has currently been set for Griducate: The goal is to secure the electricity supply for the entire population by means of renewable energies. The player starts the game with an electricity infrastructure whose supply is predominantly based on conventional electricity producers. The conversion from these fossil-fueled producers towards RESs represents one of the core aspects of the energy transition and forms the basis for a successful knowledge transfer of the defined learning objectives. To this end, the players must—to a large extent—figure out for themselves how a stable and reliable supply with electricity can be achieved. If the aforementioned conversion and the corresponding stable energy supply are achieved for a given period of time, the game is considered to be won and the player is awarded a high-score. This score indicates how well the player has fulfilled his tasks and comprises three categories: population, environment and energy supply. The scores of the individual categories indicate how successful the players have been in the respective categories. Thus, challenges arise in dealing with the environment and the population, which have to be overcome in order to achieve the highest possible score. In addition, the players are confronted with further challenges. For instance, a secure supply with electricity needs to be achieved; however, players also need to make efficient financial decisions to avoid bankruptcy.

Griducate is also intended to address the aesthetics of *discovery* and include supporting game elements for this purpose. Towards this end, the game is designed such that players need to discover interdependencies between components or their limitations without explicit hints to solve the game's objective. For instance, the power output of RESs like wind turbines strongly depends on the location where they are installed. If the area is favorable for unobstructed wind flow, the electricity production of wind turbines is higher compared to other areas.

5.3.3 *Representation of the Learning Content Within Griducate*

In this section, the mechanics and corresponding information visualizations of Griducate that aim at educating players about the initially specified learning content are presented briefly.

ENERGY GRID INFRASTRUCTURE To educate players about the transportation of electricity via power lines, their properties, and the reasons for the existence of different voltage layers, Griducate allows building *four types* of power lines. The power lines are low-voltage, medium voltage, high-voltage and extra-high voltage lines. Infrastructure components and stakeholders connected by these power lines are part of the same grid and the corresponding voltage level. Table 5.2 shows an overview of the components, stakeholders and properties of the different voltage layers within Griducate. If players attempt to connect the grid in different ways, a corresponding warning will be displayed, the action will not be conducted, and hints are shown that indicate the underlying cause for the problem (E.g., The hint: "You cannot connect power lines of different voltage layers" appears if a player attempts to connect different voltage layers without a transformer). Additional details are provided as tool-tips within the tuto-

Voltage Level	Transmission Distance	Infrastructure	Stakeholders
Low	short	low-voltage power lines, transformers	RESs, prosumers, cities
Medium	medium	medium-voltage power lines, transformers	RESs
High	long	high-voltage power lines, transformers, batteries	RESs
Extra-high	very long	extra-high power lines, transformers	coal and nuclear power plants

Table 5.2: Representation and properties of components for the infrastructure learning content in Griducate.

rial of the game. The content about the energy grid infrastructure covers questions (1)–(3) (see Section B.2.1) of the knowledge tests used within the evaluation of the prototype (see Section 5.4).

STAKEHOLDERS Griducate encompasses information about several stakeholders that participate in the technical operation of energy grids. Table 5.3 shows an overview about the stakeholders in Griducate. In particular, at the time of writing of this thesis, Griducate supports *conventional producers*, like coal and nuclear power plants, *solar panels* and *wind turbines* as representatives of RESs, as well as, cities comprising *consumers and prosumers*. Players can build all types of producers and learn about their positive and negative effects on the energy grid operation and the environment (e.g., stable production of conventional producers compared to volatile RESs). Furthermore, consumers and prosumers have preferences for different energy sources. While playing the game, players learn about these preferences and can conduct campaigns to increase the acceptance of specific resources. If such campaigns are neglected, the satisfaction of citizens decreases which can lower the final score at the end of the game. Specific information about stakeholders is addressed as questions (4) and (8) in the knowledge tests (see Section B.2.1), as the stakeholders are responsible for operating the energy grid, which is explained next.

ENERGY GRID OPERATION The energy grid operations represent game dynamics that emerge from the interplay between stakeholders, grid infrastructure, environment, and the decisions of the player. In general, players should gain knowledge about the feats that need to be accomplished to operate an energy grid in a stable way. Griducate provides players with a visual representation of the current *grid frequency* for all operational energy grids, shown in Figure 5.2. The frequency of each grid needs to be kept close to *50Hz* by building grid components, like producers, battery storage units, or by adjusting the operation existing ones. Towards this end, players learn about the influence of *volatile RESs* on the grid frequency and how the *location* and environmental effects, like the *weather* and *day-night cycles*,

Stakeholder	Positive Impact	Negative Impact
Conventional Producers	stable production, high power output, independent of the weather and daytime	high CO_2 emission, nuclear waste production, high costs
Renewable Energy Sources	available at low-, medium- and high-voltage layers, no CO_2 emission, low costs	lower production capacity, production depends on weather and daytime
Consumers	provide demand, purchase electricity (income for the player)	demand changes during the day, opinion on different energy sources can affect their acceptance
Prosumers	provide demand and production, sometimes purchase electricity (income for the player)	Production can influence grid stability, opinion on different energy sources can affect their acceptance

Table 5.3: Representation and properties of stakeholders and corresponding learning content in Griducate.

affect their electricity production. Specific information about energy grid operation is addressed as question (5)–(7) in the knowledge tests (see Section B.2.1)

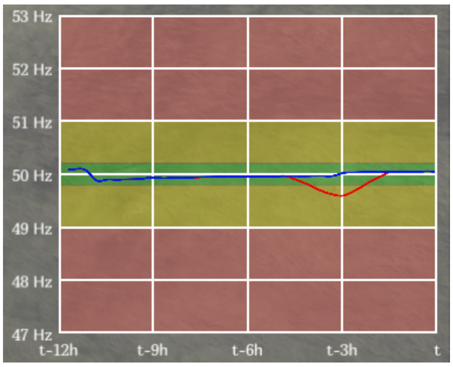

Figure 5.2: Overview of the grid frequencies of each active energy grid within Griducate. In this example, the blue grid frequency remains within the recommended interval, whereas the red one experienced a severe drop.

ENERGY GRID TRANSITION The overarching goal of the current version of Griducate is to achieve the energy transition by transforming an existing energy grid in such a way that it is supplied by 100% of RESs. In this process, players learn about the negative impact of conventional producers, which increase the CO_2 *emission* and produce *nuclear waste*. Furthermore, players need to carefully plan how they extend the energy grids since the *deforestation of woods*, to make space for building grid components, lowers the satisfaction of citizens and decreases the final score of the player. Moreover, this satisfaction is also influenced by how well-received different types of energy sources are by the population. For instance, some citizens may favor conventional sources, others may prefer renewable ones. Players can use money to run *advertisement and educational campaigns* to increase the *acceptance* of different technologies within the population and encourage consumers to become producers. Additionally, battery storage units are introduced as a means to support the mitigation of demand and supply deviations within grids that are predominantly supplied by RESs. All the aforementioned changes as well as further developments to improve existing technologies need to be conducted by the player while operating economically to avoid bankruptcy. The learning content of the energy grid transition topics is reflected in question (8) and (9) of the knowledge tests (see Section B.2.1).

