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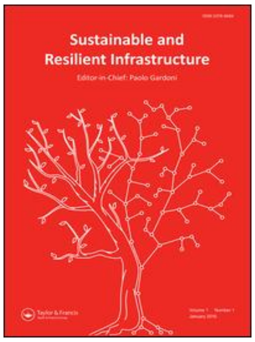

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Energy resilience through self-organization during widespread power outages

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ABSTRACT
Resilience of power systems is highly impacted by factors such as increasing severity and frequency of weather events, but also smart grid advances that introduce major operational changes in power systems. Rapidly adapting to these changing circumstances and harnessing the potential of technological advances is the key to ensuring that power systems stay operational during disturbances, thereby improving resilience. This paper addresses this challenge by presenting an approach for improving resilience through local energy resource sharing across multiple distribution systems. The approach brings together the physical and the ICT layer of power systems through a self-organization approach that automatically alters the physical grid topology and forms local energy groups in order to mitigate the effects of widespread outages. Thereby, supply and demand are locally matched, and demand met is maximized during an outage. The results demonstrate that using the proposed approach, operational resilience of impacted distribution systems is improved.

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Energy resilience; self-organization; decentralized coordination; power outages

1. Introduction

Power systems are faced with many uncertainties that can severely impact their operation. These uncertainties are caused by factors such as increased penetration of renewable resources that require more complex measures such as load shifting, load and generation forecasting and dynamic pricing, but also by an increase in extreme weather events caused by climate change, as well as challenges due to the increased complexity of power systems (Jordehi, 2018). Combined, these factors can severely impact power systems on various levels (Panteli & Mancarella, 2015b). Failure of and damage to these critical infrastructures have a negative impact on society, especially in cases of widespread outages. Widespread outages negatively impact everyday lives of people and infrastructures relying on electricity, potentially causing more than just an inconvenience in today's electricity-driven world.

As other critical infrastructures (communication, transportation, health services, etc.) on which modern society relies, depend on the availability of the electrical grid, the impact of blackouts extends beyond the power system itself. Due to this interdependence between infrastructural systems, it is crucial to make infrastructures not only more robust but also more resilient (Arghandeh et al., 2014). Even though the definitions of resilience are many, it is generally accepted that a resilient system is able to quickly recover from an external shock, adapting to new circumstances so that it provides a (sufficient) level of operation (Gasser et al., 2019; Gillespie-marthaler et al., 2018). Furthermore, a resilient system should quickly bounce back to its normal operating state and adapt to be better prepared to future catastrophic events (Arghandeh et al., 2016; Panteli et al., 2017a). The Multidisciplinary Center for Earthquake Engineering Research extends this definition to include the role of social units in mitigating disasters by carrying out activities that minimize the impact of disruptions (Bruneau et al., 2003). Boosting the resilience of critical infrastructure depends on the type of infrastructure itself, available resources, but also social components of a system (e.g., resource owners).

Another challenge that amplifies system vulnerability arises due to technological advancements and rapidly changing roles of end-consumers of these systems. In the case of power systems, this is reflected through an increase in distributed energy resources (DER) (solar panels, storage, wind turbines), typically locally owned by end-consumers. Due to the volatile nature of renewables, power systems could face even more disturbances at different scales. With the complexity of these systems increased, as well as potential infrastructure failures and information unavailability during widespread outages, centralized coordination of power systems (including generation, dispatch, and control) becomes challenging which has led to the exploration of new decentralized approaches to power system analysis and control (Joshi & Pindoriya, 2018).

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A potential solution to achieve an improved level of operation during disturbances is to harness the power of smart ICT technologies and locally owned resources, and shift the coordination from a central unit to distributed units within power systems (Panteli & Mancarella, 2015a). Decentralization mechanisms can be used to let not only consumers, prosumers and producers take independent decisions, but also the grid itself. This paper addresses this challenge from both perspectives by bringing together the physical and the ICT layer of power systems in a self-organizing approach for decentralized coordination of local energy resources in changing distribution system topologies with the aim of improving power system resilience.

By sharing resources during disturbances, normal operation can be (to an extent) restored in an impacted area. For this purpose, both social and technological components are crucial; (1) resource owners have to be willing to share their resources, and (2) mechanisms that facilitate resource sharing have to be installed. The potential impact of emergent local energy groups is explored in this paper, in combination with a self-organizing grid on improving resilience of areas affected by rapid-onset events.

The remainder of this paper is organized as follows: Section 2 further explains the concept of resilience w.r.t. power systems, while Section 3 presents the proposed approach for ensuring resilience based on self-organization. Section 4 demonstrates the application of the proposed approach through a case study w.r.t. resilience assessment. Section 5 discusses the results and potential applications of the mechanisms, and Section 6 concludes the paper.

2. Resilience of power systems

As discussed previously, many critical infrastructures on which modern society relies, depend on reliable electricity supply and predictable operation of power systems. As they can be severely impacted by uncertainties that cause outages of different scales, it is crucial to make them more resilient. Technological advances such as novel ICT infrastructures integrated within power systems, smart meters, social and operational changes related to an increased penetration of renewables, etc., pose new challenges for power system operation, but also open new possibilities to deal with uncertainties and improve the resilience of these systems. Power systems are vulnerable to these uncertainties and will require a shift in their operation to deal with them (Gasser et al., 2019).

Traditional approaches to make power systems more resilient include hardening solutions that boost the infrastructure resilience (e.g. adding new lines, moving the cables underground, etc.), but also smart operational solutions such as defensive islanding, that provide preventive and corrective operational flexibility in dealing with disruptions (Panteli et al., 2017b). Hardening enhances the physical resilience of infrastructure against an external shock, and aims to reduce the physical impact on the grid (Panteli et al., 2017b). Operational measures aim at enhancing operational resilience, making use of the flexibility of available technologies in power systems to effectively deal with a disturbance. The potential of DERs can be used to enhance system resilience. Using these resources, energy can be supplied locally, without relying on a backbone grid that can be affected by a disruption for a longer period of time (Panteli et al., 2017b). The potential of DERs is exploited through installation of microgrids, that can island and operate independently during periods of disruptions. Multiple islanded microgrids that are in geographic vicinity of each other can merge to form a microgrid cluster and gain additional flexibility for resilient operations (Chanda et al., 2016; Gabbar & Zidan, 2016; Li et al., 2017b). Another concept related to the integration of DERs are virtual power plants (VPPs) that aggregate multiple types of generation resources to jointly participate on the electricity market (Asmus, 2010). As VPPs rely on collaboration of different stakeholders, they inherently incorporate the ability to dynamically adapt to different circumstances (e.g., various stakeholder goals). Their potential to dynamically re-organize can be used to build resilient collaborative VPP architectures (Adu-Kankam & Camarinha-Matos, 2018).

