An Approach for Analyzing the Impacts of Smart Grid Topologies on Critical Infrastructure Resilience

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ABSTRACT

The generation and supply of electricity is currently about to undergo a fundamental transition that includes extensive development of smart grids. Smart grids are huge and complex networks consisting of a vast number of devices and entities which are connected with each other. This fact opens new variations of disruption scenarios which can increase the vulnerability of a power distribution network. However, the network topology of a smart grid has significant effects on urban resilience particularly referring to the adequate provision of vital services of critical infrastructures. An elaborated topology of smart grids can increase urban resilience. In this paper, we discuss the role of smart grids, give research impulses for examining diverse smart grid topologies and for evaluating their impacts on urban resilience by using an agent based simulation approach which considers smart grid topology as a model parameter.

Keywords

Smart Grids, Urban Resilience, Agent Based Simulation, Critical Infrastructure Protection, Decision Support.

INTRODUCTION

The deployment of intelligent metering for developing smart grids as a lynchpin for the ongoing Energiewende is speeding up. In the most EU member states the smart meter roll-out has already started. It is expected that almost 72% of the European consumers will have a smart meter for electricity by 2020 (European Commission, 2014). The roll-outs are accompanied by critical public debates which are essentially related to fundamental security worries and the generally noticed increased vulnerability due to undesired manipulations from external parties, see for example (Aloul et. al., 2012; Goel et al., 2015; Mo et al., 2012; Neuman and Tan, 2011). In view of these debates, unfortunately the benefits are not recognized sufficiently and there is still a need for research on the functionalities and the utilization of smart grids w.r.t. critical infrastructure (CI) protection and urban resilience.

In light of this demand, we would like to open up the attention for the urban resilience implications of smart grid topologies. The new possibilities of communication between the customers, grid components, and the grid utilities due to the introduction of smart meters allow to bridge the gap between isolated grid operation procedures and crisis response activities of CI providers and disaster management authorities. Despite the noteworthy efforts in the development of smart grids, the resilience implications of smart grid topologies are still not enough appreciated in practice and research and, therefore, request a more precise observation.

In this paper, we address this request by introducing our progressing development of an agent based decision support approach which should enable to simulate and compare different smart grid topologies, and inter alia reveal not obvious interdependencies between CIs or CI components. Focusing on the German circumstances regarding the technical distribution grid operation and the legal and practical regulations on disaster management, the results should enable assessments of the resulting level of CI service supply in an urban area. Whether the shortage or cut-off is caused by grid instability or infrastructure destruction, the simulations should allow to identify more and less robust smart grid topologies, and to find even new and better ways of managing potential risks of CI service disruptions. A main objective of our research is to obtain an enhanced understanding of how the types of smart grid topologies influence urban resilience which itself may be utilized to support the design and development of robust smart grids in urban areas in Germany.

This paper is structured as follows. First we give a short definition of urban resilience then we shed some light on advanced principles of power outage response activities and equilibrium states. Taking these considerations into account we give a short technically flavored survey on smart grids and highlight certain topological degrees of freedom in the context of urban resilience. Subsequently we describe an agent based approach for simulating CIs or CI components as a tool for assessing urban resilience and supporting decision making. Since the models of agent based simulations may be changed by varying model parameters the aforementioned topological degrees of freedom may be recognized as model parameters.

URBAN RESILIENCE AND CRITICAL INFRASTRUCTURES

There is no prevalent definition of the term "urban resilience" although there are many definition approaches available e.g. (Bhamra et al., 2011; Chelleri, 2012; Leichenko, 2011; Meerow et al., 2016). Meerow et al. (2016) proposed a more inclusive and flexible definition approach which allows an integration of many risk facets and coping mechanisms. In this work, we emphasize the urban resilience aspect of a continuous supply of CI services during crisis situations. CI services such as the supply of electricity, drinking water, and health care provide vital services for the population, thus disruptions or failures of these services are hazardous and can lead to injuries or even losses of life, property damages, social and economic disruptions or environmental degradations (United Nations International Strategy for Disaster Risk Reduction, 2015). Following the basic definition proposed by Meerow et al., we recognize the ability of cities to maintain or rapidly return to a desired level of CI services in the face of disruption scenarios as one important aspect of urban resilience. As mentioned before, our research aims at providing decision support for the development of smart grid topologies. This implies a capability that can also be understood as a mechanism to build resilience. The findings should inter alia enable to technically adapt, change, and quickly transform urban systems.

