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# Conflict Resilience of Water and Energy Supply Infrastructure: Insights from Yemen

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**Abstract:** Political instability and conflicts are contemporary problems across the Middle East. They threaten not only basic security, but also infrastructure performance. Supply infrastructure, providing basic services such as water and electricity, has been subjected to damage, capacity deterioration, and the bankruptcy of public providers. Often, in conflict countries such as Yemen, the continuity of basic supply is only possible thanks to adaptation efforts on the community and household levels. This paper examines the conflict resilience of water and energy supply infrastructure in Yemen during the armed conflict 2015–today. It contributes to resilience studies by linking knowledge on state fragility and conflicts, humanitarian aid, and infrastructure resilience. The paper presents adaptation responses of communities and public entities in the water and energy sectors in Yemen and critically evaluates these responses from the perspective of conflict resilience of infrastructure. The gained insights reaffirm the notion about the remarkable adaptive capacities of communities during conflicts and the importance of incorporating community-level adaptation responses into larger efforts to enhance the conflict resilience of infrastructure systems.

**Keywords:** infrastructure resilience; conflict resilience; community-based adaptation; water and energy sectors; humanitarian aid; Yemen

## 1. Introduction

The propagation of armed conflicts in the Middle East is a grand security challenge since the revolutions and the political changes of 2011, popularly characterized as the Arab Spring. These armed conflicts are still persistent with different intensities in the countries of Syria, Yemen, and Libya. The continuation of these conflicts poses an important risk with regard to the access and the safe water and energy supply of vulnerable populations. Considering the tens of millions of people currently affected by the prolonged armed conflicts (protracted conflicts), the provision of basic services during such conflicts will continue to be a major technical and planning challenge for policymakers and aid agencies. Furthermore, conflicts impose a particular challenge on the design and functioning of urban utilities. Wars in cities leave a heavy toll on the infrastructure supplying urban populations with health services, electricity, and fuel, as well as subsistence items such as food and water [1]. People living in “urban contexts”, namely areas where essential services such as electricity, health, water, wastewater treatment, and waste disposal services can be disrupted by conflicts, suffer from direct, indirect, and cumulative impacts of armed conflicts [2]. For example, the impacts on critical hardware of infrastructure can extend from direct damage, misuse, and lack of maintenance to the

depletion of reservoirs and collapse of the networks. In such cases, the urban population might face serious consequences such as the deterioration of services, shortages, increased costs, and health risks.

The weaknesses or vulnerability of critical infrastructure during armed conflicts can be counteracted ahead and during the conflict, as well as in post-conflict reconstruction phases. In regions expected to witness prolonged periods of political instability and thus conflicts, e.g., the Middle East, it is of paramount importance to consider the conflict resilience of infrastructure. In the last decades, urban resilience research has advanced significantly and has incorporated a wide range of methods, as well as factors (e.g., political, governance, and social related), affecting the sustainability of service provision [3,4]. Meanwhile, the importance of analyzing the resilience of infrastructure including lifeline utilities such as transport companies and power providers, as well as water and wastewater providers, has been highlighted in recent studies [5–7]. However, only a few studies have adopted a resilience perspective in the analysis of the impacts of armed conflicts on infrastructure, and hence on households, e.g., [8–10]. A resilience perspective can help examine not only the conflict's impacts, but also the adaptation measures of local populations and aid agencies, as well as the long-term perspective for recovery and infrastructure reconstruction.

This paper contributes to knowledge linking conflicts to infrastructure resilience by presenting the case of water and energy sectors during the armed conflicts in Yemen (2015–today). This armed conflict erupted with the takeover of the Houthi rebel groups (an armed militia from the northern region considered affiliated with Iran) in late 2014, and the military intervention of Saudi Arabia in 2015 to reinstall the internationally recognized government. Even before 2014, Yemen has suffered from an acute water scarcity crisis, coupled with state fragility, underdevelopment, and the mismanagement of resources [11]. The water crisis in Yemen dates back to post-independence developmental legacies that subsidized and promoted the utilization of groundwater in agriculture, thus leading to the drying-up of aquifers [12]. Since the late 1990s, Yemen, with the help of international donors, has sought to reform policies in the water and related sectors through decentralization reforms and the prioritization of urban infrastructure. However, the implementation of the reforms was inconsistent and witnessed political interferences [13]. Since 2014, infrastructure has been in bad shape so that many basic services such as water and electricity are lacking in an adequate quality and quantity. This infrastructure (e.g., water and electricity infrastructure) has been subjected to extensive damage due to (accidental) targeting by the conflict parties, lack of maintenance, or increased supply pressures due to migration [14,15]. Such an infrastructure can also be weaponized (i.e., used deliberately to impose hardships on population or to pressure an opposing conflict party), although evidence on this kind of use is more evident in other cases from the Middle East, namely in Syria and Iraq [16].

The aim of this study is to examine emerging responses of households and utilities to shortages and disruptions of water and energy services and to discuss how these responses can be integrated as a part of a conflict-resilient water and energy infrastructure. The study does not measure the conflict resilience during the ongoing war or provide consistent data on the performance of the two sectors since data availability, reliability, and accessibility represent some major problems. However, the paper relies on secondary literature, as well as major resilience and performance assessments by international donors. It provides largely qualitative insights into resilience and adaptation measures of the water and energy sectors during the unique humanitarian and security crisis in Yemen. First, some conceptual remarks on conflict resilience are introduced. Later, the conflict resilience is discussed in the context of the Middle East. Here, the relevance of reconsidering infrastructure resilience in the context of protracted conflicts is presented together with the case of Yemen. Finally, the responses in the water and energy sectors in the case of the conflict in Yemen are analyzed in depth with regard to their long-term impacts on the resilience and sustainability of service provision and infrastructure design.

## 2. Study Outline

### 2.1. Resilience and Vulnerability of Infrastructure: Framework, Terms, and Concepts

Resilience and vulnerability represent two widely discussed and closely related concepts that describe the responses of systems to shocks and gradual change [17]. The conceptual boundaries between the two concepts are not always clear. Resilience is widely defined as “the ability of a system to absorb shocks, to avoid crossing a threshold into an alternate and possibly irreversible new state, and to regenerate after disturbance” [18]. This paper adopts this definition based on systems thinking and relates it later to infrastructure resilience. In fact, this basic definition is embedded in a large body of resilience literature with varying perspectives and aims. Systems-based resilience concepts have been widely applied in research on socioecological systems [17,19] and engineering studies related mainly to earthquakes, climate-related disasters (e.g., hurricanes), and terrorism impacts on infrastructure systems [20–22]. In our case, the focus is rather on sociotechnical systems represented by infrastructure and engineered systems, and not on (socio)ecological systems (e.g., rivers, groundwater aquifers, or lakes). In these infrastructure systems, we highlight how resilience outcomes are shaped by political and institutional issues, rather than engineering designs alone. In fact, such a focus is underrepresented in studies on infrastructure resilience. These studies largely use computer-based simulations and mathematical optimizations to characterize the interdependence of infrastructure systems and indicate economic impacts of disasters or disruptions [23–26]. In these systems, under an engineering-based perspective, there has been little focus on the links between physical systems, human communities, and decision-making [27]. Furthermore, some studies sought to link environmental security and related policies to infrastructure resilience, but they largely concentrated on the characterization of risks and threats and less on resilience assessment [7,28].