5.4 EVALUATION

To investigate the suitability of the serious game prototype for educating people about energy grid topics, a user study was conduced. In particular, the goal of the study was to assess if serious games can be used to increase the knowledge of people effectively. Furthermore, the study investigated if people enjoyed using the prototype. Towards this end, the study aimed to answer the following hypotheses:

H1 *There are no significant differences in the increase of energy grid knowledge between people interacting with the serious game prototype and a text-based approach.*

H2 *People perceive the serious game prototype as more entertaining and motivating compared to a text-based approach.*

H3 *People consider the serious game prototype as more suitable for educating people about energy grid topics compared to a text-based approach.*

In the following, the design of the conducted study is explained. Afterward, the qualitative and quantitative results are presented. Finally, the findings are discussed and limitations to the study are highlighted.

5.4.1 *Study Design*

The study consists of 43 questions and is subdivided into five parts, namely *Welcome & Demographics*, *Prior Knowledge Test*, *Intervention*, *Opinion & Short-term Test*, and *Long-term Test*. A pre-test was conducted initially to test the study. An overview of the questions of the study is provided in Section B.2. The structure of the study is presented by Figure 5.3 and the individual parts are explained next.

WELCOME & DEMOGRAPHICS The participants of the study are informed about the goal of the general structure of the study. Furthermore, the data handling is explained, and the participants are

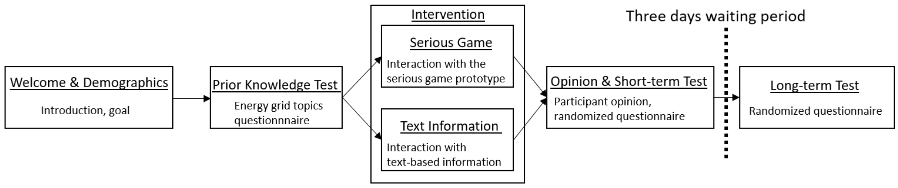

Figure 5.3: Griducate study procedure and path for the participants

informed about the voluntariness of the study. Subsequently, contact information is provided for addressing questions and concerns. Prior to the demographic questions a short motivational text is provided to explain the context of the study. The demographic information that is collected consists of *age* (interval selection), the *level of education*, *gender* and *state of employment*. Furthermore, participants are asked to self-assess their *interest* in energy grid topics, their *current knowledge* about the energy grid domain, and their *willingness to learn*, using a five-point Likert-scale.

PRIOR, SHORT-TERM AND LONG-TERM KNOWLEDGE TESTS Each knowledge test consists of nine questions for assessing the energy grid knowledge of the participants. Among the questions are dichotomous, single-selection, multiple-selection and free-text questions. Furthermore, statements are provided, where participants should indicate their level of agreement of disagreement on a five-point Likert-scale. The questions aim to assess the knowledge transfer w.r.t the energy grid topics selected for the implementation of the prototype at the time of writing of this thesis (see Section 5.3.1). For all three tests (i.e., prior, short-term, and long-term test) the same questions are used; however, the order of the questions and the corresponding answers is randomized. The prior knowledge test is conducted before any interaction with the intervention. The short-term test is conducted directly after participants interacted with one of the interventions. Finally, the long-term test is conducted after a three-day waiting period after participants interacted with one of the interventions. Furthermore, participants are not provided with the answers to the questions until the end of long-term test. The questions are shown in Section B.2

CALCULATION OF THE TEST PERFORMANCE The knowledge tests comprise nine questions that can be answered by single-selection, multiple-selection, or free-text. To assess the performance of the participants for each of the tests quantitatively, the following grading scheme is applied. Each question can yield one point such that the maximum achievable test score equals nine points. For questions with only one correct answer (i.e., free-text and single selection questions) one point is assigned for the correct answer; otherwise zero points are given. For multiple selection questions, the score for each correct answer is derived as one divided by the number of correct answers for the question. For each correct answer provided by the participant the corresponding score fraction is assigned; otherwise, if one of the provided answers is wrong, the resulting score for the answer is zero. For instance, if one question has three correct answers and a participant provides two of them without providing a wrong answer, the resulting score would be 0.66.

INTERVENTIONS For the evaluation of the serious game prototype, the participants are randomly assigned into two groups. The first group interacts with the *serious game prototype* to improve their knowledge about energy grid topics. The second group interacts with an *textual description* (In the remainder of the chapter referred to as "Text") that contains the same information (see Section B.1 for details on the text-based intervention). For the serious game prototype, the participants are asked only to play the tutorial part of the game, which is estimated to about 15-20 minutes but no hard time-limit is provided. Similarly, the text group does not have time limits on their interaction with the intervention.

OPINION To assess the participants' opinion on the interventions, corresponding questions are asked directly after they used on of the interventions. The questions aim to investigate if people are motivated to increase their knowledge by using the presented intervention and if they enjoyed the interaction. Furthermore, they should provide their opinion on the suitability of the intervention for educating people and again provide a self-assessment of their knowledge on energy grid topics

PARTICIPANTS We recruited 26 participants by advertising the survey on social media, mailing-lists and by word-of-mouth. The general target group was not limited. The advertisement encompassed a general description of goal of the study and contact information. We excluded two participants from the data set, since they only started participating in the study but did not answer any questions. Consequently, N = 24 usable data entries remain. These participants were randomly subdivided into two groups, where 11 (45.8%) participants interacted with the serious game prototype and 13 (54.2%) were assigned to the text group. Four additional participant did not answer the questions to the long-term test. These cases will be excluded for the result presentation and discussion on the long-term test. Out of 24 participants seven (29.2%) identified themselves as female and 16 (66.7%) as male, whereas one participant (4.1%) did not specify the gender. Tab. Table 5.4 shows the age and educational levels of the participants.

Age / Participants		Education / Participants	
18–24	6 (25.0%)	Secondary School	3 (12.5%)
25–30	10 (41.7%)	High School	4 (16.7%)
31–40	8 (33.3%)	Vocational Education	3 (12.5%)
		University Bachelor	3 (12.5%)
		University Master	5 (20.8%)
		University Ph.D.	6 (25.0%)

Table 5.4: Overview of the study participants.

Test	Mean	N	Var	SD
Prior	3.89	24	2.90	1.70
Short-term	6.50	24	3.01	1.74
Long-term	6.83	20	2.13	1.46

Table 5.5: Overview of the test results for the participants of both groups combined.

The participants' interest in energy grid topics was rated on a five-point Likert-scale (i.e., one indicates *not interested* and five indicates *very interested*) and is slightly positive (Mean = 3.44, N = 24, SD = 1.02). In comparison, the self-assessment of the participants regarding their energy domain knowledge is slightly negative (Mean = 2.92, N = 24, SD = 1.32). Finally, participants willingness to learn about energy grid topics is very positive (Mean = 4.17, N = 24, SD = .82).

5.4.2 *Quantitative Results*

In the following, the quantitative test results of the two groups for the prior, short-term, and long-term knowledge test are presented. Table 5.5 shows the performance of all participants within the different tests.