PRINCIPLES OF POWER OUTAGE RESPONSE ACTIVITIES

Depending on the magnitude, electricity system failures have different effects on the electricity supply and thus on the continuous supply of CI services. Failures with the potential for cut-offs can be generally distinguished between missed load balancing and physical destructions of electrical devices in the grid system. Corresponding to the initial causes of the failures, there are multiple measures available to respond to potential or concrete power outages.

Grid and market based measures are pooled in the so called measure cascade (VDN, 2007; bdew and VKU, 2013; see also the technical norm VDE-AR-N 4140) that, however, does not include measures from potentially affected consumers and disaster management authorities. From the disaster management perspective, the shortage or the cut-off of electricity is the most severe scenario. In such situations it is possible to decouple certain consumers from the grid to ensure grid stability. During this so called load reduction procedure a prioritized electricity supply for critical consumers is ensured which is already applicable in some countries see also (Münzberg et al., 2013). Another possibility is the building of isolated operating islands, where a region is disconnected from a grid to ensure a continuous supply of all or at least some consumers who are situated in the island.

Furthermore, potentially affected CI providers and disaster management authorities also possess capabilities to keep a certain amount of CI services running for a certain time. CI providers usually have coping capacities in the form of enhanced safety storages, larger tanks and emergency back-up generators. In addition, some processes are timely flexible and it is possible to reschedule, extend or delay their realization while keeping the core business of a CI service running – this is also known as process flexibility and load shifting. Furthermore, the disaster management authorities have a very limited amount of mobile emergency generators and other resources that can be used to assist CI providers in keeping their business running.

So far, the response activities of the grid utilities, the CI providers, and the disaster management authorities are not properly concerted, integrated and interlinked. There is research dealing with inter-organizational issues in emergency management during power outages see (Wiedenhöfer et al., 2011; Reuter, 2013).

A basic objective for a better integrated power outage response is the achievement of an equilibrium with regard to the available electricity and the consumers' capability and demand. For an introduction and an overview about equilibria in the context of urban resilience see (Holling, 1996; Meerow et al., 2016).

The optimal equilibrium under normal conditions allows a satisfaction of all electricity requests from all consumers. However, crisis situations are inherently characterized by a loss of system balance. Depending on the request for a stable and safe grid operation, the amount of available electricity, the still available possibilities to distribute electricity, and the customers' capabilities and demands it may be possible to reach other emergency equilibria. These equilibria might disappoint some consumers but allow a - sometimes timely limited - supply of other consumers. This mechanism can be applied to prioritize CI services and keep them supplied during a power shortage situation. Corresponding to the given situation, multiple equilibrium states with different impacts on the population, CI services, and other consumers are imaginable. In the sense of urban resilience, the objective of integrated power outage response activities should be to reach the best possible equilibrium in which the least damage to or restrictions of CI services occur.

An important equilibrium status is defined by the minimum societally accepted and lowest reasonable level of CI services. This equilibrium of "minimum level of CI service supply" ("Mindestversorgung") represents a status in which no risks or further risks occur. It implies a safe shutdown status following a reactive failing-safe principle through maintaining an emergency supply using the available coping capacities. In Germany, there is an ongoing debate about the determination of this status which is methodologically related to the definition of "protection target levels" ("Schutzziele"). Protection target levels mark supply objectives for specific CI facilities or a group of CIs of the same type to ensure basic services. For more information on protection target levels see exemplary (Bundesministerium des Innern 2009, 2011a, 2012; Fekete, 2012; Münzberg et al., 2014, 2017A).