This paper is embedded in the growing discipline of urban resilience that seeks to link physical infrastructure resilience to communities, sociopolitical challenges, and development policies [3,4,27,29]. Specifically, it focuses on basic supply infrastructure, which provides services such as electricity, transport, health, water, sanitation, or communications, whereas this paper only relates to water- and energy-related services. In this context, the paper assesses the resilience to disruptions related to conflicts (conflict resilience) caused on infrastructure (conflict resilience of infrastructure), namely infrastructure for supplying the basic services of water and energy (conflict resilience of water and energy supply infrastructure). Using the abovementioned resilience definition based on systems thinking, the paper examines armed conflicts as the main disruption to the functionality of the basic supply infrastructure systems. This focus on conflict resilience, basic supply infrastructure systems (particular basic services such as water and electricity), and social studies is highly needed for some parts of the developing world, although it is rarely used [8–10]. The paper also highlights the variety of resilience influence factors, including soft ones such as institutions, social capital, governance, and capacity development.

The conceptual framework used for the resilience assessment in this paper is outlined in Figure 1. In this place, some underlying terms and concepts in this framework can be explained. First, resilience can also be applied to a range of disruptions or shocks. These disruptions result from threats (i.e., categories of rising dangers for the functionality of a system), which include a wide range of risks as concretizations of threats [7]. In our case, a threat such as political instability can lead to risks such as armed conflicts and eruptions of violence destroying infrastructure, thus leading to disruptions of the functionality of the basic supply system. Here, responses and adaptation measures need to happen in order to restore the system’s functionality, while the relative success of these adaptation measures is determined (among others) by the vulnerability and resilience of the system. Here, we adopt the systems-based perspective of Gallopín [30], which sees resilience to be related to or as a subset of the two concepts of adaptive (or coping) capacity and the capacity of response. These concepts are used interchangeably in resilience literature, while adaptive capacity is sometimes understood differently from capacity of response and from vulnerability as the overarching concept [30].

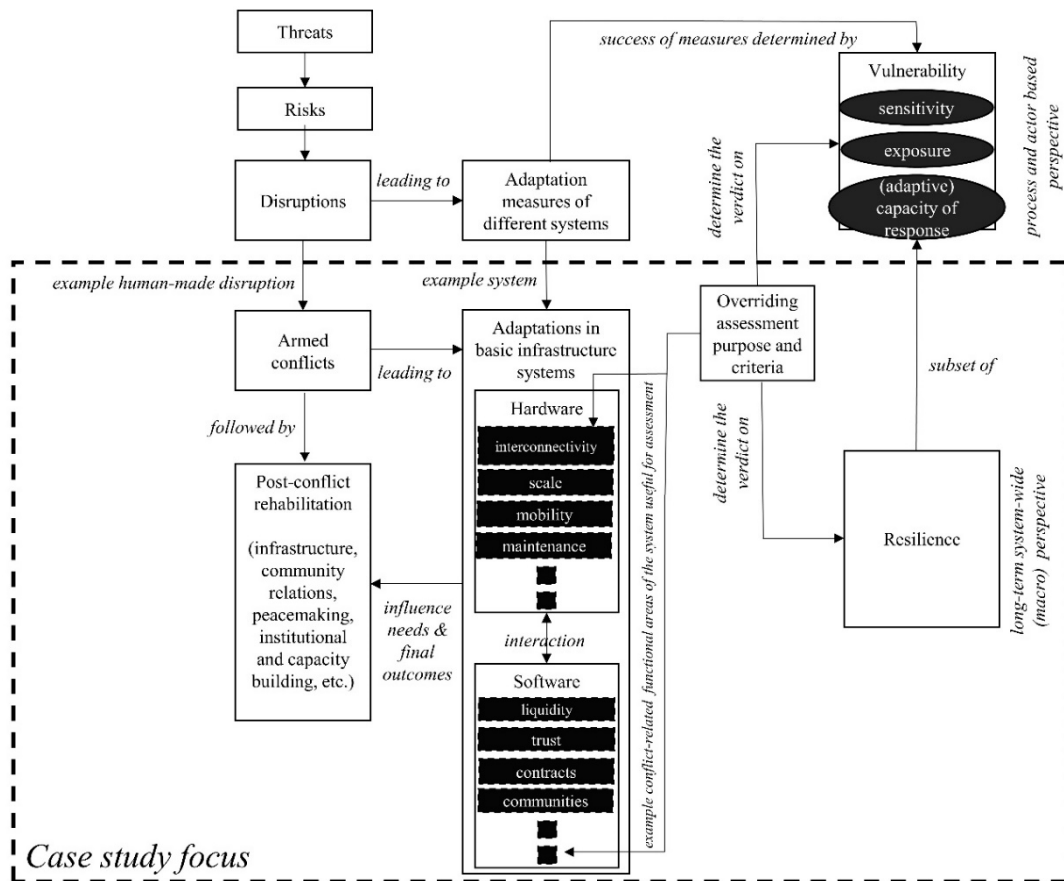


Figure 1. Conceptual framework and study outline.

With regard to the resilience and vulnerability of infrastructure systems, the two concepts are complementary, although our focus in this paper is on the resilience perspective. The infrastructure resilience and vulnerability terms used in this paper and the perspective of differentiating them can be defined further in this place. For infrastructure, “vulnerability is the collection of properties of an infrastructure system that might weaken or limit its ability to maintain its intended function, or provide its intended services when exposed to threats and hazards that originate both within and outside of the boundaries of the system” [31]. At the same time, infrastructure resilience is defined in this paper as the “resistive and adaptive capacities that support infrastructure functionality in times of crisis and stress” [32]. The incidents of vulnerability indicate a lack of resilience regarding potential threats as the sources of potential harm to the supply system [33]. The approaches of vulnerability and resilience vary in the addressed physical scale. The perspective of vulnerability is often argued to result in an actor-based analysis, which looks at the processes of negotiation, decision-making, and action. In contrast, the resilience perspective is perceived to lead to systems-based analyses by examining the interaction of social, ecological, or technical processes [34]. Furthermore, researchers also differentiate between resilience and vulnerability on a temporal scale, since vulnerability approaches enable a focus on nuanced, contemporary, and local socioeconomic realities, whereas the resilience approach often permits an analysis of longer-term system drivers [17]. In this sense, for our analysis of conflict resilience, a resilience perspective, aimed at ensuring longer-term future (conflict) resilience, cannot be realized without understanding the snapshot of the processes that underpin the foundations of vulnerability.

## 2.2. Resilience Assessment and Criteria

The assessment of conflict resilience in the case of water and energy infrastructure in Yemen is done in this paper qualitatively using the criteria highlighted in Table 1. The value of this qualitative rapid assessment lies in the contextualization of adaptation measures in relation to soft factors (e.g., communities' role) and the socioeconomic context of politically fragile (absence of strong public or state role) and underdeveloped societies such as Yemen. In such societies, quantitative resilience literature is of limited value, since it does not adequately illuminate the relationship between the conceptual pairs of fragility and stability or vulnerability and resilience [35]. In fact, infrastructure resilience research has resulted in hundreds of mostly quantitative analyses of infrastructure and communities, but with little focus on developing countries, environmental and social dimensions, and the links between infrastructure and communities [32]. Furthermore, the majority of investigated hazards and stresses are related to natural ones. Studies incorporating adaptation and adaptive capacities of communities faced with manmade crises such as the eruption of armed conflicts are lacking.