The results clearly show that all participants were able to improve their short-term and long-term knowledge about energy grid topics by interacting with both interventions. Note that *long-term* knowledge refers to three-days waiting period. To assess the effects of both interventions for improving the participants' knowledge over a longer period of time, further studies are required. To investigate the main effects of the interventions and the waiting period on the knowledge of the participants as well as their interactions within both groups, we conducted an aligned rank transformation [239] and analyzed the

Independent Variable	F-score	p-value
Game/Text	$F(1,18) = 0.096$	$> .05$
Time	$F(2,17) = 21.025$	$< .001$
Game/Text*Time	$F(2,17) = 0.192$	$> .05$

Table 5.6: Results of the ANOVAs on the aligned rank transformed knowledge score values.

Group	Mean	N	Var	SD
Game	3.99	11	3.42	1.85
Text	3.80	13	2.70	1.64

Table 5.7: Test results for prior knowledge test for the individual groups.

effects using multiple ANOVAs. We used this rank-based approach since the assumption of normality was violated for the data of the knowledge tests (Shapiro-Wilk test $p < .001$). The results are summarized in Table 5.6.

The results show that there are no significant differences in the mean ranks of the achieved knowledge test scores for the Game and the Text intervention among the participants. However, there are significant differences between the achieved test scores at different points in time ($p < .001$). Finally, the interaction between the Game/Text variable and the Time variable is not significant. We conducted a Tukey post-hoc test, which showed that the significant differences are between the prior knowledge test scores and the two tests conducted after the interaction with either the presented prototype or the Text intervention ($p < .001$). With the absence of significant differences between the short-term and long-term knowledge test, we assume that the significant differences between the prior- and short-term knowledge test are not caused by time, but are a result of the participants' interaction with the prototype and Text intervention. Therefore, hypothesis H_1 can be supported. The performance of the individuals groups within the individual knowledge tests is presented next.

> *Intervention Performance.* Both interventions achieve a similar increase in the knowledge of participants about energy grid topics.

PRIOR KNOWLEDGE TEST The results displayed in Table 5.7 show that the two groups had a lower moderate knowledge of energy grid topics. Furthermore, the randomly assigned groups did not differ significantly in their average knowledge about energy grid topics at the beginning of the study ($U = 66.5$, $p > .05$).

Group	Mean	N	Var	SD
Game	6.48	11	2.48	1.57
Text	6.52	13	3.71	1.93

Table 5.8: Test results for short-term knowledge test for the individual groups.

Group	Mean	N	Var	SD
Game	6.85	8	1.01	1.00
Text	6.83	12	3.03	1.74

Table 5.9: Test results for long-term knowledge test for the individual groups.

SHORT-TERM TEST After the interaction with the game or Text intervention, both groups significantly improved their performance in the short-term knowledge test; however, the differences between the average achieved scores of the two groups remain insignificant ($U = 64.0$, $p > .05$). This indicates that neither the game nor the Text intervention have a significant advantage w.r.t. their capability of conveying the presented energy grid topics. The results for the short-term test are shown in Table 5.8.

LONG-TERM TEST The results for the long-term knowledge test are shown in Table 5.9. The results are similar to the ones of the short-term knowledge test and the differences between the groups remain insignificant ($U = 42.0$, $p > .05$).

SUITABILITY OF THE INTERVENTIONS FOR CONVEYING KNOWLEDGE ABOUT ENERGY GRIDS In this chapter, it was mentioned multiple times that increasing the knowledge of people is no mean task and is influenced by several aspects, like motivation of people to learn something new, their enthusiasm, and their access to corresponding knowledge. To assess if the presented prototypical game is a suitable candidate for educating people about energy grid topics, several questions were asked to investigate peoples' opinion on the game. In comparison, people that interacted with the Text intervention were asked the same questions. The questions are shown in Section B.2.2 and the results to the Likert-scale question are presented in Table 5.10

The results show that for all categories the presented prototype achieves a higher average score that the Text intervention. To investigate if these differences are significant, we conducted four Mann-

Category	Intervention	Mean	N	Var	SD
Enthusiasm	Game	4.27	11	.418	.65
	Text	3.00	13	1.67	1.29
Motivation	Game	4.27	11	.418	.65
	Text	3.08	13	1.58	1.26
Suitability	Game	4.18	11	.36	.60
	Text	3.00	13	1.17	1.08
Entertainment	Game	3.73	11	1.02	1.01
	Text	2.77	13	1.36	1.17

Table 5.10: Results of the questions on peoples' opinion on the game and Text intervention.

Category	U	p-value
Enthusiasm	27.5	$< .05$
Motivation	30.5	$< .05$
Suitability	28.5	$< .05$
Entertainment	37.5	$< .05$

Table 5.11: Results of the Mann-Whitney U tests on peoples' opinion on the prototype and Text intervention.

Whitney U tests (see Table 5.11). The tests showed that the differences for all categories are significant. Therefore, hypotheses H_2 and H_3 can be supported.

> *Peoples' opinion on the interventions.* People perceive the presented prototype as significantly more exciting, motivating, suitable for learning about energy grid topics, and entertaining compared to the Text intervention.

SHORT SUMMARY OF IMPORTANT RESULTS The presented prototype and the Text intervention increased the energy grid knowledge of people significantly. The average knowledge increase does not differ between participants interacting with the serious game prototype and the Text intervention. However, the presented prototype is perceived as significantly more exciting, motivating, suitable for educating people, and entertaining compared to the Text approach.

5.4.3 *Discussion & Reflection*

In this section, we discuss the results and findings of the conducted user study.

PERFORMANCE OF THE SERIOUS GAME PROTOTYPE The main goal of the presented serious game prototype is to convey knowledge about energy grid topics. Whilst the information that is required to increase the knowledge of people can be provided in various ways, the motivation of people to learn about energy grid topics is crucial. We selected a Text approach for comparison, since reading is one of the most basic and important abilities to enable people to interpret and understand information [206].

The results of the conducted study show, that the serious game prototype is capable of significantly increasing the energy grid knowledge of people, similar to the Text approach. Moreover, this knowledge seems to persist for both the short-term scenario as well after three days of waiting time. Since there was no significant change in the knowledge of people between the short-term and long-term knowledge test, we assume that time (i.e., the three-days waiting period without interacting with the interventions) did not have a strong influence on peoples' knowledge. This indicates that the prototype is able to convey the information specified in this study similarly well as the Text approach.

However, the interaction of the participants with the serious game prototype mainly consisted of playing the tutorial of the game in order to learn the basic controls and goals (Participants were not limited to playing only the tutorial). In the tutorial the majority of information is presented as text to support the actions conducted by the participant. Consequently, it cannot be excluded that the Text representation of information in the game is at least partially responsible for the increase of knowledge of the participants. To investigate the impact of the textual information representation within the prototype, further studies are required that specifically test for the knowledge that is not presented as text. This can provide insights how the actual gameplay influences the knowledge of people, but this requires a careful design of the possible actions and consequences in the game such that people can draw the correct conclusions (i.e., conclusions that fit the desired knowledge transfer).