An integrated interlinkage of these measures would expand the possible actions to respond to power outages. We therefore propose the definition of successive safety conditions which represent different escalation scales and imply different measures of grid utilities, CI providers, and disaster management authorities. Figure 1 displays the safety conditions and the effects of responses from distribution grid utilities, CI providers, and authorities.

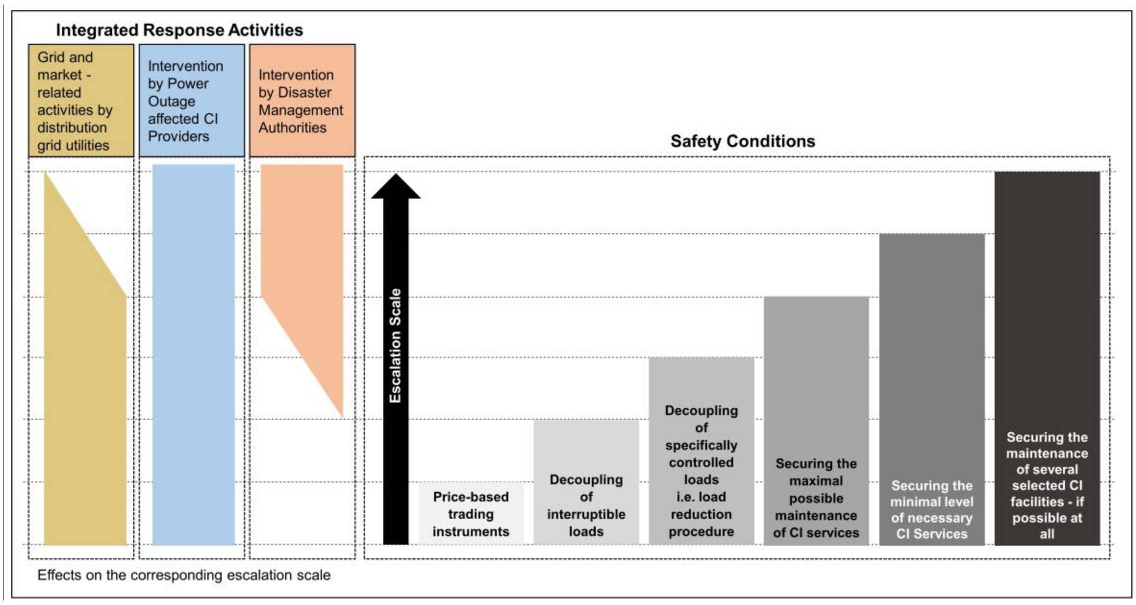

Figure 1. Overview of safety conditions and how integrated response activities of grid utilities, CI providers, and disaster management authorities effect the safety conditions.

The successive safety conditions contain

- price-based trading instruments,
- decoupling of interruptible loads,
- decoupling of specifically controlled loads i.e. load reduction procedure,
- securing the maximum possible maintenance of CI services,
- securing the minimum level of necessary CI Services, and
- securing the maintenance of several selected CI facilities - if possible at all.

Price-based trading instruments are policy and market measures that use economic variables (e.g. markets, price) to provide incentives for market participants to match electricity consumption with generation. It is to be expected that smart meters and dynamic pricing of electricity will play a more important role in the daily usage of electronical devices as today. They will also be used to reduce or eliminate risks in the sense of an enhanced reliable and stable electricity supply. The competence for price-based trading instruments lies within the consumers and the electricity utilities.

In some countries such as Germany, industrial consumers can conclude contracts with electricity utilities which determine interruptible loads. Interruptible loads can be decoupled if it is necessary to stabilize a grid. In return the consumers receive appropriate incentives. Although this measure may be seen as a market-based instrument, it is only used in those emergency situations in which other market-based instruments didn't succeed in stabilizing a grid.

The next escalation step contains a specifically controlled load reduction. As already mentioned, this may include a prioritized and discriminating supply of facilities that provide CI services such as hospitals, dialysis clinics, or general practitioners. If even this measure is not successful, a large-scale power outage would be unavoidable.