**Table 1.** Description of the rapid resilience assessment and used criteria.

Category of Infrastructure System Properties	Assessment Areas Relevant for Conflict Resilience	Qualitative Conflict Resilience Criteria
<b>Hardware</b>		
System configuration	Interconnectivity: Interdependence within infrastructure units and with other systems	Existence of self-sufficient supply (e.g., closed-loop) systems, ability to absorb sudden shocks without cascading impacts (safe failure)
	Scale: Size of the system	Ability to integrate small-sized systems to backups and larger systems
	Centralization/decentralization: Level of accumulation of infrastructure and management tasks	Decentralized systems availability
	Mobility: Ability to dismantle and relocate the system	Existence of mobility at least partly (dismantling and rebuilding), or through portable design
System resources	Maintenance and resource availability: Conservation of assets	Design, know-how, and (low-tech) resources to maintain the functionality of the system
	Baseline: Pre-conflict infrastructure problems	Ability to integrate emergency response to holistic infrastructure planning issues
<b>Software</b>		
Actors relationships	Role of the Government: Public control, oversight and planning	Level of public support, involvement, and capacities
	Community relationships and involvement: Communities' participation and quality of relationships and trust	Level of communities' participation and cooperation in community
Formal regulation	Institutional arrangements: Contractual issues such as monitoring instruments and transaction costs (exchange costs related to lack of information exchange, legal ambiguity, and transportation requirements)	Tackling market imperfections and contractual problems in infrastructure-related transactions
	Liquidity and equity issues: Availability of financing mechanisms and affordability	Ability of large population segments to access/afford infrastructure services

The resilience assessment is based on qualitative criteria related to functional areas relevant to key properties of the infrastructure systems (Figure 1). These areas and the used qualitative criteria are described in Table 1. They target different system properties or characteristics such as the configuration, resource use, relationships among actors, and regulation. Following Anand [36],

the areas are classified in the physical ('hard') capital of societies and the social ('soft') capital of networks. These criteria, listed in Table 1, represent a selected subset of criteria used in the larger study carried out at TH-Köln, University of Applied Sciences to analyze the conflict resilience of different infrastructure adaptation measures in selected conflict-ridden countries in the Middle East and the East African region. They provide a systematization for the descriptive assessment of the Yemeni case and are referred to in Section 5 of this paper. The criteria are similar to those used in studies on infrastructure resilience, particularly with regard to rehabilitation efforts in post-conflict settings [5,17–20,32,36–43], while they relate to systems-based resilience literature highlighting multidimensional resilience interventions (technical, organizational, and economic) [7,44] and political economic studies on the importance of social context, legacies, and learning from experience in developing countries [29,45].

### 2.3. Study Relevance, Method, and Data

Hazards related to armed conflicts are quite contemporary and relevant for politically fragile regions such as the Middle East, while the communities' reactions reveal much about the adequacy of current infrastructure designs to face future challenges related to supply security. In this paper, we look closer at adaptation and changes of functionality of water and energy infrastructure during the armed conflict in Yemen while incorporating the communities' perspective. In this sense, the paper contributes to literature that stress the importance of understanding adaptation efforts of communities and the ability of such efforts to strengthen systems' resilience and ultimately improve human security in fragile and conflict-affected societies [36,37,41,46,47]. It also provides valuable insights for the infrastructure rehabilitation and post-conflict construction in such societies. The adaptation efforts in the water and supply infrastructure in Yemen reveal the importance of involving communities, providing more decentralized infrastructure solutions, using renewable energies, and enhancing conflict resilient infrastructure design. They are also reminders of the importance of linking emergency aid to long-term development in a way that anticipates disruptions by conflicts and incorporates the social context of fragile and under-developing states.

The paper represents a qualitative assessment based on narratives and firsthand accounts of bottom-up, community-based adaptation to violent conflict. The focus of the paper is on urban water and energy infrastructure, the nature of adaptation measures, and the contributions to the overall conflict resilience of infrastructure. The above-highlighted assessment framework served as a guideline to systematize the discussions of the adaptation measures in Yemen. The criteria were evaluated qualitatively without formal scoring. The aim was to gain insights on the nature of adaptation, the relevance for infrastructure resilience concepts, and eventual shortcomings. The evaluation through the resilience assessment goes beyond resilience studies carried out by donor organizations, which have focused on accounting for infrastructure damage, measuring performance deteriorations, and gathering perceived problems as well as reconstruction needs [14,48,49]. In contrast, the resilience analysis in this paper links adaptation measures to broader academic discussions on urban resilience, infrastructure systems in developing countries, community-based adaptations, and development aid. The resilience assessment was originally developed in a more extended form for a larger study that scored the conflict resilience of community- and donor-driven infrastructure interventions in conflict-ridden countries in the Middle East and Africa.

The paper relies on sources such as third-party reports, international newspapers, as well as interviews with experts from Yemen carried out between 2017 and 2019. For the energy sector, the paper relies on secondary literature and newspapers, as well as data collected onsite from unstructured interviews with households and small-scale solar energy providers in Sana'a in 2019. Secondary literature was used either for the description of the adaptation efforts, or, in the case of academic literature, to build and contextualize the assessment framework. The firsthand accounts were suitable to depict the solar energy use phenomena and analyze some aspects such as actors and contracts. We also relied on open, semi-structured interviews with experts from donor organization conducted in 2017 on the solar energy adaptation measures in Yemen. These interviews were partly recorded. They were

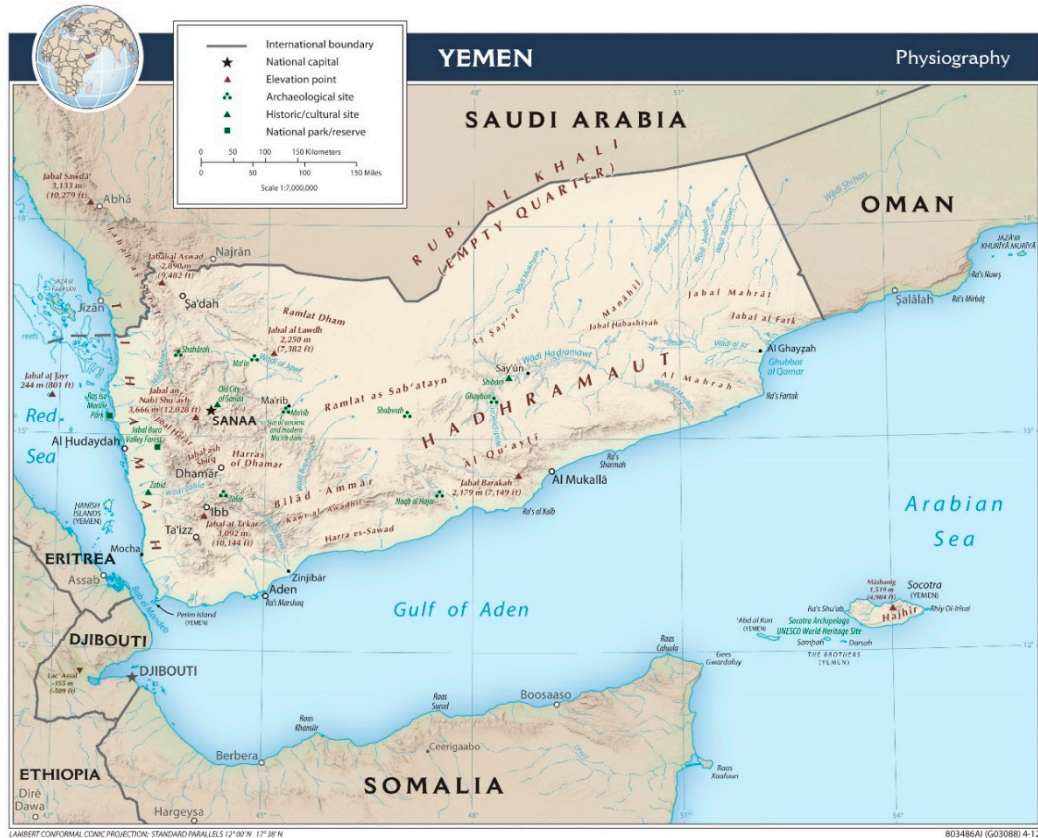
guided toward gaining insights relevant for the scoring of earlier highlighted resilience assessment framework, and they were complemented by major reports of donors on resilience efforts, particularly in the water sector. However, reliable surveys on the magnitude of solar energy use in Yemen are lacking. For the water sector, we rely on donors' reports resulting from comprehensive surveys of the situation of water utilities conducted in Yemen during the conflict. These quite reliable data were obtained from the local office of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (the German donor organization for technical cooperation) in Sana'a, Yemen, in 2019.