Concepts such as microgrids have a fixed geographic location and cannot adapt to changing circumstances in real-time. Thus, a mechanism that allows more flexibility to respond to changes is needed. Furthermore, to mitigate the potential effects of central coordination during outages (such as single point of failure that can propagate widespread outages), decentralized coordination during disturbances can improve system resilience.

The combination of traditional control operations with novel ICT technologies and DERs opens up new possibilities to make power systems more resilient in case of widespread blackouts. Locally owned DERs have the potential to mitigate the effects of small- and large-scale outages by providing electricity to affected consumers and prosumers. It is estimated that 90% of the consumer outages are related to distribution systems (DSs), the most vulnerable parts of the network (Arghandeh et al., 2016; Office & August, 2013). These outages can affect a single DS, or spread to multiple DSs. When multiple distribution systems are affected, a control operation called distribution system reconfiguration (DSR) can be used to alter the topology of power systems by opening and closing the switches that connect different DSs. Under normal operating conditions (i.e. no outages), DSR is performed periodically to achieve objectives such as minimum loss, voltage control, etc. (Rao et al., 2013). During outages, however, reconfiguration is an event-based activity and is invoked to provide the emergency restorative supply to the unserved demand until the fault is repaired (Li et al., 2017a).

In general, reconfiguration is performed by the central grid operator. However, in a widespread outage, the reach of the central grid operator is limited. This can be because of physical component failure or loss of ICT which may cause islanded grid operations. Thus, there is a need for decentralized reconfiguration that can withstand multiple failures and still perform reliable operation under outage conditions. DSR plays an important role in maximizing system resilience as it supports load restoration in an event of a widespread outage and optimizes local energy sharing between load and generation.

Most approaches from literature that focus on the resilience of power systems consider the power system itself as given. The resilience of a power system is consequently assessed under various circumstances, for example, by changing loads, thereby ‘stress testing’ the power system. In contrast, in this paper, the power system is not assumed as given, but rather aims to improve the resilience of power systems by proposing an intervention in a form of a decentralized coordination mechanism based on self-organization.

3. Energy resilience through self-organization

An agent-based mechanism is proposed that brings together the physical layer and the ICT layer of power systems in an approach for decentralized coordination based on self-organization. The approach automatically directs both the physical topology of the grid and changes in supply and demand of individual consumers and prosumers. At the physical layer, the topology of affected DSs is changed by performing distribution system reconfiguration. Given the changed topology, supply and demand are matched at the ICT layer to form local, self-sufficient energy groups. As centralized coordination is challenging during outages, both operations are performed in a decentralized way. In that way, multi-level self-organization is achieved (both at the grid level and the level of consumers and prosumers).

Decentralized coordination on both of the layers is achieved using different types of autonomous agents. Here, an agent is a piece of software that has local information and is able to share this information with other agents on different layers and perform autonomous actions based on their own and aggregated information. The presented approach does not use traditional optimization methods to perform either the group formation or the distribution system reconfiguration, but relies on self-organization using an agent-based approach based on decentralized message exchanges.

At the ICT layer consumer and prosumer agents (C/PAs) are installed at consumers’ or prosumers’ ends and have information about their demand and/or supply profile. C/PAs are assumed to have perfect information about production and demand. In practice, this can be approximated for the near future using forecasting techniques (Park et al., 1991; Suganthi & Samuel, 2012). C/PAs share this information with agents on the physical layer (to alter the topology) and with each other (to locally match supply and demand). By doing so, they organize themselves (*self-organize*) into energy groups that locally minimize S/D mismatch and maximize demand met. The groups have to abide by the laws of the physical grid, which is ensured by bi-directional communication with agents from the physical grid.

At the physical layer, two types of agents are distinguished: a bus agent (BA) and a coordinator agent (CA). These agents are located beside physical grid components, and perform power flow calculations and system reconfiguration. BAs represent network buses and gather information about net supply and demand of consumers and prosumers connected to their representative bus. They obtain this information by communicating with C/PAs located on those buses. CAs coordinate with BAs to gather information of distribution system parameters such as losses, switch status, energy utilization, etc. and initiate the process of DS reconfiguration. This way, centralized coordination is eliminated and the grid is able to reconfigure itself (*self-organize*).

Figure 1 illustrates the proposed approach: once an outage that affects multiple distribution systems occurs, the C/PAs from the ICT layer start sharing the information about supply and demand profiles with BAs on the physical layer. BAs aggregate this information to compute the net generation/demand of the bus.

Using this information, BAs exchange messages with connected neighboring BAs to compute partial power flow solution. The CA collects the information on loss and utilization from power flow solution of all scenarios that reflect different topologies of grid connection and determines the optimal solution to the reconfiguration. CA issues signal to all BAs to enact the optimal topology. The concerned BAs initiate signals to the switches if their status has to be changed (open or close) as per CA’s optimal scenario, and the topologies are changed.

Once the agents on the physical layer change the topologies of DSs, C/PAs find other C/PAs connected on the physical layer and share supply/demand profiles with them. Agents with the best matching profiles (minimum S/D mismatch) form local energy groups

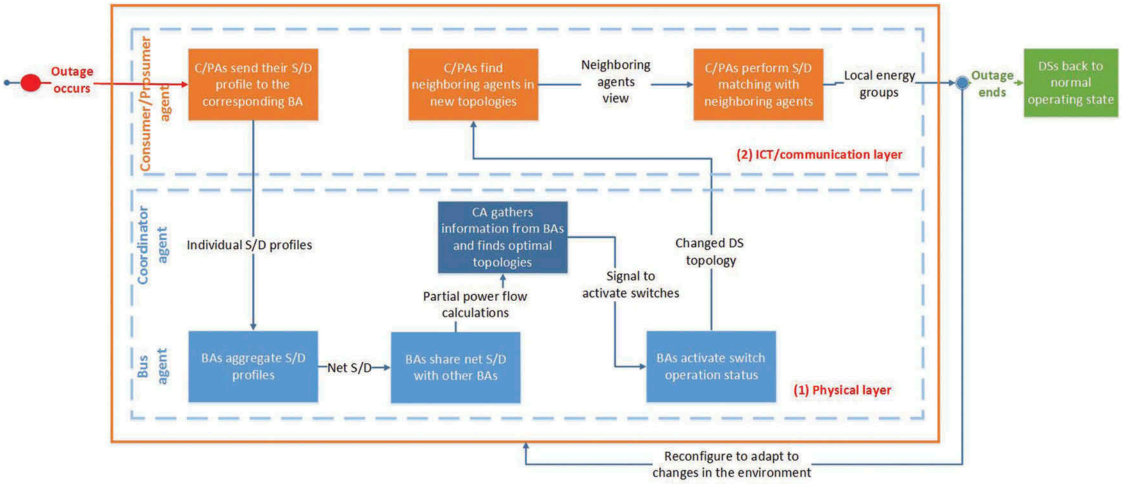


Figure 1. An approach for ensuring energy resilience.

that ensure energy resilience for their members. These groups are virtual and not necessarily geographically co-located. However, they do use the existing physical infrastructure to perform energy sharing, and thus need to be part of the same distribution system or connected to other distribution systems via the grid. As the proposed approach is used to ensure resilience, the entire process is dynamic, so that both the grid and the formed groups can dynamically reconfigure to be able to quickly respond and adapt to changes in the environment. In such a way, if supply and demand fluctuate, DS topologies can change and new energy groups are formed to minimize the mismatch. Finally, once an outage terminates and the backbone grid is restored, affected distribution systems return to their normal operating state, with original topologies, and the formed energy groups cease to exist.