In this escalation stage, the objective should be to secure the maximal possible maintenance of CI services considering all available opportunities including smart grid topologies that are introduced in detail in the next section.

The next higher escalation stage is reached if the power distribution grid can only ensure the "minimum level of CI service supply". This case implies a strong system disorder that can no longer be handled by grid utilities alone. Such cases basically require high efforts of the affected CI providers, consumers who rely on CI services, and the disaster management authorities in charge.

The highest escalation stage is achieved if even this is not possible anymore. In such cases of fundamental disorder, the objective is to at least maintain several selected CI facilities if this is possible at all.

Each safety condition inherently considers the limited coping capacity of consumers who rely on CI services. The response activities from grid utilities, CI providers, and authorities contain multiple bundles of measures. They cover different safety conditions with different intensities. The coverage and intensity of the measures are illustrated exemplary in Figure 1 by the thickness of the corresponding effect bars.

SMART GRID STRUCTURES

The generation and supply of electricity is currently about to undergo a fundamental transition. Due to the integration of smart meters, the consumers in the classical sense will have the potential and the eligibility to consume, produce and distribute electricity. The therefore necessary smart meters are electronic devices that monitor electricity consumptions and generations and allow two-way communications with other meters. The usage of smart meters necessitates a power grid technology which allows a bi-directional energy and communication flow and which is equipped with the following key features:

- Decentralization: Individuals are allowed to generate and feed in power.
- Load Balancing: The total sum of produced power might exceed the current load/demand or vice versa. However, to keep a stable electricity supply it is important that in-feed and consumption form a equilibrium.

In order to maintain grid stability, smart grid components handle the aforementioned issues with respect to available resources e.g. power storages or by controlling and managing the demands of the costumers. A more detailed description of a smart grid and its components may be found in (Kabalci, 2016; Muscas et. al., 2015).

If we think about smart grids in the context of cities we are dealing with a huge and complex network consisting of a vast number of devices and entities which are connected with each other. Hence a smart grid must incorporate an Advanced Metering Infrastructure (AMI) that leverages enhanced layers of network technologies i.e.

- Private networks like Home Area Network (HAN), Industrial Area Network (IAN), Building Area Network (BAN), and
- Wide Area Networks (WAN) which comprise Local Area Networks (LAN) like Neighborhood Area Networks (NAN) and Field Area Networks (FAN).

A private network forms a command-and-control layer within a customer's premise which connects sensors and other appliances. A LAN defines an interface between smart meters and distribution substations utilizing gateways and field components. WAN is a network of power utility assets e.g. power plants, substations, distributed storages etc.

A smart grid construed as a distribution grid fundamentally relies on a rigorous Distribution Management

System (DMS) in order to avoid power outages and maintain grid performance. The architecture of a DMS allows a partitioning into several locally arranged and interconnected operation centers which themselves may be considered as local DMSs. A precise and secure operation of an Energy Management System (EMS) of a smart grid heavily depends on the degree of accuracy of the transmitted quantities of interest - so called Concentrators, integrated in LANs, aggregate data from smart meters and relay them to local DMSs.

So far we gained a rough impression of the massive complexity of a smart grid in terms of network layers and components. On the one hand the two-way communication and power flow architecture opens new possibilities like integrating and controlling distributed power generation and supply resp. on the other hand such a heterogeneous and complex network increases vulnerability of the energy system which is clearly comprehensible by the following example:

Corrupted data - as depicted in the following paragraph - sent by a concentrator to a DMS, e.g. over- or underestimated voltage profiles, might erroneously cause the EMS ask for more or less power production or supply respectively. This could potentially lead to further unwanted cascading effects within the distribution grid escalating into power outage.

Smart grid instabilities may be caused by system induced failures. Referring (Aloul et. al., 2012), many components of a smart grid are located not on the utility's premise and are therefore prone to physical damage. Since IT systems are relatively short lived it is quite likely that outdated devices are still in service e.g. anti-virus software may be deprecated or hardware components may not comply with the latest requirements. Furthermore, the great number of devices are potential entry points for malicious cyberattacks like,

- malware spreading which may infect smart meters or other devices and can add or replace functions and disseminates,
- injecting false information by faking sensitive smart meter that can cause wrong decisions, and
- Denial-of-Service attacks by manipulating IP protocols that can delay, block or corrupt the transmission of information in order to make smart grid resources unavailable.