### 3. Case Region: Conflicts, Infrastructure, and Resilience in the Middle East

Basic infrastructure, such as the one providing water and energy services, is vulnerable to a multitude of risks and hazards, including the destructive consequences of armed conflicts. According to international law, specifically the Geneva Convention, conflict parties are not allowed to "attack, destroy, remove or render useless objects indispensable to the survival of the civilian population, such as food-stuffs, agricultural areas for the production of food-stuffs, crops, livestock, drinking water installations and supplies and irrigation works" (Article 54 of the 1977 Protocol I to the Geneva Convention), cited by the authors of [50]. Despite such provisions, infrastructure is damaged both directly as targets in armed conflict, to weaken the authority and legitimacy of rulers, and indirectly as collateral damage. There is also comprehensive evidence of the damage of environmental infrastructure in the current Middle Eastern conflicts. In addition to the destruction of infrastructure by conflict parties in Syria, Iraq, and Yemen, critical infrastructure, such as water, has been weaponized by nonstate actors, such as the Islamic State and others, who have targeted water-service infrastructure such as dams, pipelines, and treatment plants [16]. In fact, radical groups, such as the Islamic States, have been increasingly instrumentalizing water resources and water systems for economic and political reasons [51]. This pattern of weaponization of basic commodities has continued until now (late 2020), with reports of the Islamic State seeking to deliberately destroy crops by burning thousands of acres in Syria and Iraq in 2019 [52] and militias seeking to shut down water supply during the COVID-19 crisis [53]. In this case, the food and water securities of vulnerable population groups in these regions are immediately affected. Still, as the 2014 Gaza conflict shows, even if a certain conflict does not lead to an immediate threat on food security, it affects households' resilience through a declined adaptive capacity due to the loss of income and livelihood [10]. Here, the case of Yemen (location map in Figure 2) is illustrative for the problems of underdeveloped countries suffering from decades of conflicts of state fragility, which can be also linked to resources such as water and energy. In fact, the depletion of water resources (e.g., groundwater over-abstractions favored by high-energy subsidies and an expansionist agricultural agenda) and the lack of sustainability policies have contributed to increased vulnerability and political disintegration in Yemen [12,54].

The adaptive capacity of households and communities affected by armed conflicts and disruptions in the supply infrastructure is not only threatened by the dissemination of poverty and the loose community ties in urban settings, but also by the centralized design of infrastructure. Due to the connection of an urban area to a widespread web of large-scale and often centralized infrastructure in the Middle East, the supply of essential services is particularly vulnerable [55]. Service disruptions in one infrastructure system can lead to a cascading effect across all systems. For instance, a damaged electrical transmission line can immediately shut down the electricity supply to water infrastructure (water treatment, water distribution, wastewater treatment), hence potentially cutting the safe water supply and wastewater treatment for an entire area. If the hospital in this area is also affected by the electricity and water cut, this greatly reduces the public health service and increases the risks posed to public health and well-being. Combined with dysfunctional wastewater treatment plants and potentially overflowing wastewater in the city, the scene for health disasters, such as cholera outbreaks, is set. In fact, cascading effects or failures are common for the highly interlinked and complex infrastructure system, since some disruptions can lead to a much bigger failure than the original loss, regardless whether the original loss resulted from a flood, earthquake, terrorist act,

war, another disaster, or shocks [56–58]. This has been the case of the cholera outbreak in Yemen. This outbreak has become the largest one in recorded history, with more than 1.2 million cases since 2017, and can be directly linked to the destruction of the water, sanitation, and hygiene infrastructure since the start of the bombing campaign in 2015 by the coalition led by Saudi Arabia [59].



**Figure 2.** Map of Yemen (source: Public domain provided by United States Central Intelligence Agency’s World Factbook).

Even before the current conflict in Yemen, the basic supply sectors were already vulnerable and underperforming (see key statistics in Table 2). The Yemeni population has largely depended on limited oil and gas resources for energy supply and groundwater aquifers for water supply. Due to production disruptions and the destruction of infrastructure (particularly since 2015), the energy consumption has decreased significantly, with solar energy becoming an important option (Table 2). With regard to water, Yemen suffers from a water scarcity problem, with significant deteriorations of water services after the conflict (see Section 4.1). The destruction of water and energy infrastructure has continued until today (late 2020). It has led to the propagation of alternative supply modes and self-organization structures within the affected communities, often with little help from the outside. The armed conflict in Yemen, which escalated in March 2015, compounded an already severe protracted humanitarian crisis following mass protests in January 2011. As of December 2018, more than 20 million people were food insecure, including 10 million with extreme levels of hunger, around 18 million people lacked safe water and sanitation services, and around 20 million (around 80% of total population) with no access to adequate healthcare [60].



**Table 2.** Key development, energy, and water statistics for Yemen.

General Development Indicators <sup>1</sup>				General Energy Statistics <sup>2</sup>				
GDP per capita, PPP (current international \$) (2013)	Population ages 15–64 (% of total) (2019)	United Nations Human Development Index (scale 0–1) (2020)	Poverty headcount ratio at national poverty line (% of population) (2014)	Available renewable energy resources (TWh)	Available fossil fuel based on current production 2015 (TWh)	Production (ktoe), 2018 with 2014 in ()	Imports (ktoe), (2018 with 2014 in ())	Exports, (ktoe), 2018 with 2014 in ()
3689	58%	0.4	49%	17,529	47	1796 (16,289)	1612 (4769)	NA (12,976)
Electricity consumption 2018 with 2014 in () <sup>2</sup>								
Oil	Natural gas	Solar PV	Total	Final consumption (consisting of industry, residential, ect.) <sup>i</sup>	Industry	Residential	Commercial and public services	Other non-specified UN
2836 (4698)	315 (2948)	458 (9)	3609 (7655)	2192 (4553)	64 (161)	1769 (3047)	200 (750)	159 (595)
Key Water indicators								
Total renewable water resources (Billion cubic meter per year) <sup>1</sup>	Water resources per capita (cubic meter per person per year) (2014) <sup>1</sup>	Water dependency ratio (percentage of water used from sources outside the country) <sup>3</sup>	Total water withdrawals (Billion cubic meter per year) (2005) <sup>1</sup>	Water stress: freshwater withdrawals as % of available resources (2014) <sup>1</sup>	Water withdrawals for agriculture, domestic and industry sectors respectively (% of total withdrawals) (2005) <sup>1</sup>	Water withdrawals by source, namely groundwater, surface water, desalination and treated wastewater (2000) <sup>3</sup>	Use of improved sanitation facilities (2012) (% of population) <sup>4,ii</sup>	Use of drinking-water from improved sources (2012) (% of population) <sup>4,ii</sup>
2.1	81	0%	3.5	227.68%	91%, 7%, 2%	70.5%, 29%, 0.3%, 0.2%	53%	55%

Sources: <sup>1</sup> World Bank [61]; <sup>2</sup> International Energy Agency [62]; <sup>3</sup> Food and Agricultural Organization of the United Nations [63]; <sup>4</sup> World Health Organization [64]. Notes: <sup>i</sup> Final consumption is calculated after accounting for losses, energy industry own use and statistical differences; <sup>ii</sup> National data on access to water and sanitation exist for the pre-conflict period. Recent donor reports indicate as much as 18 million (around 60% of population) without access and in urgent help for water, sanitation and hygiene services.