Subsections 3.1 and 3.2 explain both the decentralized DSR and supply and demand matching process in more detail. Subsection 3.3 describes the metrics used to assess the achieved resilience.

3.1. *Self-organizing grid (Physical layer)*

As distribution systems are changing due to technological and social changes introduced with smart grids, the conventional way of DS operation and analysis is challenged (Joshi & Pindoriya, 2018; Lipari et al., 2018). To support these changes from the grid perspective, the grid itself can be given a means to perform traditional operational measures such as network reconfiguration in a decentralized fashion, eliminating the single point of failure. A fault tolerant decentralized reconfiguration mechanism proposed in (Nord- man & Lehtonen, 2005; Saxena & Abhyankar, 2018) is extended to provide the means for self-organization with minimum loss and maximum utilization of local resources given power flow considerations.

Two agents are distinguished, i.e., a Bus Agent (BA) and a Coordinator Agent (CA). A CA coordinates with the substation buses' BAs to gather information of individual DS's parameters such as losses, switch status, energy utilization, etc. In addition, the BA continuously monitors its representative bus and stores all associated parametric attributes. Parameters P and Q (active and reactive power) are collected from the consumer and prosumer agents located at i^{th} bus. Figure 2 shows a diagram of the decentralized distribution system reconfiguration process. Once an outage occurs, BAs collect supply and demand profiles from C/PAs representing consumers and prosumers connected to their representative buses and compute the net S/D at the bus. This information, along with other network parameters is aggregated by the CA, which uses this information to formulate different topology scenarios. For each considered scenario, the CA directs the substations BAs to compute distributed power flow and losses of their respective DS. BAs compute the distribute power flow using forward backward sweep behavior (Saxena & Abhyankar, 2017).

$$I_{inj,BA_i} = \frac{P_{BA_i} - jQ_{BA_i}}{V^*_{BA_i}} \tag{1}$$

$$V_{BA_i} = V_{BA_{i+1}} + I_{BA_{i+1}} * Z_{BA_{i+1}} \tag{2}$$

$$I_{BA_i} = I_{inj,BA_i} + I_{BA_{i+1}} \tag{3}$$

$$loss_{BA_i} = I^2_{BAi} * R_{BA_{i+1}} \tag{4}$$

$$Demand_{BA_i} = Util_{BA_{i-1}} + x_{i,3} \tag{5}$$

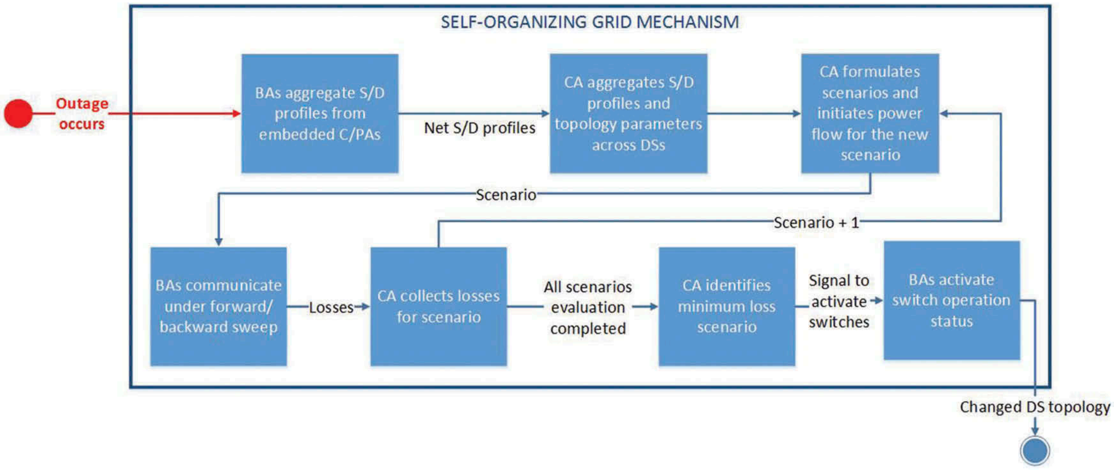


Figure 2. Decentralized DS reconfiguration algorithm.

Here, V and I are voltage and current to be computed where give Z is the impedance, R is resistance, and $x_{i,3}$ is the active power demand. Each BA_i computes the bus voltage V_{BAi}, partial system losses $loss_{BAi}$ and partial demand $Demand_{BAi}$ using (1)–(5). At substation BA, power flow convergence is checked using (6). If the power flow does not converge, a forward sweep is initiated and proportional voltages are computed using (7). If the power converges, then the computed losses and net demand by DS is sent to CA.

$$\gamma = \frac{V_S}{V_1} \tag{6}$$

$$V_{BAi} = \gamma * V_{BAi} \tag{7}$$

A CA coordinates with all the substation BAs to gather information of system losses and energy withdrawn by substation under all considered scenarios. From the pool of possible reconfiguration scenarios, the CA selects the one with the minimum loss and maximum utilization of resources as the optimal scenario. Then, messages are issued to the respective BAs to operate the switches. The advantage of self-organizing, decentralized DSR is that the neighboring agents can automatically provide the functionality of the failed agent without central coordination, as discussed in (Saxena & Abhyankar, 2018). The implementation of an optimization method for distributed DS reconfiguration is considered to be out of scope and left for future research.

3.2. Self-organized energy-sharing (ICT layer)

The self-organizing energy approach extends the principles of decentralized supply and demand matching proposed earlier in (Čaušević et al., 2019) to steer the actions of C/P agents on the ICT layer. As opposed to the original work, the proposed mechanism is used without consumer prioritization. The mechanism is dynamic, adapting to the changes in the environment (e.g. hourly fluctuations in supply and demand) by reconfiguring groups to better match changing energy demands. Groups reconfigure hourly, based on their own supply and/or demand and obtained information on local supply and demand in the system.

During an outage, prosumers first meet their own demand, and then distribute the leftover supply to other affected members. Instrumental to the mechanism is that local resource owners in impacted distribution systems are willing to share their resources. It is assumed that once an outage occurs, resource sharing is instantaneous. Thus, there is no time delay that affects resilience of the system.