Another interesting finding is related to peoples' self-assessment of their knowledge about energy grid topics. Participants were asked to assess their own knowledge about energy grid topics before and after they interacted with the interventions using a five-point Likert scale (one indicates that a participant considers herself not knowledgeable and five indicates the assumption of strong knowledge about energy

Intervention	Mean	N	Var	SD
Game (initial)	3.18	11	2.36	1.53
Game (interaction)	3.64	11	1.25	1.12
Text (initial)	2.69	13	1.23	1.11
Text (interaction)	2.69	13	1.06	1.03

Table 5.12: Results of the self-assessment of the participants' energy grid knowledge before and after the interaction with the interventions.

grid topics). Table 5.12 provides an overview of peoples' *initial* self-assessment and after the *interaction* with the intervention.

While the average self-assessment of the participants remained the same for the group that interacted with the Text intervention, the average value slightly increased for the group that interacted with the proposed prototype. Although the differences are not significant, participants of the game seem to be more confident about the knowledge they gained in the interaction with the intervention. This fits with the results that the increase of knowledge in both groups is significant. One explanation for the differences between the groups and the fact that no significant increase in self-assessed knowledge occurred as a result of the study may be closely related to the Dunning-Kruger effect [57]. In this context, people may have gained (initial) insights into the complexity of energy grid topics. This insights may have helped them to improve their self-assessment, which may be more conservative compared to their initial assessment. Simultaneously, they improved their knowledge about the specific energy grid topics covered within the study. The combination of both aforementioned effects may explain the slight increase in the self-assessment of the game group, while the assessment of the text group remained the same on average.

PEOPLES' OPINION ON THE SERIOUS GAME PROTOTYPE As shown in Table 5.10 participants that interacted with the serious game prototype rated it, on average, strongly positive in contrast to the Text approach, which received mediocre scores. The results indicate that the interaction with the game prototype is exciting for people and motivates them to learn more about energy grid topics. However, further investigations are required to analyze if the game prototype actually increases the motivation and excitement, or if it is only motivating and exciting for people that are already motivated and excited to learn about energy grid topics. The initial assessment of the participants' interest in energy topics (Mean = 3.44, N = 24, SD = 1.02) and their willingness to learn about these topics (Mean = 4.17, N = 24, SD = .82) do not provide suitable data to analyze the impact of the game on people that are not interested or unwilling to learn, as the mean values are positive. The lack of this data is reasonable since the topic and goal of the study were explained in the study invitation, therefore, there is a high probability that participants are at least interested in topics about energy grids.

The participants also consider the game approach as well-suited for educating people about energy grid topics and considered it significantly more entertaining compared to the Text approach. These result indicate that the serious game prototype works as intended (i.e., convey energy grid knowledge while being entertaining and exciting) and can be used to convey knowledge in the domain of energy grids. Furthermore, if people consider the interaction with the prototype entertaining it is more likely that they use it more frequently or for longer periods of time. This stronger interaction can further improve the increase of knowledge, especially for longer periods of time.

5.4.4 *Limitations*

The user study was advertised on social media and networks, mailing-lists, and by word-of-mouth. Consequently, the majority of participants are in a typical age-range of university students. This slightly impedes the generalizability of the study since results can dramatically differ for different age groups. For instance, in 2017 the majority of gamers was estimated to be in the age-range between 21–50 years[3]. Nearly all participants of the study fit into this age range, therefore, there is an increased probability that they have experience in playing video games. However, for older age-groups the situation may differ drastically. Further investigations are required to precisely address both age-groups that were underrepresented in this study. Younger age-groups, e.g., 7–17 year to represent school children and young adults, and older ones, like 50+ years to represent people that likely grew up without video games.

The strategies for distributing the user study may also result in a bias of the participants towards the content of the survey. Since the distribution was started by the author of the study, some contacts that were reached by using the previously mentioned distribution strategies may be socially connected with the author. Therefore, it cannot be excluded that some answers of participants are biased. Furthermore, as the author of the study is an employee in the field of computer science, corresponding social contacts have an increased probability to be involved in the same field. Consequently, these participants may have an initial bias towards the concept of (serious) computer games.

The alternative concepts for educating people was limited to a Text approach. However, several other concepts exist for educating people about various topics, like E-learning approaches. Further stud-

3 https://www.statista.com/statistics/722259/world-gamers-by-age-and-gender/

ies should encompass additional concepts for educating people to see which ones are the best-suited, e.g., for educating different age-groups.

The topics that were selected as knowledge that needs to be conveyed in this study consisted of mainly technical aspects. Whilst these topics are a simple starting point that is relatively easy to represent and implement within a prototypical game setting, other topics need to be included in the prototype as well. Especially topics that support people in their future—increasingly responsible—role within energy grids. Therefore, suitable representations and actions in the context of the serious game need to be developed that allow people to learn about increasingly complex topics.

The duration between the short-term and long-term test was specified as a three-days waiting time period without further interactions with the interventions. This specification has several drawbacks: Firstly, the prohibition of further interaction with the intervention prevents insights into the prototype's capability for motivating and exciting people for longer periods of time. Secondly, this also limits information on the amount of knowledge participants could have accumulated by interacting more with the prototype. Further studies should investigate if the motivation and excitement of people for the serious game approach lead to a stronger voluntary interaction with the prototype.

5.5 CONCLUSION

Energy grids are large-scale socio-technical systems that require both novel technical solutions and social advances of involved stakeholders to maintain a continuous and resilient supply with electricity. In this chapter we highlighted the importance of well-informed people in the context of the energy grid transition and, especially, for the resilient operation of holonic energy grids.

However, educating people about energy grid topics is no simple task. We showed that serious games can be leveraged as an effective tool to convey knowledge about energy grid topics which is significantly more exciting, motivating, and entertaining compared to text-based learning. We are confident that this technique can be used effectively to teach people about important feats and challenges in the context of energy grids and their transition towards smart grids.

Additionally, as increased knowledge—by itself—is not sufficient to increase the acceptance and motivation of people, we discussed strategies for motivating people based on *monetary* and *non-monetary* incentives and highlighted the benefits for their application in energy grids. Several approaches have been tested within different areas of energy grids; however, their wider application suffers from low user acceptance or the lack of technical means to adequately support them (e.g., a comprehensive ICT-infrastructure). Within holonic energy grids, as they were presented previously in this work, these approaches, and, especially, their combination needs to be investigated thoroughly to develop concepts that are accepted by people.

6 CONCLUSION

Over the course of this thesis, three main contributions were made that improve the resilience of smart energy grids. Firstly, a semi-formal model was presented, which structures energy grids as holarchies, which are dynamic hierarchies of holons facilitating the autonomous operation of sub-parts. Holarchies that emerge from the application of the proposed model strongly depend on the integration of heterogeneous stakeholders (e.g., enterprises, private households) and their local resources for maintaining a continuous supply of electricity during hazardous situations. In this context, flexibilities were proposed to empower stakeholders to participate in mitigation processes by making local resources available. Secondly, the emerging challenge of reorganizing holons within holonic energy grids and allocating the resources offered as flexibilities was addressed by customizing and evaluating three metaheuristic optimization algorithms. Finally, this thesis emphasized that technical solutions alone are not sufficient to improve the resilience of future energy grids, but well-informed, active and motivated people become increasingly important. Towards this end, a prototypical serious game approach was proposed for educating people about energy grid topics. Furthermore, as knowledge—by itself—is considered to be insufficient to motivate people to participate and take on an increasingly responsible role within holonic energy grids, techniques and measures for motivating people were discussed.