## 4. Infrastructure Resilience: The Case of the Yemen Conflict

### 4.1. Water Sector

Insufficient supply of safe water is a major component of the ongoing humanitarian crisis. Since the 1990s, the water sector in Yemen has been at the center of attention for the government and donor organizations due to multiple performance shortcomings in this sector, as well as its importance for poverty-related policies. In the mid-1990s, the Yemeni governments initiated a series of reforms to reorganize the sector in order to counteract the severe water shortage problems, bad shape of infrastructure, and lack of efficiency in this public sector. The sector reforms resulted in the introduction of demand management. They also introduced policies to manage water resources in an integrated way on the watershed level (groundwater basins) and, importantly, to decentralize the services delivery to the level of independent water corporations [65,66]. As a result, independent water utilities (Local Corporations) were established in the capital cities of the governorates. These Corporations received financial and technical support from international donors (particularly German donors) in order to improve services, adopt commercial practices, decrease water leakages in infrastructure, and develop monitoring systems. In the wake of the decentralization and commercialization reforms in the urban water sector, the sector performance improved, although political interferences and mismanagement did not disappear [13]. With the start of the war in 2015, some operations of the utilities came to a halt due to the destruction of infrastructure, unpaid customer debt, and fuel shortages [49]. In fact, energy is a key element to the safe water supply in Yemen. Drinking water supply, which mainly depends on groundwater extraction, requires huge amounts of energy for diesel-run generators, pumps, and well-drilling equipment.

In addition to political fragility and mismanagement, the water sector in Yemen has been experiencing scarcity problems with overexploitation of groundwater resources and recurrent water shortages [11]. Some cities, such as Ta'iz, have experienced a severe water stress for decades due to population growth, environmental degradation, corruption, and institutional incompetence [67]. In the young history of the modern state in Yemen, national policymaking in the water sector has had many shortcomings. It has failed to provide universal services, to adapt the traditional water allocation systems (e.g., tribal-based rules and ancient water harvesting techniques) to modern innovations, and to curb the propagation of water-intensive cash crops such as *qāt*, a mild stimulant used by Yemenis and the leading agricultural crop grown domestically [12]. Facing the failures of public services, Yemenis were used to rely on aid projects and alternative supplies such as private wells and water tanks, although the public water services were provided at relatively low prices [68]. With the start of the armed conflict in 2015, the water sources changed dramatically. The water network now supplies only a minority of households, while the majority of households rely on private wells, water tankers, and even water harvesting techniques, including manmade cisterns, ponds, and other smaller roofed techniques [69]. Water tankers and illegal wells have been around for many decades in Yemen. Nonetheless, the magnitude of the propagation of self-constructed water harvesting techniques and their share of supply cannot be determined. Some donor organizations have deliberately supported water harvesting in agriculture upon the start of the political instability periods [40]. However, the majority of the efforts are community-based and self-organized.

With regard to the water and sanitation infrastructure, the deterioration of services has been severe since the start of the conflict in 2015. Table 3 provides figures on the population increase, as well as the water and sewerage coverage, in 2014 and in 2017. Most of the indicated utilities are located in major urban agglomerations. The remarkable increase in population between 2014 and 2017 is indicative of the high rate of urbanization in the predominantly rural society of Yemen but is also related to the increase of the number of internally displaced people. Ta'iz is an exception in this dataset, since its population increased by a relatively low rate, while the coverage of water and sanitation services was cut significantly by almost one half. This fall of coverage was much more than the average national decrease of water coverage from 68% in 2014 to 59% in 2017, and of sewerage coverage from

52% to 44% [48]. In fact, Ta'iz is one of the cities that has witnessed fighting on a regular basis. Besides, it has effectively been under siege by the Houthi movement since the start of the conflict. Overall, most of the service deterioration has occurred in the largest cities of Sana'a, Aden, Hudaydah, and Ta'iz. Smaller cities with relative stability, such as Ibb or Mukalla, have reported minor improvements or no changes in coverage rates despite the significant increase in population. Considering these coverage numbers, the private water supply through water tankers providing water from private boreholes, springs, or dug wells currently covers around 40% of the urban population [14]. However, the public supply coverage does not guarantee a continuity of supply, particularly during the current conflict, which has destroyed some infrastructure, leading to supply interruptions. Therefore, one can expect the importance of private water supply to be much higher than this official 40% figure.

**Table 3.** Service coverage of major water utilities in 2014 and 2017, based on data from [48].

Water Utilities	City Population in Thousands		Population Increase	Water Coverage		Sewerage Coverage	
	2014	2017		2014	2017	2014	2017
Ja'ar/Zinjibar, Al-Husn, Al Kood, Al-Makhzan	101.0	108.4	7.4%	84%	80%	47%	44%
Aden	855.9	957.2	11.8%	92%	86%	79%	69%
Amran	70.1	74.6	6.4%	49%	50%	32%	36%
Dhamar	205.5	228.5	11.2%	76%	70%	46%	42%
Mukalla	322.4	351.4	9.0%	93%	91%	63%	62%
Al Shehr	109.2	120.1	10.0%	89%	83%	43%	40%
Hajjah	71.0	77.6	9.3%	99%	99%	60%	55%
Mabian	50.0	52.5	5.0%	46%	46%	-	-
Hudaydah	564.3	622.0	10.2%	82%	75%	49%	41%
Bajil	73.9	80.8	9.3%	74%	77%	44%	41%
Zabid	37.7	41.2	9.3%	95%	92%	80%	74%
Ibb	324.4	349.3	7.7%	77%	80%	61%	66%
Al Hawta, Tuban	140.8	163.8	16.3%	82%	71%	-	-
Sa'ada	70.0	79.0	12.9%	35%	36%	-	-
Sana'a	2824.0	3234.0	14.5%	48%	43%	45%	40%
Taiz	633.1	654.3	3.4%	80%	38%	70%	38%

A comprehensive study of damage, resilience, and construction needs was carried out by the German donors, see [14,48]. Some of the resilience factors suggested by this study include improving governance and management performance during crisis, enhancing capacities and skills of staff, strengthening financial capacities to cover minimum operation needs, enhancing customer management to increase billing collections, increasing service coverage, providing renewable energy systems, and investigating alternative sources such as reclaimed wastewater or rainwater. Largely, these resilience recommendations are selective and based on input from water utilities on needed interventions. As this paper argued earlier, infrastructure resilience needs to be tackled systematically, e.g., across the different properties and functional areas of the infrastructure systems (balancing hard and soft issues). It is also feasible to develop a set of resilience strategies to tackle different types of resilience in a system (e.g., technical, organizational, economic resilience strategies) [44], to strengthen different systems' capabilities (e.g., withstanding, absorptive, restorative or adaptive capability) [6], or to combine both approaches [7]. Another way is to incorporate resilience measures across the value chain of basic supply sectors such as water, energy, and food. This value chain can be related to the material throughput (e.g., production, delivery and transport, consumption, disposal). A policy value

chain also exists for the three sectors with various tools for integrative analysis, namely the value chain of policy formulation and planning, coordination and regulation, and practical management [70]. Whereas reviewing resilience strategies for all hard and soft infrastructure subsystems across these value chains was difficult in the scope of this paper, it is important to have realistic expectations and to link resilience measures to communities' ongoing adaptations.