Figure 3 shows a diagram of the supply and demand matching mechanism performed at the ICT layer. The system is designed in such a way that each consumer and prosumer has a device on which a stand-alone piece of software is installed. The software is an intelligent agent that has local information about its owner's geographic location and its supply and demand (e.g., daily load and production profile or their forecasts), and can exchange that information with other agents in the system. During an outage, agents use a distributed information exchange algorithm (e.g., gossiping) to find other neighboring agents in the same DS. In the next step, agents exchange information about their supply and demand with their neighbors. Information is exchanged in the form of messages that contain each agent's S/D profile and the mismatch calculation between the sending and receiving agent. Mismatches are calculated as in (Čaušević et al., 2019), including the amount and the number of hours of overproduction and underproduction. Agents then send requests to join the

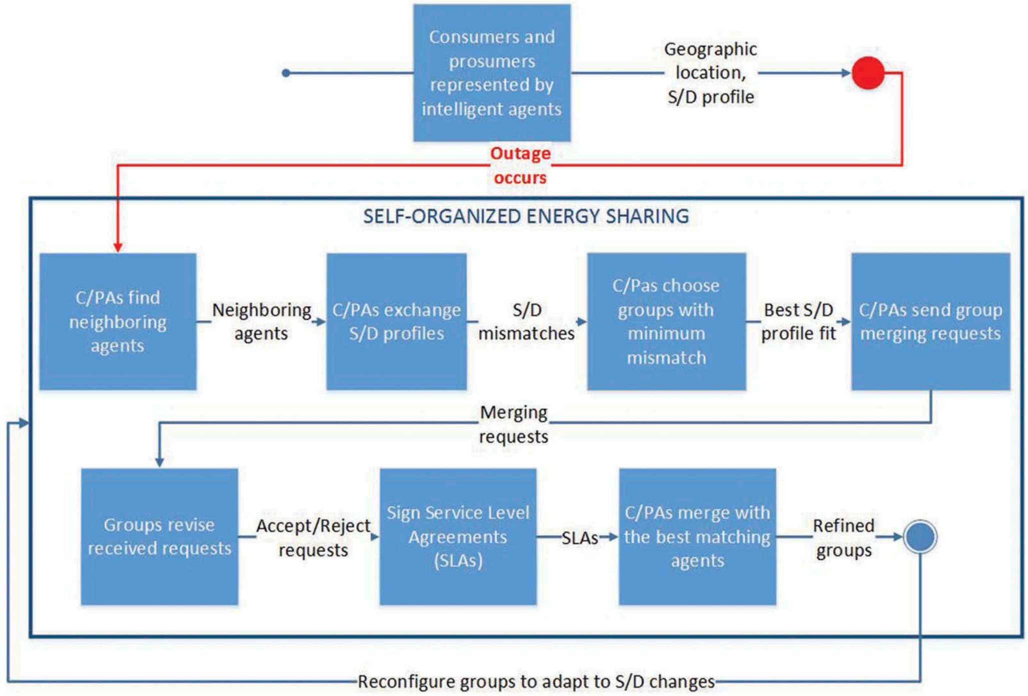


Figure 3. Distributed energy-sharing algorithm.

(Adapted from (Čaušević et al., 2019)). Under the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/))

agents whose profiles best match theirs in terms of minimum mismatch. As each agent has a list of calculated mismatches, and all the exchange is performed in a decentralized manner, no traditional optimization methods are necessary to perform the selection. Once the requests are sent, the receiving agents accept the best-matching requests (using the same minimization approach, and with respect to the amount of their overproduction), and the groups are formed. The groups merge so that the demand is best met. As the system is dynamic, the groups reconfigure if there are changes in supply and demand to adapt to the new environment. Group reconfiguration is performed on an hourly basis, as the load and production profiles are hourly.

3.3. Resilience metrics

Measuring the improvement of power system resilience requires metrics designed to this purpose. Most studies on resilience use the so-called *resilience triangle* (Tierney & Bruneau, 2007) as the main measure of resilience. This triangle depicts the loss of functionality of a component or a system from and during a damage. Figure 4 depicts a typical resilience triangle, where a fully functioning system fails to operate at time t_{oe} (e.g., due to a weather event), and continues to recover throughout the event, regaining is full functionality at the end of disruption (t_{ee}). The area of the created triangle indicates the resilience of an impacted system. The smaller the area, the more resilient a system is. Thus, resilience-boosting measures aim at reducing the area of the triangle. Variations of the resilience triangle are used, one of them being the *resilience trapezoid*, proposed in (Panteli & Mancarella, 2015c), that gives more insight into rapidity of component failure and recovery. Two main concepts are assessed: operational and infrastructure resilience (Panteli & Mancarella, 2015c). The operational resilience metric assesses operational performance of a system under disturbance through parameters such as the amount of generation capacity available during a disturbance.

With more consumers becoming prosumers that have more local control, local resource owners become directly involved in a system's operational resilience. The concept of operational resilience is used to capture the effect of a disturbance on impacted consumers and prosumers. Here, the operational resilience is captured using three metrics:

(1) Demand met (DM) – This metric assesses how much demand is met during the disturbance, given that resource owners share available energy resources. The aggregate demand met for all the consumers and prosumers is calculated, per hour of an outage. An aggregate of the demand met for the duration of the event is calculated (DM_{agg}).

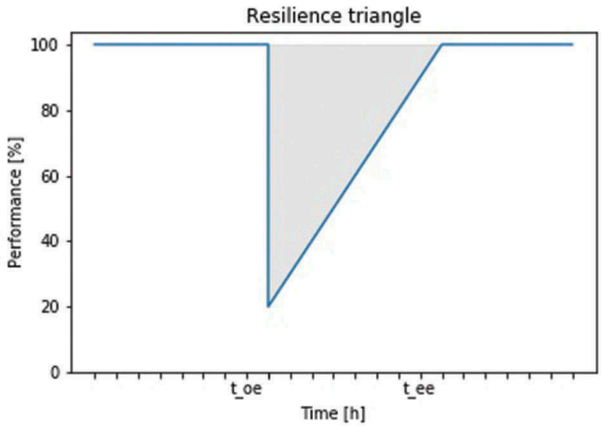


Figure 4. Resilience triangle. (Aadapted from (Panteli et al., 2017a)). Under IEEE license number 4673051363436

(2) Consumers served (CS) – This metric assesses the percentage of consumers and prosumers whose demand is fully met during the disturbance period, per hour of the outage.

(3) Resilience area (RA) – This metric calculates the area of the resilience triangle (Tierney & Bruneau, 2007), an indicator commonly used to measure resilience. The resilience area is expressed as the integral of the area between resilience curves for the duration of the event, and the main objective is to minimize it. This metric demonstrates (1) the loss of performance of the systems in terms of each of the above metrics, and (2) the improvement of resilience compared to a situation where no energy resources are shared during a disturbance. For this purpose, two resilience area indicators are distinguished, respectively, namely, resilience loss (RL) and resilience improvement (RI). Resilience area is an aggregate metric over the whole duration of the disturbance.

Demand met and consumers served are the two main metrics used to specify operational resilience of a power system. The resilience area indicates the overall improvement in resilience when prosumers share local resources during a disturbance.