This chapter summarizes the core contributions and finding of this dissertation, draws conclusions and presents an outlook to future work.

6.1 Summary and conclusions

The immense size of the energy grid infrastructure, the complexity of involved processes, and the heterogeneity of participants raises numerous challenges for maintaining a stable and continuous supply of electricity and operating the energy grid resiliently [31, 33, 142, 177, 196, 207]. These challenges are further aggravated by the ongoing transition of the energy grid towards a more ecological and increasingly distributed smart grid [8, 74].

This thesis tackled several challenges (see Chapter 1) to improve the resilient operation of smart grids in the presence of hazardous situations. The main contributions and findings within the three contribution chapters (see Chapter 3, Chapter 4, and Chapter 5) are summarized next.

HOLONIC SYSTEM MODELING AND SIMULATION Chapter 3 proposed a semi-formal model for representing smart grids as *holarchies*, dynamic hierarchies facilitating quick system reconfiguration and strong integration of heterogeneous stakeholders. After an introducing holonic systems and emphasizing the need for simulation in energy grids, the chapter made the following core contributions:

- Providing a semi-formal model for representing smart grids as holarchies to enhance their resilient operation by enabling the dynamic separation and autonomous operation of sub-parts (holons).
- Improving the mitigation of hazardous situations within holons by empowering stakeholders to participate in mitigation processes. Towards this end, the model enables fine-grained local decision-making for adjusting the electricity production and consumption locally, and enables stakeholders to offer local resources as *flexibilities* to support the mitigation demand and supply deviations.
- Providing a modeling and simulation environment (HOLEG) that reflects the holonic smart grid model and allows developing and testing of novel concepts and algorithms in a safe environment.
- Investigating the willingness of people to participate in the aforementioned mitigation concept and analyzing their main concerns.

The holonic system model and the simulation environment HOLEG were used as a basis for subsequent contributions within the rest of this thesis.

The results showed that most people would be willing to participate in actions to support the mitigation of hazardous situations by providing local resources, even if their own satisfaction deteriorates in the process. Especially during emergency situations, people showed an increased willingness for participation. However, numerous concerns remain that impede the willingness for participation. Among the most prominent ones are IT-security and privacy concerns that are induced by the requirement of increasingly digitizing peoples' homes. Another major concern is related to fairness among the participant within the mitigation process. The willingness of people to contribute to the mitigation of hazardous situations by using local resources indicates that concepts, like the proposed semi-formal model and flexibilities, can increase the resilience of future energy grids. However, great care must be taken while developing the technical solutions that enable controlling appliances within peoples home to minimize safety and security risk for local devices and the people.

HOLONIC ENERGY GRID ADAPTION In Chapter 4, this thesis addressed the complex challenge that emerges by combining a holonic system architecture with the utilization of local flexibilities to mitigate hazardous situations in energy grids. Holarchies are capable of *reorganizing* their encompassed holons and facilitate the *autonomous* operation of sub-parts (holons). Especially within autonomous holons, flexibilities must be leveraged for maintaining the balance between demand and supply to provide a continuous supply with electricity. In this context, the chapter presented the following contributions:

- Specifying the *Holon Problem* as a multivariate optimization problem by combining the reorganuzation of holarchies and the allocation of flexibilities for mitigating demand and supply problems, which enables the application of a wide range of optimization algorithms.
- Making solutions to the Holon Problem assessable and comparable quantitatively by providing a cost function that incorporates, operational constraints of energy grids as well as numerous ecological, economic and resilience criteria.
- Customizing and comparing three metaheuristic optimization approaches to find near-optimal solutions to the Holon Problem within limited time-horizons.

The Holon Problem was modeled as a binary optimization problem, which then was addressed by customizing binary variants of established metaheuristic optimization approaches based on ant colony optimization (ACO), genetic algorithm (GA), and particle swarm optimization (PSO). The approaches were compared exensively within a simulated holarchy modeled in the HOLEG simulation environment. Furthermore, the performance of the algorithms was analyzed using various time-horizons for limiting the execution time of the algorithms and highlight their applicability realistic scenarios.

In Chapter 4 we conclude that metaheuristic optimization approaches are well-suited to address the Holon Problem and to mitigate hazardous situations within holonic energy grids. In this context, all approaches were able to find near-optimal solutions while adhering to various time constraints and trade-off between solution quality and time for finding solutions. Despite the fact that finding optimal solutions cannot be guaranteed with the application of metaheuristics, it could be shown that with a well-defined parameter selection, the approaches provide near-optimal solutions consistently. In particular, the results showed that the found solutions strongly improve the overall problem situation while maintaining a low probability for decreasing prosumer satisfaction in the process. Therefore, metaheuristic optimization is well-suited to find solutions that can mitigate the problem situation while considering important aspects of prosumers and overall energy grid resilience.

IMPROVED ENERGY GRID RESILIENCE THROUGH PROSUMER AWARENESS AND ACTION Chapter 5 addresses the non-technical challenges that emerge within holonic energy grids and the strong involvement of people into the mitigation processes. In particular, the chapter highlights the importance of increasing the knowledge of people about energy grid topics and the benefits of active, aware, and motivated people on energy grid resilience. In this context, the chapter made the following contributions:

- Highlighting the benefits of active and aware people on the resilient operation of energy grids.
- Presenting numerous monetary and non-monetary incentivization strategies that can be leveraged to increase the motivation of people to accept and participate in novel concepts like the proposed holonic model and flexibilities.
- Proposing and evaluating a prototypical serious game approach for conveying knowledge about energy grid topics to increase the awareness of people and support them in taking on an increasingly responsible role within future holonic energy grids.

The chapter showed that educated, active and aware people can have a strong impact within the different phases of resilience considered in this work. We emphazised that increasing the knowledge of people about energy grid topics yields increased awareness and can support them in becoming more active participants. The results of the evaluation of the serious game prototype showed that it is well-suited to significantly increase the energy grid knowledge of people and at the same time is significantly more motivating, exciting, and entertaining compared to learning with educational texts.

However, education—by itself—is insufficient to support the acceptance and participation in novel concepts, like a holonic system structure and flexibilities. Towards this end, numerous strategies are available, based on monetary and non-monetary incentives, that can increase the acceptance of novel concepts and motivate people to participate. Several approaches have been investigated by related work within different areas of energy grids; however, their wider application suffers from low user acceptance or the lack of technical means to adequately support them (e.g., a comprehensive information and communication technology (ICT)-infrastructure). Within holonic energy grids, as they were presented previously in this work, these approaches, and, especially, their combination needs to be investigated thoroughly to develop concepts that are accepted by people

6.2 OUTLOOK

Various aspects for improving the content presented in this thesis as well as opportunities for further research are briefly discussed in the following.