In fact, the recommended measures by donors to enhance the resilience of the water and sanitation supply are difficult to imagine in the short term due to the lack of funds, fragmented public institutions with two de facto governments in Aden and Sana'a, and multiple territorial militias, as well as the departure of donors due to the security concerns. In fact, the donor's role has been mostly confined to emergency aid, while national policymaking is largely absent. This means that most of the adaptation efforts are decentralized with loose coordination mechanisms. More revealing about the resilience needs of the water sector are the recommended projects. These include rainwater harvesting, desalination, the reuse of reclaimed water, decentralized and low-cost sanitation, renewable energy, and energy-saving systems [14]. However, some of these options, such as desalination and reclamation, are costly and have thus not yet been implemented. Other systems, such as solar energy for water pumping, have been widely adopted during the crisis, and many of such projects have been supported by donors. Figure 3 shows photovoltaic systems that have been installed during the conflict by a public water utility and a private water well operator in the capital city in Sana'a. Solar energy is increasingly used for water pumping in private wells of powerful elites for agricultural uses, as well as for the sale of water to private entities (water tankers) that resell water at high costs to households across the city.



(a)

Figure 3. Cont.



(b)

**Figure 3.** (a) Photovoltaic for water pumping and utilities operations: A pumping station of a private water well run on solar energy in the capital city of Sana'a. (b) Solar panels on the roof of a building of the Sana'a Water and Sanitation Corporation for operating a public water well nearby (pictures by the authors).

#### 4.2. Energy Sector

Yemen has one of the lowest electricity coverage rates in the Middle East. Before the war, the public energy supply system was weak, with only 40% of the country's population having access to electricity compared to the regional average of 85% [71]. Further, only about 23% of those who live in rural areas (75% of the population) had access to electricity [71]. The energy sector has faced serious challenges, including a low-generation capacity, high electricity losses from the grid (approximately 30% of production capacity), and the pressure to increase the generation capacity by 400% until 2020 to meet only the residential demand. Despite the low access rate of electricity, only about half of the people depended on the public grid, whereas the other half gained access through private sources such as diesel generators, kerosene, and liquefied petroleum gas (LPG). All of this implied serious health issues and environmental impacts.

Armed conflict-related electricity and diesel scarcity, war damage to major ports such as Al Hudaydah, and a strict trade blockade imposed by the Saudis have caused fuel imports to reach a reported 1% of the monthly requirement in September 2016 [72]. The fuel shortages led to long electricity blackouts. Before the crisis, Sanaa received around 18 h of power daily. In early July 2016, transformer stations in Sana'a supplied several neighborhoods in the capital with around four hours of power every five days. The deteriorating electricity coverage significantly affected lives of vulnerable population groups, especially in coastal regions relying on air conditioners with temperatures reaching as high as 40 degrees Celsius [73]. Shortages of fuel undermined the operation of a variety of sectors such as water, sanitation, industrial production, health services, food storage, transportation, and schools. Moreover, the energy shortage increased water tariffs, thus decreasing the peoples' financial resources to cover other expenses and increasing the costs of food production [74].

The nature of the response in Yemen is a decentralized, self-managed, and consumer-driven adaptation. Here, there is almost a complete absence of any national-level or donor-driven coordination. The national power grid supplied the city of Sana'a with just a few hours of power a week after

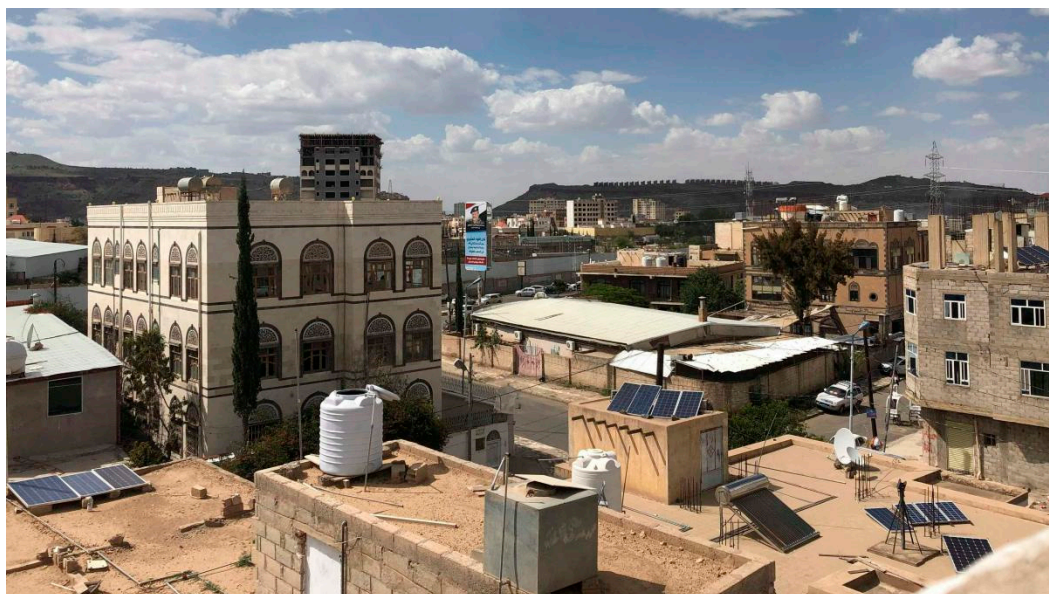
the shutdown in the spring of 2015. People relying on the public power grid were left in the dark. Moreover, residents depending on diesel-run generators could not afford to run them after the price of fuel soared. As a result, solar energy became a measure of last resort, and what started as a coping mechanism became a nationwide phenomenon. Whereas the renewable energy share before the conflict was estimated to be only at about 0.009% of the total energy mix [71], nowadays, solar-installation and related businesses are present throughout Yemen in all kind of varieties (see Figure 4). Magdi Mansoor, a Yemeni journalist, described the presence of solar businesses in Sana'a as such: "In my neighbourhood, for instance, there are more than five solar businesses within 200 m from my home. Some of them are home-appliance stores that now sell solar units and energy-efficient appliances" [75]. It is remarkable to notice the individual adaptation mechanisms go beyond the household level. The sale of solar units does not seem to be restricted to traders and specialists. On the contrary, traders from other sectors found the solar market as a substitute for their declining trade [73]. According to the Small & Micro Enterprise Development, a project of the Yemeni Social Fund for Development (SFD), sales of solar panels have increased by over 2000% from 2015 to 2016 [75].

The solar panels and the equipment needed for their installation (batteries, electric wires) enter the country through the Saudi controlled port of Aden and the Saudi border crossing of al-Tuwaij, as well as through the Sana'a airport (air traffic heavily restricted by the Saudi) and the port of Hodeidah. The products are mainly imported from India, China, Canada, and Vietnam, with no specific party overseeing their importation. The trade of solar panels is encouraged through tax incentives. However, the extent to which solar panels are imported is not documented. Sources estimate that "in 2015, the importation of solar panels from India and China through the two outlets controlled by the Houthis amounted to \$40 million, while the cost of importing batteries and wires reached \$90 million" [73]. The individual creativity goes beyond the trading and purchase mechanisms. Pro-poor installment plans and small-scale systems, designed to light a few lamps serve as a safe alternative to LPG lamps or candles, let even less affluent Yemenis participate in the solar market [73]. Furthermore, the Yemeni must have gained the capacity to alter and individualize the solar systems to their needs. Solar panels have been seen to power wheelchairs or serve as portable phone chargers [76].