4. Assessing energy resilience: a case study

To illustrate the effect of sharing local resources in self-organized energy groups affected by outages, a case study is conducted that considers a large-scale outage that affects three distribution systems. The damage is assumed to be upstream, making the backbone grid unavailable to the three DSs. Note that this does not affect the ability to locally open and close switches that connect the DSs. Thus, reconfiguring the topologies of the three DSs is still possible. To assess the achieved energy resilience using the proposed approach, a best-case and a worst-case scenario are used. A fully operational grid during no outage scenario is taken as the best-case (all demand is met), whereas a grid with no resource sharing during an outage is taken as the worst-case scenario. To be able to share local resources, this case study assumes that the local infrastructure that enables energy sharing is not physically impacted. It is assumed that once an outage happens, both reconfiguration and energy sharing instantaneously take place. Thus, there is no time delay before recovery commences.

In the present context, immediate energy sharing is on the pretext of grid interconnection. If the sources and the loads are connected, energy transfer is instantaneous. Upon a sudden loss of network resources, the energy sharing could take a while which depends on the restoration time. Grid restoration is performed by opening or closing of switches at different grid sections, that allows instantaneous energy transfer with the restored grid section. However, the time-lapse in decision-making and actual switch operation induces delay in the energy resource sharing. The problem is different from the typical everyday reconfiguration as it is primarily operated under distributed paradigm where there is no centralized data and the grid periodically examines itself and takes corrective action for reconfiguration. The proposed approach does not include repair actions, but it provides temporary relief to the grid by changing the grid topology so that the maximum available load can be restored under an contingency event. The aim here is to reconfigure the system as fast as possible, such that the system does not lose stability. Typically, reconfiguration occurs within milliseconds. The damage repair is subject to physical repairs somewhere upstream in the grid, if any. Once the fault is restored, the system base configuration can be restored.

4.1. System setup

For illustration purposes, a modified IEEE 16-bus system (Alemohammad, Mashhour, & Saniei, 2015) divided into three separate distribution systems is considered. Figure 5 shows the topologies of each of the DSs and the total supply and demand profiles of the three distribution systems over a period of 24 h. As seen in the figures, distribution systems 1 and 3 have overproduction during the day, whereas the demand of the distribution system 2 is always higher than its supply. Thus, without the backbone grid, the demand of DS 2 is not met at any hour of the day. Each DS consists of multiple buses spread throughout the network, and has a limited number of local renewable resources (in this case, solar panels). Each of the buses has a number of consumers (*C*) and/or prosumers (*P*). The number next to the abbreviation denotes the number of consumers and prosumers on a specific bus. Figure 6 shows the distribution of consumers and prosumers on each of the buses of separate DSs. The DSs are connected with switches (SW1, SW2, and SW3) that can be open and closed when DS reconfiguration is performed (see Subsection 3.1).

Following (Čaušević et al., 2019), daily hourly load profile data is obtained from NEDU (NEDU - Verbruiksprofielen, n.d.), the Dutch energy data exchange, and represents an average load profile of a Dutch household consumer. The load profile is varied to add some variation in consumer loads. As solar panels are considered as the type of locally owned energy resources, Dutch solar irradiance data (Koninklijk Nederlands Meteorologisch Institut, n.d.) is used to calculate the production of solar panels as in (Patel, 1999). In the case of the Netherlands, an average rooftop area on which solar panels can be installed is $\approx 33\ m^2$ (Lemmens et al., 2014). To account for rooftop orientation, and w.r.t. the standard residential solar panels of an area of $1.63\ m^2$ (Matasci, 2017), prosumers are modeled with a minimum of 6 and a maximum of 12 solar panels per household (randomly determined per prosumer).

The main objective of this case study is to demonstrate how operational resilience of multiple distribution systems during a widespread outage can be improved using a multi-layered self-organized approach to local energy resource sharing across impacted DSs.

For the purpose of the case study, all three distribution systems depicted in Figure 5 are assumed to be affected by the outage. Thus, consumers and prosumers from all three DSs rely only on locally available resources. When no local resources are shared, prosumers meet their own demand, while other consumers are not supplied with electricity. When local energy resources are shared, prosumers share excess power (i.e. after meeting their own demand) with others that are physically connected to them.

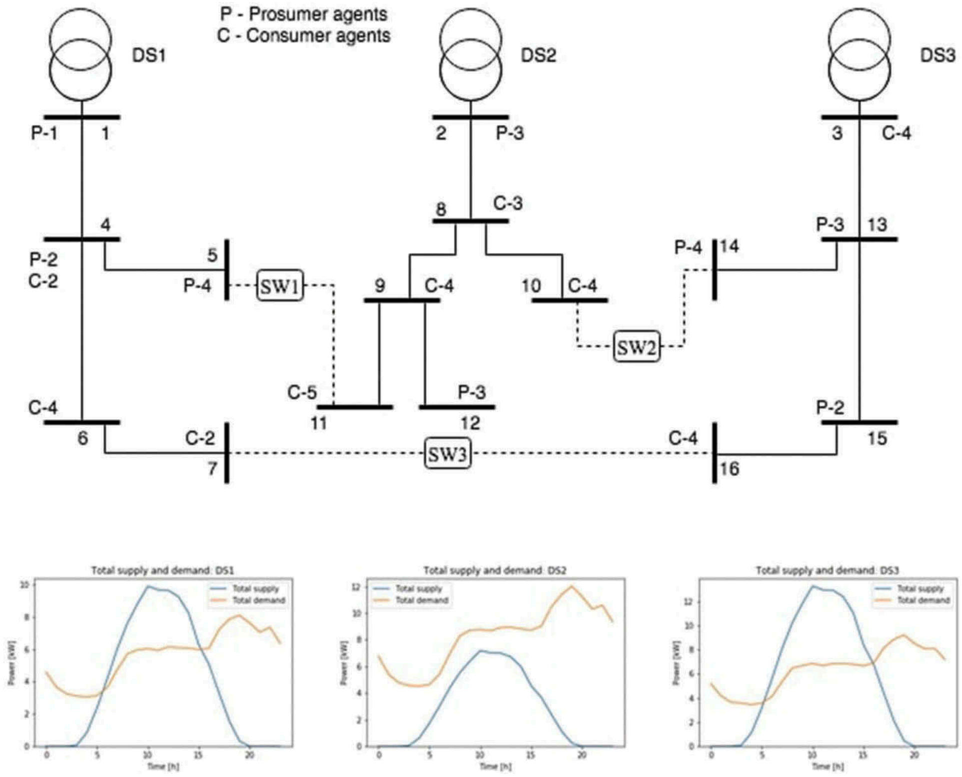


Figure 5. Topologies and aggregate supply and demand profiles of the three distribution systems.