The rationale for designing a smart grid is to consider it as a union of interconnected micro grids which may be disconnected from the smart grid and operate autonomously in island mode (Bower et. al., 2014). Analogously to a smart grid a micro grid also consists of the same structural components as a smart grid. A smart grid subdivided into micro grids has the potential to restrict cascading effects and hence to be less vulnerable against disruptions. Cascading effects due to dysfunctionalities of certain components or propagation of malware throughout a smart grid might be prevented by disconnecting the affected micro grids from an overall smart grid. Although having isolated dysfunctional micro grids from the smart grid of a city, CI interdependencies may cause issues in other parts and reduce the resilience of the city as a whole.

Today, there are first practical concepts and schematic framework definitions available how to deploy micro grids to serve electricity to local CI providers e.g. (Jung et al., 2016; New York State Energy Research and Development Authority et al., 2014).

Referring to the previous section on power outage response activities the EMS or DMS of a smart or a micro grid should focus on the maintenance of CI services. The topology of a smart grid in the sense of the preceding paragraphs has a massive influence on the possibilities of how an EMS makes decisions for example if it seeks for certain equilibrium states. Therefore an EMS should also take into account the implemented and available coping capacities of the CI services and the disaster management authorities. The objectives in this escalation stage should be to secure the maximal possible maintenance of CI services.

This motivates the following question Figure 2:

A) What are optimal micro grid configurations for a city in the sense of maximum urban resilience?

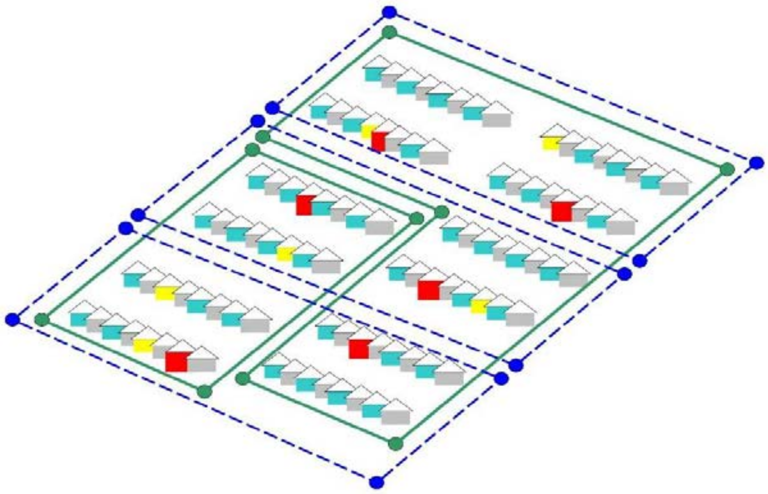

Figure 2. A city contains of multiple buildings. Red and yellow colored buildings indicate different CI types in some segments of a city, where varying sizes imply varying levels of importance of the CI type. The union of green framed and the union of blue framed areas subdividing this urban segment represent two different versions of micro grid installations resp.

Another aspect of grid design is the topology of LANs - number and configuration of components like concentrators, overlaying network structures to provide redundancies - may have an effect on vulnerability.

This further topological degree of freedom implies the following question Figure 3:

B) What are optimal configurations of components e.g. concentrators or intelligent knots in general within a smart/micro grid in the sense of maximum urban resilience?