Furthermore, another adaptation response can be highlighted, namely the dissemination of private electricity vendors on the neighborhood level, particularly in major cities such as the capital city of Sana'a in the territories held by the Houthi rebels. The private vendors use diesel generators of around 100–200 kW to provide electricity to houses in the neighborhood at costs of around Yemeni Riyal 260 (in 2019, around USD 50) per kWh. Whereas this price is almost 10-times the average price consumers used to pay to the public supplier before the war, many households opt for this option in order to be able to use certain appliances (e.g., for water pumping from underground cistern to rooftop containers) or to be able to maintain commercial shops. In order to subscribe to this private electricity vendors, a one-off fee of around USD 50 is required, alongside an additional payment of the costs of the meters and cables. Some households decide to have both rooftop solar panels and connections to private vendors in order to switch between the two or to avoid the high maintenance and replacement costs of the solar panels once they are unusable. Besides, the supply of the private vendors is not reliable, since it depends on the availability of diesel fuel on the market, and agreed prices might change suddenly. The private electricity market functions independent of the public supplier. At the same time, the Houthi-administrated government extracts taxes and other inconsistent duties from these suppliers.

It is noticeable that the response of donors and the international community in Yemen to the obvious need and demand from the population has been weak. Despite the good reception of solar energy among the public, only a few aid agencies started to implement solar energy on a larger scale. An example is the EU funded program Enhanced Rural Resilience in Yemen (ERRY) implemented by the Food and Agriculture Organization of the United Nations (FAO), together with other international organizations, which started in March 2016. It aims to enhance the resilience of rural communities, among others, through improved access to sustainable energy. It supports the installation of solar

pumps targeting rural agricultural communities as an attempt to improve domestic food security. Furthermore, solar-powered desalination is being planned and piloted by some water utilities with the support of the GIZ [74]. Solar energy projects in agriculture have been established by donor organizations across the Middle East with mixed methods and results [77]. As mentioned previously, the available data on (solar) coverage for Yemen are weak and unreliable. Many of the described projects are in a planning stage or under implementation. Thus, an evaluation of the achievements is largely missing. UNDP published a fact sheet of the ERRY progress in 2016, stating that three solar energy resilience building initiatives were formulated, under which 800 households received solar energy applications in a total of 20 rural communities. Those appliances enhance the energy resilience and access for 20 health services and 20 education systems. Furthermore, four economically productive assets enhanced their production through solar energy systems [78].



(a)



(b)

**Figure 4.** (a) Photovoltaic for households' energy needs: Small rooftop photovoltaic systems widely used by households in the capital city Sana'a. (b) Diesel-powered electricity generators at a facility of a private vendor in the capital city of Sana'a (pictures by the authors).

## 5. Assessment and Discussion

The responses of communities, infrastructure planners, and donor organizations toward water and energy supply problems are examined in this section with regard to their suitability for enhancing the conflict resilience of the infrastructure systems on the long run. We assess the conflict resilience using the earlier described assessment criteria for infrastructure resilience and infrastructure rehabilitation in the context of conflicts and state fragility. We highlight some of the key recommendations from this literature for infrastructure planning, hardware issues, and the role of community.

First, infrastructure planning needs to consider the optimal level of centralization, size and the interconnectivity in the supply infrastructure. Highly centralized and highly interconnected infrastructure can be vulnerable to sudden disruptions, and thus might lead to an “unsafe failure” with cumulative or cascading effects across several systems [43]. At the same time, a highly fragmented infrastructure can be difficult to manage, with high transaction costs and a low potential for synergies. In the case of the conflict in Yemen, apart from the modest efforts of donors and public utilities to rehabilitate the infrastructure, most adaptation measures are decentralized and community-driven, with little national-level guidance, backup systems, or integration to larger infrastructure networks. For example, the decentralized, demand-driven solar development in Yemen represents an adaptation option that is less vulnerable to the risks that are likely to harm the system in a context of armed conflict. The household-based solar panels are singular entities that are not affected by missing surrounding infrastructure or the need for a strong public role. Similarly, the water adaptation efforts through the increased use of homemade harvesting techniques and private water tanks are decentralized and loosely connected efforts. The demand-driven increase in sales and installations of solar panels and the reliance on the private water supply have enhanced decentralization, which might have improved the households’ resilience to a breakout of the supply system. At the same time, the infrastructure hardware used in the adaptation measures exhibits a large degree of mobility, but fails to address sufficient upscaling and does not contribute to the strengthening of the current public system, e.g., improving storage capacities or maintaining the system’s parts. For Middle Eastern countries, protracted and recurrent conflicts demands more decentralization and mobility in infrastructure planning. However, a minimum level of coordination and national-level involvement through standardization and regulation is still important.

Second, with regard to the infrastructure systems’ resources, the evaluation of the respective criteria (maintenance, resource availability, and missing baseline) is mixed. On the one hand, the response by the Yemeni communities using small renewable energy applications and private vendors relies on a limited availability of monetary resources, the endless resource provided by the sun, the development of solar energy craftsmanship locally, and the high mobility of the units. In this sense, households were able to weather the shortcomings to some extent. On the other hand, the maintenance of these parts is dependent on the imports of batteries and spare parts through controlled trade gates, such as the ports and the airport, and is thus vulnerable to external decision-making and the power games of warring parties. Besides, storage techniques are costly and less efficient if managed on a microlevel. Hence, the full potential of conflict resilience is not exploited, as the efforts do not connect to the existing infrastructure systems.

The hardware adaptation efforts represent an uncoordinated bottom-up approach that does not consider or contribute to a missing baseline. An upscaling of single household units does not contribute to any infrastructure rehabilitation or construction. Moreover, the household-based production of solar energy, which mostly does not lead to self-sufficiency due to the lack of upscaling, undermines the establishment of an independent and conflict resilient energy supply system that would increase the conflict resilience of the whole system on the long run. Similarly, in the water sector, rainwater harvesting and private supply through private wells are not connected to the supply network and they do not guarantee wide access, particularly for economically vulnerable groups. In the context of the wider region, adaptation efforts need to build on existing infrastructure to improve the baseline of utilities, networks, and data. An example of a better alternative is the installation of water kiosks



(water service points) by public utilities to provide low costs and easily accessible clean water for households. In such projects, e.g., practiced in South Sudan, the public utilities can better integrate these emergencies solutions into the supply network after the main conflict phase.

Third, resilience measures need to incorporate a strong role for both the communities as well as the public entities. This is particularly important in the Middle East, where the notion of states and nations is historically weak and communities (e.g., tribes, families, neighborhoods, cities, religious affiliations, etc.) can be more important for self-identification and as institutionalized forums of cooperation. In this presented case of Yemen, there is an evident bias toward community-based efforts and self-organization. In a way, the individual household-based solutions can be summed up to the decentralized implementation of a parallel system. However, even if the implementation is a momentum that came out of the communities, it is a microscale decision-making process that takes place on a household level. It often involves the community in minimal ways. Increasing community-based cooperation has an enormous potential to increase the contribution to the systems' conflict resilience. In fact, the idea of involving communities requires further research in terms of the contributions of these communities depending on the social fabric (e.g., types of communities) and capacities and legacies (e.g., historic role and previous empowerment), as well as their involvement in a specific conflict (e.g., inter- or intra-community conflicts). In the case of Yemen, communities have long-standing legacies of service provision and conflict-resolution in the absence of the state. At the same time, the current conflict is arguably less among communities (e.g., certain tribes, religions, or neighborhoods) but might be more regional (e.g., Northern elites against those in the middle and south of Yemen) and political (e.g., as a proxy war of regional superpowers or a war over the shape of the future Yemeni state) [15]. Still, the presumption that communities (even if involved in armed conflicts) can have a stronger interest in preserving infrastructure than centralized states, the military (e.g., regular armies, militias, or foreign proxies), or rogue nonstate actors (e.g., terrorist organizations) might be true, but requires future research in the case of the Middle East. At the same time, alongside communities, some public involvement would still be needed for infrastructure resilience. With little public involvement in the adaptation efforts in Yemen and a strong participation on the individual household levels, the system units did not address any social cohesion and might have undermined political and institutional levels. In fact, there is an urgent need for public involvement in advancing alternative supply, such as renewables-based energy production, which exhibits a great potential in Yemen [79].