COMPLEXITY OF CONSTRAINTS In this work, *constraints* were introduced as a mechanism to limit the use of flexibilities for problem mitigation processes depending on two main aspects: firstly, *technical constraints* limit the use of flexibilities based on aspects that—if violated—could compromise the safe operation of the underlying holon element. Secondly, *personal constraints* reflect limitations that are based on the personal preferences of the prosumers that offer a flexibility, like, time of use or environmental factors. While numerous technical constraints could be solved by, for instance, "smart" holon elements that automatically monitor their operational constraints, personal constraints can quickly become extremely complex. As an example, a constraint may comprise multiple conditions that can again depend on other existing constraints. For instance, using a battery as a flexibility could be constrained by a temperature limit, like temperature must be above 10°C and, additionally, no electric vehicle is currently connected. However, if a electric vehicle is connected, these constraints may change towards a 5°C temperature limit and a state-of-charge restriction, like SoC > 70%. To reflect such combined and potentially interdependent constraints, an improved formulation technique for constraints and the corresponding checking needs to be integrated into the flexibility model.

HOLEG IMPROVEMENTS The HOLEG modeling and simulation environment is an open-source project which is contiuously being further developed. As stated in this thesis, HOLEG reflects the holonic model proposed in this work. To enable some holarchy properties, like the quick reconfigurability through *splitting* and *merging* processes, HOLEG makes some assumptions and simplifications. For instance, it is well-known that connecting two autonomously operating parts of the energy grid is challenging in asynchronous current grids [54]. However, the underlying representation of the power flow model of HOLEG is not yet capable of adequately representing the necessary details to adequately simulate the corresponding phenomena. Consequently, this is an aspect that affects the generalizability of conclusions drawn from simulations that require the merging of separated energy grids in an asynchronous current setting. To address this, a fine-grained AC power-flow model needs to be integrated into the HOLEG simulation environment, which adequately represents the required parameters and allows simulating emerging effects more closely to the real-world phenomena.

PROTOTYPING THE PROSUMER INTEGRATION FRAMEWORK The prosumer integration framework (PIF) presented for the evaluation in Chapter 3 aims to empower *passive* consumers and evolve them into increasingly *active* prosumers. Those prosumers are capable of contributing to problem mitigation processes by harnessing local resources for adjusting the demand and supply in holonic smart grids. The functionalities of the PIF were implemented within the HOLEG simulation environment and can therefore be investigated from a conceptual point of view (e.g., by generating scenarios to analyze "what if" questions). However, crucial aspects that can influence the acceptance of the PIF, the usability, and the impact on real-world devices and prosumers, could not be adequately analyzed. For example, one of the main concerns of people stated within the conducted survey was the lack of trust between them, their energy provider, and third party-enterprises for providing the technology required for implementing the PIF. To investigate these concerns, the PIF needs to be implemented in a real-world prototype using state-of-the art technologies and then be investigated in a real-world scenario.

LARGE-SCALE INVESTIGATION OF DIVERSE STAKEHOLDERS As stated in Section 3.5.5 several limitations had to be considered for analyzing the results of the survey to investigate peoples willingness to actively participate in holonic energy grids. In particular, further investigations are required to assess the willingness for participation of people from different countries, since it can be assumed that energy grids can drastically differ in stability and service quality depending on their location (e.g., cold countries vs. hot countries).

IMPROVEMENTS FOR THE COST FUNCTION The metaheuristic optimization approaches in Chapter 4 rely on a cost function for assessing the quality of their found solutions. Consequently, the quality of such an objective function strongly affects the performance of the optimization algorithms. While the presented cost function comprises numerous optimization criteria, like, for example, demand and supply balance and ecological performance of allocated flexibilities, a variety of criteria exist that have not been integrated yet, but might have a beneficial impact on the operation of the optimization approaches. Consequently, further research is required for specifying important resilience properties, economic and ecological criteria, and corresponding measurements for improving the cost function presented in this work.

IMPROVED SOLUTION STRATEGIES FOR SOLVING THE HOLON PROBLEM This thesis used metaheuristic optimization approaches to address the Holon Problem presented in Chapter 4. In this work, the Holon Problem was investigated holistically, where the goals was to find a solution that affects the entire holarchy and its encompassed flexibilities. However, problems within holonic energy grids may be increasingly relevant sub-parts of the grid, or may be addressed by delegating the mitigation process to lower layers within the holarchy. This limits the amount of available resources and reconfiguration possibilities to address the Holon Problem. From this limitation numerous research perspectives emerge: For instance, which other optimization approaches (e.g., greedy optimization algorithms) are increasingly good or better suited to solve the Holon Problem in this limited scenario. Another research direction could be determining the "optimal" size of holons that maximize their resilience.

COMBINATION AND APPLICATION OF MOTIVATIONAL STRATEGIES In Section 5.2.3 we presented monetary and non-monetary strategies for incentivizing people to increase their motivation. Whilst individual monetary and non-monetary strategies have been investigated by related work in the domain of energy grids, further research is required to analyze the combination of several approaches and their effectiveness for motivating people to participate actively within energy grids. Furthermore, the impact of increased knowledge on the acceptance and effectiveness of different motivational strategies could support the advancement of research within this domain and allow adjusting motivational strategies to different types of people and their preferences.

EXTENDING THE LEARNING CONTENT OF GRIDUCATE The serious game prototype (Griducate) proposed in this work (see Section 5.3) mainly addressed technical aspects of the energy grid infrastructure, stakeholders involved in operational processes, and basic challenges emerging from the energy transition (e.g., volatile renewable energy sources (RESs)). However, many more topics can be used as educational content to support people in better understanding their role within future energy grids and improve their awareness. For instance, Griducate could be extended to educate people about the potential impact of electric vehicles and corresponding vehicle to grid technologies. Furthermore, content about the negative consequences of hazardous situations and their implications for the energy grid and connected sectors could be integrated to improve peoples' understanding of the interconnectedness of infrastructures.

EXTENDING THE EVALUATION OF GRIDUCATE In Section 5.4.4 some limitations of the conducted user study for evaluating the proposed serious game prototype were presented. These limitations can be addressed by improving future evaluations of the prototype. For instance, future user studies should involve a representative number of participants from various age groups to improve the generalizability of results. Furthermore, to investigate the suitability of Griducate compared to other strategies for education, future study should compare the serious game with other approaches from the domains of e-learning and edutainment. It is likely that serious games are not the best solution for each individual person, but further comparisons may provide insights into which solution should be used to educate different people about energy grid topics.

Part I

Appendix

A

SURVEY ON PROSUMER PARTICIPATION

A.1 QUESTIONNAIRE ON THE PROSUMER INTEGRATION FRAMEWORK

This questionnaire was given to the participants for assessing their willingness to be increasingly involved in holonic energy grids. The study was reported in Section 3.5 and the PIF was presented as an "Energy Assistant" to ease the understanding of the participants.