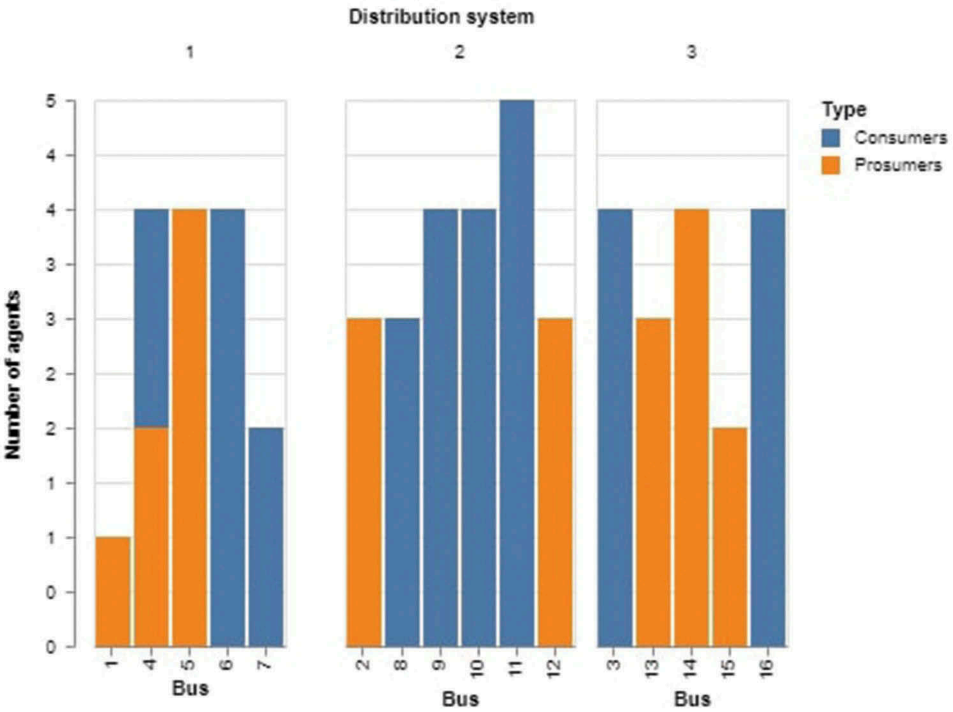


Figure 6. Number of consumers and prosumers per distribution system (per bus).

The outage is simulated over a 24-h period, with results for different outage durations and time occurrences presented. A 24-h outage is simulated to demonstrate the performance of the mechanism over a longer period of time and the potential to improve the system's resilience in such a setting. Subsection 4.2 presents the experiments and the results in detail. Note that the objective of the experiments is not to perform an in-depth study of the efficiency of the proposed approach over a long period. Factors such as physical grid infrastructure and topology, types of available local resources, as well as weather conditions and seasonal variations highly impact the performance of the approach and limit its applicability to specific scenarios.

4.2. *Case study simulation*

The case study simulates a large-scale outage when the backbone grid is no longer available. The results are presented in two sets: (1) DSR results show the optimal topology configurations for every hour over 24-h period, and (2) energy resource sharing results show the effect of local energy group formation with respect to demand met and overall resilience improvement across DSs, and compares the generated results to no resource sharing scenario. It should be noted that, even though the results are presented separately, the simulations are run iteratively for every hour, performing first DSR and then energy sharing.

The first set of results is presented in Table 1 and shows the optimal hourly reconfiguration topologies over a period of 24 h. At the beginning, all DSs operate independently. The DSR objective is to maximize local resource utilization and minimize system losses. In early hours, demand is greater than supply for all DSs, thus all switches are open, as there is not enough supply to meet the demand in any of the DSs (see Figure 7 (a)). At hours 6 and 15, when supply and demand in all three DSs start to rise, the three DSs are connected together, and both DS1 and DS3 supply some demand for DS2 (see Figure 7 (b)). In mid-day, depending on the amount of overproduction

Table 1. Reconfiguration results for large-scale outage.

Hour	SW1	SW2	SW3	DS configuration	Remarks
0–5	Open	Open	Open	DS1, DS2, DS3 separate	Figure 7 (a)
6	Close	Close	Open	DS1, DS2 and DS3 connected	Figure 7 (b)
7–8	Open	Close	Open	DS1 separate, DS2 and DS3 connected	Figure 7 (c)
9–14	Close	Open	Open	DS1 and DS2 connected, DS3 separate	Figure 7 (d)
15	Close	Close	Open	DS1, DS2 and DS3 connected	Figure 7 (b)
16–23	Open	Open	Open	DS1, DS2, DS3 separate	Figure 7 (a)

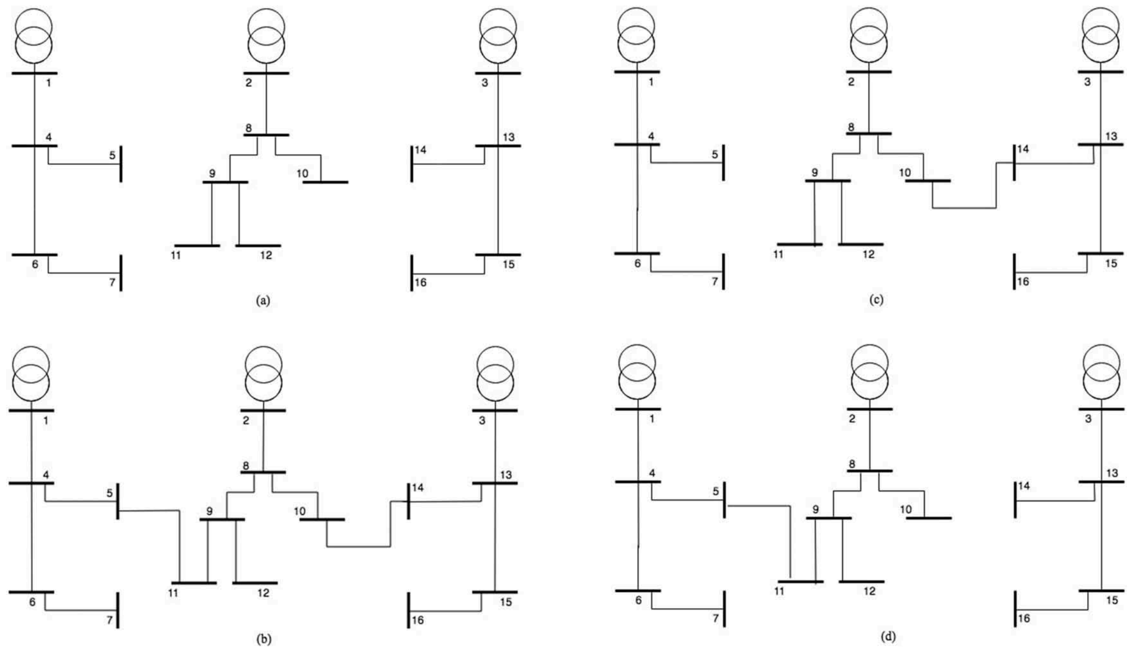


Figure 7. IEEE 16 Bus distribution system.

in DS1 and DS3, the two are interchangeably connected to DS2 to meet its demand (see Figure 7 (c) and (d)). In the later part of the day, demand again increases and the system reverts to the early hour configurations. This case assumes that the production is non-dispatchable and the demand not served must be shedded.