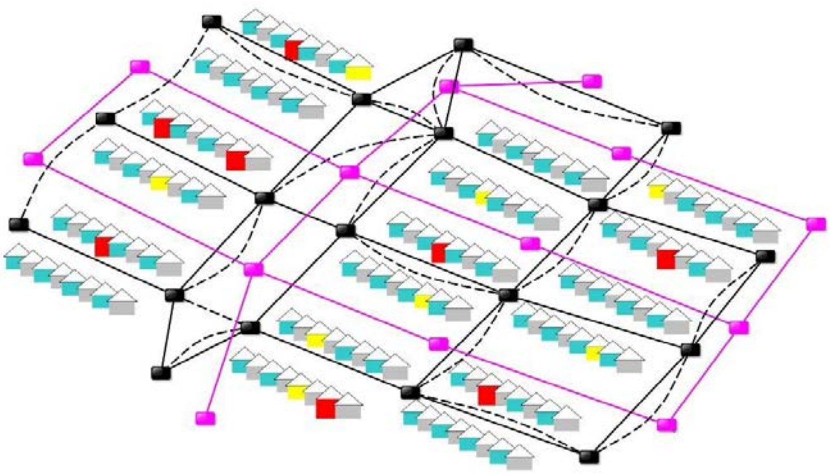

Figure 3. Red and yellow colored buildings indicate different CI types in some segments of a city, where varying sizes imply varying levels of importance of the CI type. Black and pink knots representing intelligent knots belong to different networks. There are three different networks: Two black networks - continuous and dotted edges -, the pink network.

AGENT BASED SIMULATION OF CRITICAL INFRASTRUCTURES

Models such as Aspen by Sandia national lab, SMART by Argonne national lab, and CIMS have demonstrated that agent based simulation is an appropriate method for assessing CI interdependencies and CI disruption impacts - for a review see (Ouyang, 2014; Pederson et al., 2006). The agent based approach seems to be very promising for addressing the questions A) and B) which we posed in the previous section.

The key idea of the agent based approach under consideration is to represent urban CI entities like hospitals, pharmacies or components of CIs e.g. smart grid components by appropriate software agents, where an agent is located in some environment and is able to behave in an autonomous manner according to a specific set of predefined rules. Based on practical experiences, the distribution of responsibilities and the power of decision making, and the legal perspective, this focus is highly beneficial for end-users in the light of specific spatial-temporal circumstances due to a disruption taking into account concrete characteristics of CI entities in the considered urban region e.g. CI type, size, location, implemented coping capacities, interdependencies. This approach enables to identify appropriate counter measures that are specifically tailored to the circumstances of the considered urban area.

Agent modelling of a city's local CI entities/components considered as service providers, e.g. water supply networks, hospitals or smart/micro grid components requires a fundamental grasp on

- internal processes in order to gain a notion of how the state of an agent or a concrete CI facility like a hospital or a pharmacy depends on external factors,
- the way how they are physically embedded into the environment and virtually attached to cyber-, communication- and information networks, and
- the types of services that are offered.

Dysfunctionalities of such entities caused by natural disasters or malicious attacks may have a massive impact on vital services and trigger some sort of crisis management. Depending on the type, massiveness, duration of disruptions and the types of involved CIs or CI components the following possible crisis management patterns are thinkable:

- CI entities belonging to the same type may organize themselves locally in groups pursuing an optimal provision of services following a prioritized list of tasks which should be fulfilled. This procedure seems to be an effective way of targeted communication with external groups of the same entity type or a crisis management group as well as realization of concrete measures.
- Within these groups negotiations may lead to solutions pursuing protection target levels or equilibrium states such as the minimum level of supply.
- A crisis management group collecting information from various CI owners and stake holders can assess the city's state and in case of depleted coping capacities of CIs decide to intervene by applying certain counter measures.
- If we think about enhanced installations of smart grids, certain counter measures may be triggered automatically by *real-world* agents without involving human decision making processes by self-healing capacities see for example (Deconinck et al., 2008, 2010; Rigole et al., 2008), where these *real-world* agents are included into our model as agents representing CI components.

The agent's behavior based on accessible environmental or internal status data e.g. degree of availability of important resources like electricity or power etc. is endowed with crisis management capabilities in the above sense. The way crisis management or negotiations is performed can be parametrized which itself may serve as decision support for response during a crisis. CIs from all sectors are successively included into the model according to a prioritized list. The first maturity level of the model focuses on the implementation of electricity supply, water supply, and entities of the health sector such as hospitals, pharmacies, GPs, etc.