A.1.1 *Questions on Demographics and Energy*

The participants were asked the following questions after the welcome section of the survey:

(1) How old are you? (Selection)

(2) What is your level of education? (Selection)

(3) Which country do you live in? (Selection)

(4) I deal with the "Smart Grid" (intelligent energy grid) in my professional or private life. (dichotomous statement)

(5) I have a rough idea of how electricity is generated and distributed in our current power grid. (dichotomous statement)

(6) I am familiar with the term "energy transition" and its meaning is clear to me. (dichotomous statement)

(7) I consider the reduction of fossil energy sources (nuclear power, coal, etc.) to be sensible. (dichotomous statement)

(8) I think it makes sense to cover the majority of the power supply in the future with renewable energy sources (wind-/water power plants, solar plants). (dichotomous statement)

(9) I consider a renewal/adaption of the electricity grid to achieve **ecological** objectives (e.g., reduction of CO_2 emission) to be sensible. (dichotomous statement)

(10) I consider a renewal/adaptation of the electricity grid to achieve **economic** objectives (e.g., integration of new technologies, creation of new business fields) to be sensible. (dichotomous statement)

(11) I consider it desirable to produce the amount of electricity I require myself. (dichotomous statement)

(12) I consider it desirable to generate more electricity than is needed for my own needs and to feed it into the power grid (e.g., by installing more solar panels than necessary to supply myself). (dichotomous statement)

(13) Ecological aspects (e.g., reduction of CO_2 emission) influence the way I use electronic devices. (dichotomous statement)

(14) Economic aspects (e.g., reduction of the electricity costs) influence my usage of electronic devices. (dichotomous statement)

(15) I can imagine supporting the balance of demand and supply in the future energy grid by consuming additional electricity (e.g., by charging an electric vehicle). (dichotomous statement)

(16) I can imagine supporting the balance of demand and supply in the future energy grid by producing additional electricity (e.g., by reducing my local consumption and feeding more locally produced electricity into the grid). (dichotomous statement)

A.1.2 *Questions on the Notification Functionality*

After the initial questions, participants were presented with an exemplary problem scenario and the high-level concept of the PIF. Afterward, the *notification* functionality of the PIF was explained and the following questions and statements were presented.

(1) I consider the distribution of general warnings on civil protection to be useful. (5-point Likert scale)

(2) I prefer the following media for receiving problem and disaster notifications. (Multiple selections)

(3) I am aware that there are smartphone apps that are used to receive disaster control messages. (dichotomous statement)

(4) I am currently using one of the following apps / I have already used one of the following apps. (Multiple selections)

(5) I consider the distribution of warnings about imminent problems regarding the power supply to be useful. (5-point Likert scale)

(6) I consider receiving messages about upcoming power supply problems in my area to be useful. (5-point Likert scale)

(7) I find it sensible to extend existing warning concepts by the possibility to receive problem alerts regarding the power supply. (5-point Likert scale)

(8) Notifications about upcoming problems with the power supply would help me to prepare for them. (5-point Likert scale)

(9) Notifications of power supply problems allow me to mitigate potential consequences, like delays due to incorrect clock time display, or the failure of important equipment like the fridge. (5-point Likert scale)

(10) I consider it reasonable to receive a warning about power supply problems at least this long prior to the problem situation. (Multiple selections)

(11) I consider the following information to be important when warning about imminent problems with the power supply (multiple selection possible). (Multiple selections)

A.1.3 *Questions on the Management Functionality*

After the explanation of the *management* functionalities of the PIF participants were presented the following questions and statements were presented.

(1) I am interested in "smart"devices. (devices with the ability to communicate digitally, which can be integrated into the home network, e.g. via WiFi). (5-point Likert scale)

(2) I can imagine purchasing one or more "smart" devices in the near future. (5-point Likert scale)

(3) Which of the following "smart" devices do you already own (multiple selection possible)? (Multiple selections)

(4) I can imagine purchasing "smart" devices in the future, which communicate with a smart meter (intelligent electricity meter) via my home network. (dichotomous statement)

(5) I consider a digital overview (e.g., with the help of a smartphone) of the power consumption and power production of devices to be useful. (5-point Likert scale)

(6) I consider the digital control of the power consumption of devices to be useful (e.g., switch-off or regulation). (5-point Likert scale)

(7) I consider an assignment of devices to control profiles (e.g., absence profile, time-of-day-dependent profiles) to control several devices simultaneously to be sensible. (5-point Likert scale)

(8) I consider the possibility to compare different control profiles for devices (e.g., regarding the total power consumption) to be useful. (5-point Likert scale)

(9) In the course of a day, the availability of different devices seems to me to be of varying importance (e.g., in the morning, the toaster is more important to me than in the evening). (5-point Likert scale)

(10) Over the course of several days, the availability of different end devices seems to be of varying importance to me (e.g., the washing machine is more important to me on weekends than on working days). (5-point Likert scale)

(11) I consider the classification of end devices into priority classes (representation of the current importance of a device) to be useful. (5-point Likert scale)

(12) I consider the classification of end devices into priority classes to be useful as long as the configuration effort is very low (e.g., monthly configuration effort). (5-point Likert scale)

(13) I find a learning-based procedure for classifying end devices into priority classes useful (based on the use of devices at certain times). (5-point Likert scale)

(14) I prefer a learning-based procedure for classifying end devices into priority classes to manual classification. (5-point Likert scale)

(15) If the general power supply were to be impaired, switching off all end devices in the household would be a great burden. (5-point Likert scale)

(16) If the general power supply were to be impaired, switching off some end devices in the household would be a great burden. (5-point Likert scale)

(17) If the general power supply were to be impaired, I would find it advantageous to be able to use individual high-priority end devices (e.g., stove at 6pm, washing machine at weekends). (5-point Likert scale)

A.1.4 *Questions on the Management Functionality*

After the explanation of the *mitigation* functionalities of the PIF participants were presented the following questions and statements were presented.

(1) I believe that the possibility of prosumers being increasingly involved in the problem mitigation of future energy grids makes sense. (5-point Likert scale)

(2) I can imagine supporting the power grid in its mundane operation by offering flexibilities. (5-point Likert scale)

(3) I can imagine supporting the power grid in an emergency situation by offering flexibilities (impending blackout). (5-point Likert scale)

(4) It is very important to me that my active role in the electricity grid is merely an offer on my part and that I can withdraw the offer regularly (e.g. daily, weekly). (5-point Likert scale)

(5) It is very important to me that I can effectively withdraw my offered flexibilities at any time and with immediate effect. (5-point Likert scale)

(6) The use of my flexibilities to support the electricity grid is only an option for me if I am **profitably** compensated for it. (5-point Likert scale)

(7) I would offer my flexibilities to support the power grid even if I am **not compensated** for it. (5-point Likert scale)

(8) The use of my flexibilities to support the electricity grid is only an option for me if I receive a **fair** compensation for my expenses. (5-point Likert scale)

(9) It is important to me that my offer of flexibilities does **not interfere** with the use of my end devices (e.g., device not usable due to its current use as a flexibility). (5-point Likert scale)

(10) It is important to me that while my offered flexibilities are used, the effective impairment to use my local devices is kept **low**. (5-point Likert scale)

(11) Assigning my flexibilities a time window in which they are available, as well as setting a required amount of compensation for their use are sufficiently fine-grained configuration options. (5-point Likert scale)

(12) Are there any additional settings you would like to make for configuring flexibilities? (dichotomous statement)

(13) In order to prevent a complete power outage, I am willing to accept that certain **low-priority** flexibilities in my household will be switched off by the power grid operator. (5-point Likert scale)

(14) In order to prevent a complete power outage, I am willing to accept that certain **high-priority** flexibilities are switched off by the power grid operator. (5-point Likert scale)

A.1.5 *Final Questions and Statements*

At the end of the survey, the participants were presented the following final questions and statements.