The second set of results demonstrates the effect of energy resource sharing across DSs. The effect of local supply and demand matching is compared to both the fully operational grid with no outage when all demand is met via a backbone grid (best-case) and the grid with no resource sharing during an outage (worst-case).

With respect to DS reconfiguration results from Table 1, hourly simulations are run, and individual and aggregate demand met of DSs are observed. Using the configurations from Table 1, Figure 8 shows the hourly results of the simulations in terms of the demand met (in kW). As indicated by the blue line, at times of the day when there is solar production, the demand met is very high, compared to the system when no local resources are shared.

Figure 9 compares the aggregate demand met for all three impacted DSs using the presented approach with the worst-case scenario, when no resources are shared.

To illustrate the impact on resilience, two simulations are run with different outage time and duration. The outage happens at time t_{oe} and ends at time t_{ee}. Figure 10 and Table 2 shows the results of the simulations in terms of operational resilience metrics (see Subsection 3.3). During a 24-hour-long outage, compared to the worst-case scenario (no energy resource sharing), resilience is improved by 24.70% in terms of demand met, and by 25.12% in terms of consumers served. In the case of a shorter outage during the time when supply is high, e.g., from 7 AM to 15 PM, the achieved resilience in terms of demand met is improved by 58.62%, and by 58.71% in terms of consumers served. The results demonstrate the full potential of the proposed approach for achieving a high level of operational resilience. The simulation also shows that the resilience depends on the type and number of resources available (e.g., the resilience of the system is low when there is no solar production, if only solar is available). However, the proposed system can deal with outages of any duration, provided there is some locally generated power, lasting from minutes to hours or days.

5. Discussion

As discussed in Section 3, the presented approach requires that local resource owners agree to share excess power supply during outage periods with other consumers and prosumers, and form local energy groups during outage periods. These groups are highly adaptable by being able to reconfigure to respond to changes in the environment. Group members are chosen by local resource owners based on the best profile match that minimizes supply and demand mismatch. To account for other factors that can be incorporated in choosing members (e.g., energy resource type, consumers type, price, etc.), negotiation mechanisms such as WS-agreement (Andrieux et al., 2005) or automated negotiation (Clark, 2014) can be used. However, those are outside the scope of this paper. Groups are assumed to be formed and reconfigured hourly.

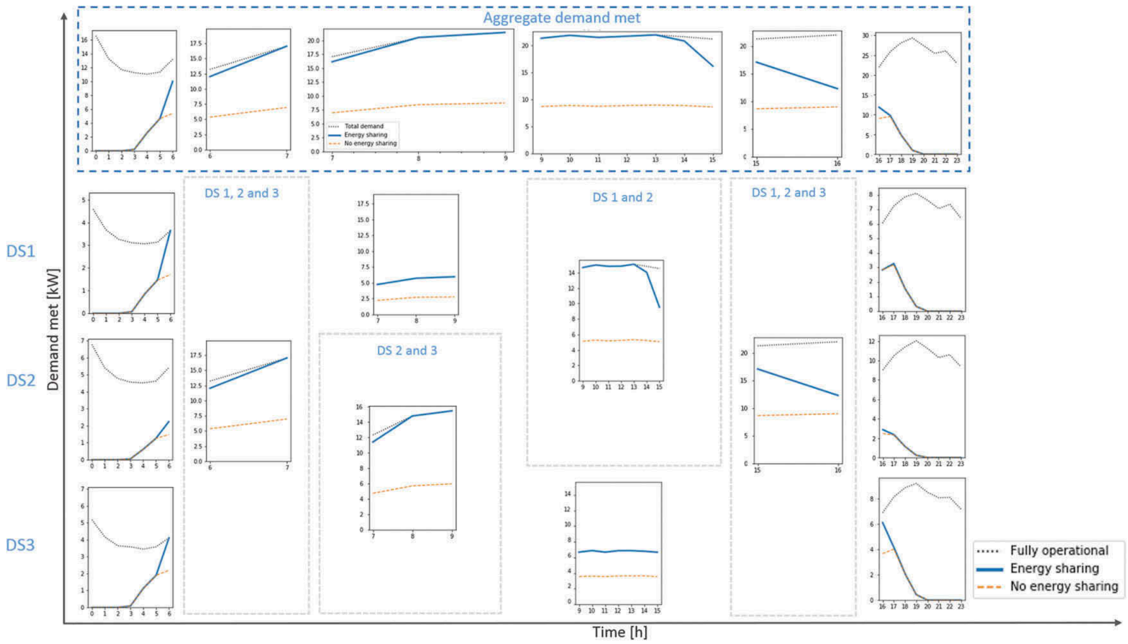


Figure 8. Hourly demand met assessment: DS reconfiguration with energy sharing.

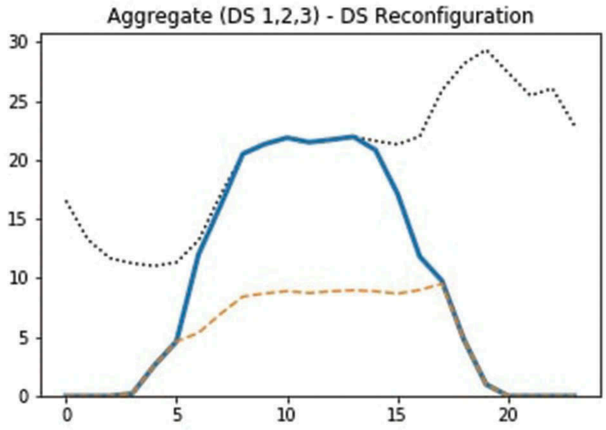
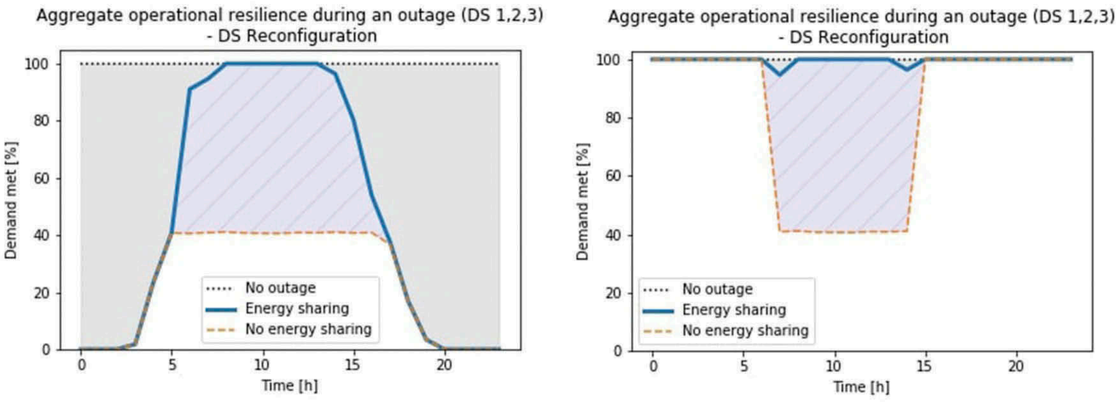


Figure 9. Demand met – A comparison between no resource sharing and the presented approach.