A generic tool for specifying disruption scenarios, interpreted as the temporarily lasting failure of services provided by CIs or CI components represented as agents, is a crucial part of the simulation framework.

Having setup a simulation framework which complies with the paradigm of agent based modelling in the aforementioned sense plausible disruption scenarios e.g. a local six hours lasting power outage may be simulated and resilience of certain CIs or the city as a whole may be assessed (for more insights of our previous work also see Münzberg et al., 2017A; Raskob et al., 2015A, 2015B).

An application that allows the assessment of resilience of cities serves as a suitable tool for decision support for crisis managers as well as urban planners if it offers the opportunity to vary model related parameters like CIs' response activities, negotiation patterns, crisis management, determinations of protection targets or the design of CIs.

Certain entity types - water supply, hospitals, pharmacies, and dialysis clinics - of the city of Karlsruhe, Germany, were preliminarily modelled as agents using the REPAST agent framework in eclipse Figure 4

Figure 4. An agent based realization of some critical infrastructures of the city of Karlsruhe. The different icons indicate water supply, hospitals, pharmacies, and dialysis clinics. The green and blue bars indicate the state of the power respectively water supply of the according structure for the considered point in time of the simulation.

Much work has to be done concerning building adequate agent models and their validation. We have already realized expert workshops (see Münzberg et al. 2017B), but we are also accompanied by CI providers and practitioners to ensure validity of our models and end-user orientation.

SMART GRID TOPOLOGY CONSIDERED AS MODEL PARAMETER - RESILIENCE ASSESSMENT AND DECISION SUPPORT

In the section on smart grids we shed some light on possible design options for smart grids in an urban context:

- subdividing a smart grid into interconnected micro grids which may be isolated from the overall network
- configurations of intelligent knots in local networks.

These topological degrees of freedom can be considered as model parameters which also may be varied i.e. changing parameters means changing the smart grid topology.

Power outages in cities which utilizes complex smart grid technologies with a high degree of connectivity of CIs or CI components of different types may expose new or rather unexpected interdependencies of CIs.

A simulation framework based on agent based modelling as depicted in the previous section may enable decision makers, urban planners or power providers to find optimal solutions for enrolling or enhancing smart grid technology in the sense of robustness.

In the light of the two resilience related questions A) and B) in the section on smart grids many smart grid instances may be tested against a vast number of disruption scenarios, e.g. cyberattacks on smart grid components.

Referring to question A) in the section on smart grid structures the following simulation type is proposed: CIs of varying importance and relevance are distributed over an urban area. Different arrangements of micro grids can be taken into consideration where CIs of one type can be located in different micro grids depending on their importance, e.g. one micro grid shouldn't accommodate too many of the biggest and most significant hospitals in the city; it seems to be more sensible to have them in different micro grids. The EMS might enforce the disconnection of certain micro grids from the overall network in case of failure of crucial components in order to protect CIs and reach certain protection target levels.

Referring to question B) in the section on smart grid structures the following simulation type is proposed: Certain redundancies may be tested in the sense of overlaying network structures. Certain CIs should not only depend on just one connected local network - i.e. failures in parts of one local network wouldn't imply an interruption of the power provision of the CIs since other undisrupted parts of the micro grid to which the CIs are also connected are still able to deliver power.

With the help of systematic studies of urban resilience related quantities by combining the aforementioned simulation types smart grid topologies which are adverse may be identified but also those which are optimal in the sense of robustness or urban resilience Figure 5 - comparing different topologies against certain disruption scenarios resilience related quantities which apply the maximum achieved safety condition see Figure 1 may be taken into account.