(1) I am afraid that the Energy Assistant will reveal my behavioral habits regarding the use of electronic devices to the network operator. (5-point Likert scale)

(2) I am afraid that unauthorized third parties could be granted access to my end devices by using the Energy Assistant. (5-point Likert scale)

(3) I am willing to accept slightly increased acquisition costs for my end devices for the realization of the Energy Assistant. (5-point Likert scale)

(4) I have the following additional concerns regarding the use of the Energy Assistant in my home. (Free-text)

(5) I consider the **notification features** of the Energy Assistant to be useful. (5-point Likert scale)

(6) I consider the **management features** of the Energy Assistant to be useful. (5-point Likert scale)

(7) I consider the **mitigation features** of the Energy Assistant to be useful. (5-point Likert scale)

(8) Overall, I consider the Energy Assistant to be a useful measure to support the stability of future electricity grids. (5-point Likert scale)

(9) I would be willing to install the Energy Assistant in its presented form in my home. (5-point Likert scale)

(10) Do you have additional comments and concerns about the presented Energy Assistant and its corresponding functionalities? (Free-text)

B

SERIOUS GAME USER STUDY

The serious game prototype presented in this work was evaluated in a user study. In the following, the questions and auxiliary materials used within this study are listed.

B.1 TEXT-BASED INTERVENTION

The following three paragraphs were provided to the group of participants that should increase their knowledge by a text-based intervention. The texts were translated into English from the original German version within the user study.

ENERGY GRID *The colloquial term electricity grid refers to a network for the transmission and distribution of electrical energy. Electricity is transported via electrical lines (so-called power lines) from producers (e.g. power plants) to consumers (e.g. households, businesses), where it is then consumed. On its way from different producers to consumers, electrical energy often has to cover long distances. In order to reduce transmission losses during transport and to connect participants in the electricity grid over long distances, there are four voltage levels in the European interconnected grid. These transport electrical energy at different voltages. The rule is that a higher voltage leads to lower transport losses and thus electricity can be transported over longer distances. The following grid levels are distinguished: extra high, high, medium and low voltage levels. For example, the extra-high voltage level is used to connect large producers such as coal-fired power plants to the grid. The electricity generated is transported over long distances to households by means of extra-high voltage. However, since electricity consumers in households require a lower operating voltage, households are connected to the low-voltage level. Transformers (or substations) are needed to connect the different grid levels with each other and to enable the flow of electricity across different grid levels.*

GRID FREQUENCY *In order to ensure a continuous flow of electricity, it is necessary to produce as much electricity as is needed at any given time. A main indicator for determining deviations between production and consumption in an electricity grid is the grid frequency. If as much electricity is being produced as is currently being consumed, then the grid frequency for the European interconnected grid is 50 Hertz (Hz). If more electricity is produced in the short term than can be consumed at the same time, the grid frequency increases. In the case of increased electricity consumption, on the other hand, the grid frequency decreases. Since consumption and production change constantly, there are deviations of the frequency from the 50Hz. Smaller deviations of short duration are automatically compensated by the grid and have no further consequences. Stronger and longer-lasting deviations lead to the initiation of appropriate countermeasures and, in the worst case, if the grid frequency does not stabilize, can lead to power failures.*

ENERGY TRANSITION *As climate change continues to advance, the electricity grid of the future is facing more and more challenges. Due to the high* CO_2 *pollution from coal-fired power generation, as well as public safety concerns about nuclear power plants, the decision was made in Germany to phase out these types of electricity production within the next few years. In their place, new, climate-friendly producers must step in to close the emerging supply gaps. Wind and solar power plants, which are connected to the low-, medium- and high-voltage grid, are considered the leading representatives. These producers are based on renewable energy sources, but their output is dependent on the current weather and light conditions. Thus, the location, weather conditions and time of day are important factors for electricity production from renewable energy sources. The integration of renewable energy sources at different grid levels results in a change from simple consumers to so-called "prosumers" in the context of the energy transition. Prosumers are former consumers who can generate their own electricity by installing a solar system, for example. An important component for the effective use of these renewable energy sources is energy storage (e.g. batteries). These can be used to store surplus electricity (which is not needed at the moment) and release it back into the grid when needed (e.g. at night).*

B.2 QUESTIONS FOR THE STUDY ON SERIOUS GAMES IN ENERGY GRIDS

In the following, the questions for the knowledge tests for the evaluation of the serious game prototype (Griducate) are presented. Note that these questions were used for the prior, short-term, and long-term knowledge test, but the order of the questions and corresponding answer choices were randomized. Subsequently, the questions for assessing peoples' opinion on the interaction with the interventions are provided.

B.2.1 *Questions for Assessing the Participants' Knowlege about Energy Grid Topics*

(1) How many voltage levels exist in conventional energy grids? (Selection)

(2) What is/are the main reason(s) for operating energy grids using multiple voltage levels (Multiple selections possible)? (Multiple selections)

(3) Which component(s) are essential for transmitting electricity between different voltage levels (Multiple selections possible)? (Multiple selections)

(4) Which voltage levels are typically used to connect renewable energy resources (Multiple selections possible)? (Multiple selection)

(5) Which of the following parameters is a main indicator for determining deviations of the balance between demand and supply of electricity? (Selection)

(6) In addition to the current strength and voltage, the grid frequency is an important aspect in the operation of an electricity grid. What is the optimal grid frequency for the European power grid? (Free-text)

(7) Which of the following statements is true (Multiple selections possible)? (Multiple selection)

(8) What is a prosumer? (Selection)

(9) Name a technology that is essential for securing electricity supply through predominantly renewable energy sources. (Free-text)

(10) Do you have further questions or comments? (Free-text)

B.2.2 *Questions for Assessing the Participants' Opinion on the Serious Game Prototype*

(1) The concept used for conveying knowledge about energy grid topics excites me. (5-point Likert scale)

(2) The concept used for conveying knowledge about energy grid topics motivates me to want to learn more about the topic. (5-point Likert scale)

(3) I think the concept used for conveying knowledge about energy grid topics is suitable for informing people about this topic. (5-point Likert scale)

(4) I enjoyed the interaction with the concept for conveying knowledge about energy grid topics. (5-point Likert scale)

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DECLARATION

I hereby confirm that the submitted thesis with the title "Resilience in Critical Infrastructures" has been done independently and without use of others than the indicated aids. I assure that I have not previously or concurrently applied for the opening of a promotion procedure with the doctoral thesis submitted here.

Darmstadt, 01.09.2021

Rolf Uwe Egert,
01.09.2021