(a) (b)

Figure 10. Demand met during an outage: A comparison between no resource sharing and the presented approach.

Table 2. Aggregate resilience assessment for Distribution Systems 1, 2 and 3.

$t_{oe} - t_{ee}$ [h]	DM_{agg}[%]	RL_{NOES}[%] DM	RL_{ES}[%] DM	RI_{ES}[%] DM	RL_{NOES}[%] CS	RL_{ES}[%] CS	RI_{ES}[%] CS
00–24	47.45	75.11	50.41	24.70	77.94	52.82	25.12
07–15	98.99	59.15	0.53	58.62	59.26	0.55	58.71

Table 3. Reconfiguration under DG placement at DS2.

Hour	SW1	SW2	SW3	Remarks
0–23	Close	Close	Open	Figure 7 (b)

However, as frequency of cluster reconfiguration depends on availability of (fine-grained) data, forecasts or other external and internal inputs, this parameter can be altered. Note that depending on the size of the system and communication infrastructure, this can potentially create a delay in cluster formation. To avoid the delay, negotiation can be performed in advance, prior to an outage, based on local knowledge of supply and demand (or their forecasts), so that default groups are already formed. When an outage occurs, the group formation part based on S/D mismatch calculation can be skipped, and the default groups can instantaneously function autonomously, adapting to changes as needed. As such, they can operate as in a loosely coupled way even with the backbone grid available. This pre-formation increases responsiveness to disasters and rapidity in terms of restoring normal operation of the system, and can guarantee resilience.

The role of local energy groups in power systems can be further emphasized by not only asking permission from resource owners to distribute their excess production, but to also give them power to decide how and to whom to distribute it. A set of policies/institutional regulations should be developed with other types of resilience measures and metrics. Future work will assess resilience of different types of members of local energy groups (e.g., schools, supermarkets, hospitals, offices, households) with respect to their social importance.

Achieved resilience depends upon several factors, such as the type of local resources available, the amount of generated power by the resources, the number and load demand of consumers, time of occurrence and duration of disturbance, etc. In the case study discussed in this paper, only solar production is modeled as a local resource. The results show that depending on the time of occurrence and duration of disturbance, the performance of a system might still be sub-optimal (depending on outside circumstances such as renewable generation). This indicates that the resilience of the system can be further improved. This *resilience gap* can be overcome by using different types of renewable energy sources, such as wind turbines or energy storage devices (e.g., batteries, electric vehicles).

However, using only renewables that are volatile, the load cannot be constantly fully matched and at times it might not be met at all. To bridge this gap, diesel generators (DGs) or dispatchable technologies (such as battery power, biogas) can be installed in a system to provide energy support to residual load and system losses. Where a DG or dispatchable technologies are placed depends on the location itself, see for example (Ettehadi et al., 2013) for methodologies currently deployed.

From the case study experimentation, DS2 is a suitable candidate for DG placement due to lesser generation availability in DS2 subsystem. In a contingency scenario, DG placed on DS2 can also supply energy to nearby DSs and enhance system resiliency and stability with minimum efforts. The corresponding reconfiguration results are also reported in Table 3 for all hours. These results correspond to the fact that all shedded loads in the previous case are now supplied by the newly installed DG located in DS2.

Although the proposed approach provided a vision for the future, a promising step towards such systems can be seen in several projects based on peer-to-peer technologies, such as Piclo, SonnenCommunity, Smart Watts, TransActive Grid, and several others (Zhang et al., 2017). However, these projects are primarily developed and implemented to be used as energy trading platforms and do not take the physical elements of the power grid into account. The main challenge of applying the proposed system in real-life lies in laying the cyber-physical infrastructure that could operate in real-time for a large-scale complex power system. Although not a difficult task, the integration of intelligent electronic devices at each node and mapping of the underlying circuit would require a major upgrade of existing power systems. Initiatives with smart meters follow similar strategy, where our proposed approach can complement existing infrastructures to provide system resilience. In terms of the ICT infrastructure, the application of such a system would require installation of software (an agent) at appropriate nodes, either on existing or new devices, and configuring them to perform the assigned tasks. Another key challenge is the social component, as prosumers have to be willing to share their excess production. The existence of local energy initiatives and communities is a promising indication of the feasibility of such an approach.

6. Conclusions

During large-scale blackouts caused by severe weather events, the traditional centralized coordination of power systems becomes challenging, and consumers and prosumers in impacted areas have to rely on local resources and coordination schemes to function during disturbances. Global information on supply and demand might not be available, making traditional supply-demand balancing impossible.

This paper presents an approach for improving resilience of power systems based on decentralized coordination of (1) local resources and (2) the grid itself. Self-organizing energy groups form by locally matching their supply and demand and sharing local resources, while components in self-organizing distribution networks reconfigure themselves. As the approach is fully decentralized, the need for a central unit of coordination and a joint information repository is eliminated.

Consequently, there is no single point of failure, which means that even if a part of the system is unavailable, the rest of the system is unaffected and can still perform supply and demand balancing. In such a loosely coupled, self-organizing system, consumers and prosumers are less dependent on others. Both network and energy group reconfiguration are automatic, making the system more resilient and responding faster to new circumstances. The results demonstrate that by using these two mechanisms combined, resilience of impacted distribution systems in terms of demand met and consumers served is improved.

The approach is generic and can be used in different settings where the backbone grid is not available. As it uses both distribution system reconfiguration and local energy group formation, it is scalable and can be applied to both localized and widespread damages which affect multiple distribution systems.

An ICT-enabled platform of this type can provide the functionality required to mitigate power outages, providing a more resilient power system. Integrated with traditional, but modernized operational measures for distribution system reconfiguration, decentralized energy resource sharing shows a promising potential for facing future challenges of power systems in face of uncertainties, given that local resource owners are willing to share excess generation.

In the future work, mechanisms for negotiating membership in these groups, supported by operational adaptive distributed system reconfiguration, are to be explored. Different types of service level agreements will be used to ensure supply reliability for the members of the groups.

Data availability statement

The datasets analyzed during the current study are publicly available by NEDU and Koninklijk Nederlands Meteorologisch Institut (KNMI) repository, http://nedu.nl/portfolio/verbruiksprofielen/and http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi

The IEEE 16-bus system data is available in the publication (Alemohammad et al., 2015) with DOI: 10.1016/j.epsr.2015.03.014.

The results data and the simulation tool are available from the corresponding author on reasonable request.

Disclosure statement

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