Fourth, regulatory aspects of the current infrastructure adaptation measures (e.g., contracts, transaction costs, legal clarity, and financing) are vague. At the current scale, the information exchange between providers and customers is clear, and the sourcing of information happens individually. However, information exchange and sourcing are not organized through intermediaries (e.g., public entities or donor organizations providing regulation, funds, and knowledge) in a way to increase the conflict resilience of the overall system. Here, the role of donors does not seem to go beyond single projects and does not incorporate flexible solutions that enhance the overall infrastructure system. Such a project mentality in humanitarian aid has been criticized for its unsustainability and the lack of contribution to resilient infrastructure on the long run [39]. Furthermore, despite the intensive informational exchange that exists between the customer and vendors, some risks exist with regard to pricing and monitoring of the contracts. Despite the apparently increasing sale options and increased competition for alternative water and energy supplies, there is not an overall regulation to guarantee transparency, efficient pricing systems, dissemination of technologies, and adequate access for vulnerable groups. Here, the role of public policies needs to be strengthened in order to create a more accessible and fairer infrastructure system. This is also true for adaptation measures or infrastructure rehabilitation efforts toward improving infrastructure resilience. Such measures need to consider distribution or poverty aspects. They can also be embedded in a transformative agenda that seeks the enhancement of well-beings, rights, and capacities of individuals and communities [45].

Ultimately, the infrastructure-related responses to the current conflict in Yemen represent an interesting case of community-driven and self-organization-based adaptation, but they do not illustrate a best case of conflict resilient infrastructure. Whereas we still do not know the extent of these adaptations due to the lack of data, this paper provided some narrative evidence indicating the importance of these measures in mitigating the current conflict-related supply disruptions. They are made possible by necessity, but also by the increased availability of low-cost technologies for harvesting renewable and recyclable resources. The importance of this case lies in the implications for infrastructure design and rehabilitation in post-conflict situations. Here, there is a need to rethink the viability of highly centralized and interdependent infrastructure systems in societies suffering from protracted conflicts. Future research needs to explore ways to optimize the conflict resilience of supply infrastructure in a way that achieves key physical design criteria such as mobility, resource availability, maintenance, and the contribution to the missing baseline. We provided some examples worth exploring, such as community-based grids or network-connected water kiosks. At the same time, it has become evident that soft factors, such as communities' involvement, some level of public guidance, and flexible but clear institutional arrangements, are equally important for long-term conflict resilience of infrastructure. Overall, the proposed sets of adaptation measures will depend on the nature of the conflict, the concrete resilience benefits, and the implications on communities in terms of improving supply, equity, and livelihoods.

## 6. Summary and Conclusions

With the increase in political instability and armed conflicts within some countries of Middle East, critical infrastructure supplying households with basic services such as electricity and water has been affected directly or indirectly. Direct damage of infrastructure, deterioration of the performance of utilities, increased customer debts, discontinuity of services, and the collapse of the whole urban networks are some consequences of conflicts. The vulnerability of such infrastructure to conflict-related shocks and stresses can be counteracted through a better understanding of the challenges facing basic supply infrastructure and a better analysis of the communities' behavior during conflicts. It is vital to link isolated strands of research on humanitarian aid, state fragility, and conflicts, as well as infrastructure resilience and vulnerability.

In this paper, we presented adaptation responses of households, communities, and public actors toward maintaining the water and energy supply during the armed conflict in Yemen. We assessed the contribution of these responses from an infrastructure resilience perspective in order to contribute to knowledge on how to improve conflict resilience of infrastructure on the long-term and how to incorporate responses and adaptive capacities of communities into the larger perspective of systems resilience. The issue of infrastructure and conflict resilience is contemporary and urgent for the politically fragile region of the Middle East and beyond. The propagation of political instability since 2011 has left a devastating toll on infrastructure and communities, while recent developments indicate a dangerous pattern of weaponization of critical infrastructure. Furthermore, the adaptive capacities of Middle Eastern societies have been weakened by decades of politics favoring social fragmentation, unequal distribution of resources, and highly centralized supply systems.

Yemen presents an illustrative and rare case of microscale driven adaptation favored by the availability of regenerative technologies. In the water sector, the state of the public services has been deteriorating for decades due to rapidly rising population, high rates of urbanization, over-abstraction of vulnerable groundwater, mismanagement, and clientelism politics. The decentralization and commercialization reforms of the urban supply in the last decades did not solve the underlying problems of corruption, rising demands, and inefficient allocation. As a result, with the eruption of violence in 2014 and the beginning of the war in 2015, the reliance on private vendors using own groundwater wells, as well as water harvesting structures on a household and community level, increased. This private water market meant an increase in prices and the use of renewable energy for pumping purposes. At the same time, public utilities have been facing serious difficulties with

performance while coverage of services decreased in almost all urban centers. With the help of donors, some emergency supply and rehabilitation projects took place.

Still, public projects encouraging large-scale exploitation of alternative supplies such as rainwater, desalination, or reclamation are still not implemented. With the absence of a strong role of the public sector, communities and the private sector have become more important. In fact, the most transformative adaptation happened in the energy sector where photovoltaic applications for small household uses spread across the urban and rural areas. The dissemination of solar technologies, as well as the capacities to individualize photovoltaic applications, have increased significantly with solar energy being used both by single households and some public entities for self-consumption. Furthermore, for higher energy requirements, private supplies on the neighborhood levels increased significantly, but their services are still reliant on the inconsistent supply of fossil fuel (diesel) and the willingness of households to pay high prices.

Concerning the contribution of the adaptation responses to the overall resilience of the infrastructure system, some critical characteristics of these responses are missing. Whereas the adaptation responses increased decentralization and improved community involvement, they remained highly fragmented, disconnected, and without any overall public regulatory or coordination interventions. These microscale adaptation efforts are necessary for weathering the crisis but are unlikely to effectively strengthen the overall system's resilience. In fact, their incorporation in the supply infrastructure needs to be deliberately targeted through the involvement of public entities and donors. In addition, stronger modes of community participation are needed, e.g., for improving the monitoring and relevance of services, the ownership of infrastructure, as well as the commitment to maintenance and rehabilitation. Integrating neighborhood-based solutions, such as water kiosks or district-level generators for emergencies into the public utilities' operations, can help to improve the mobility of the system. It also ensures the continuation of maintenance, operation, and service provision at affordable costs.

In summary, the resilience responses of the households and communities in Yemen have been remarkable for establishing parallel supply systems in short periods that have helped people cope with the devastating impacts of the conflict in some limited ways. However, considering the widespread poverty and the rural face of Yemen, it is doubtful that the benefits of these established systems can reach vulnerable groups. Besides, for the current self-organized and private systems to continue in another form after the conflict, public involvement, coordination and planning can transform these adaptation efforts into components of a flexible and conflict resilient supply infrastructure for the future.

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