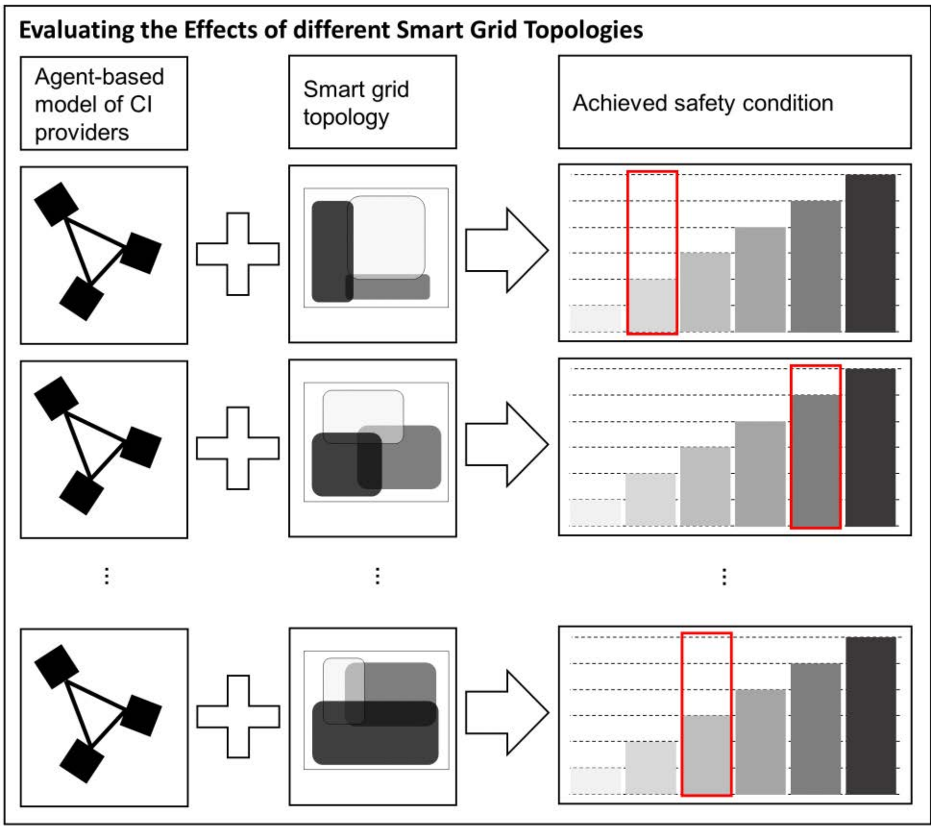

Figure 5. Resilience assessment of smart grid topologies against disruption scenarios via agent based simulations.

Best robustness results can further be evaluated against cost efficiency aspects to find optimal smart grid solutions.

CONCLUSION

Modern smart grid technologies are based on a high degree of connectivity and automation in order to integrate a vast number of distributed energy resources in a reliable way. In the light of CIP such complex networks bear the potential of increased vulnerability if the EMS and DMS are not adequately prepared. This work emphasizes the massive impact of smart grid topologies on urban resilience referring to the adequate provision of CI services.

Our agent based simulation approach, where CIs and CI components are modelled as agents embedded into an environment and virtually attached to cyber-, communication- or information networks, also includes the ability to define various disruption scenarios.

Although agent based modelling relies on a great quantity of input data it gives many opportunities to evaluate and develop resilience improvement strategies (Ouyang, 2014), and among others a major property is scalability i.e. new CIs or CI components may be successively modelled, and included into the environment or any network.

As described in this work our ongoing research aims to interpret the topological degrees of freedom for designing a smart grid as model parameters which may be changed to realize different smart grid topologies which themselves are studied against various disruption scenarios.

By assessing different CI dependent smart grid topologies and enhanced EMSs pursuing certain protection target levels we may identify those which are adverse but also those which are optimal in the sense of robustness or urban resilience.

It would be interesting to compare our analytical findings and modelling approach with the results of system dynamic approaches like those of (Canzani, 2016; Laugé et al., 2015) and other interaction models like those of (Turoff et al., 2014) resp.

A main objective of our ongoing research is to establish a software tool based on agent based modelling which supports decision making during a crisis as well as facilitates city planners or CI owners to design or redesign future or existing CIs e.g. smart grids.

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