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Conflict, Health, and Electricity

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Conflict, Health, and Electricity: An Empirical Assessment of the Electrification of Healthcare Facilities

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Abstract

While the effect of energy on conflict is well-studied, scholars have rarely investigated the impacts of conflict on electricity (setups) and healthcare. Prolonged violence has exacerbated Yemen's energy crisis — a dynamic which has also affected healthcare facilities. We construct and analyse a dataset of healthcare facilities, including their power mix and conflict situation. The study addresses both researchers of the energy-health-conflict nexus and Yemen analysts. We perform interviews, QGIS mapping, hierarchical clustering, and logistic regressions to review the situation, identify relevant patterns, and estimate the conflict's impact.

Our analysis reveals that most facilities (58%) have no electricity, but patterns are diverse and non-trivial. Rural facilities have either never had electricity ('Deserted Village Units') or their power has been cut off ('Brownout Stations'). In contrast, some facilities in cities have switched to sophisticated hybrid systems ('War-torn City Hospitals'). A large, spatially concentrated group of mid-sized facilities managed to go from no electricity to all-solar ('Solar Centres'). The role of conflict is non-monotonous and depends on the exposure and type. Both the most-affected and least-affected facilities tend to have electricity, while those in between are left behind. Ground combat decreases the probability of obtaining solar energy, while airstrikes do not. Knowledge and knowhow remain a strong lever to support development, e.g. by promoting hybrid systems and solar mini-grids. The dynamics showcase the transformative and redistributive moment of conflict which deprives some of electricity but facilitates novel technologies elsewhere. We advocate for research and policy focusing on technological shifts in conflict-affected countries.

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Keywords: health; energy access; conflict; clustering; solar; Yemen

1. Introduction

Yemen's prolonged war has ravaged its energy system. Fighting, underfunding, and diesel shortages have wreaked havoc on the nation's underdeveloped power grid and left communities and cities without electricity [1]. These developments have also hit healthcare facilities, which are facing not only Covid-19 but also the world's largest cholera epidemic and the consequences of widespread malnutrition [2-4]. Generally, both electricity access and healthcare provision are central challenges in fragile countries. Of 759 million people without access to electricity, 86% live in fragile contexts, i.e. in conflict or with weak public services. First, logistical and financial challenges along with heightened investor risk make it harder to sustain energy supply [5]. Second, energy infrastructure presents an attractive target for violence [6]. This fact has been discussed in relation to various examples [7], including Yemen [8]. Regarding health, nearly 3.5 billion people still lack access to full basic healthcare [9]. Healthcare facilities require stable electricity to provide modern medical treatments [10] — something that is ever more important during violent conflict.

Besides the question of whether facilities are electrified – *if* – is the additional matter of *how*. While in some cases, hospitals may (still) receive electricity from a public grid, others may be forced to operate off-grid — typically using diesel generators or solar panels. The latter are increasingly considered a general remedy in fragile contexts, due to their decentral and self-sufficient nature [11]. Yemen, in particular, has witnessed massive, bottom-up-led growth of solar energy, which has become the country's most significant source of electricity [1] — a development that is in line with previous studies emphasising its potential for renewable energy [12, 13].

These developments offer the chance to assess the exact patterns and extent to which conflict impacts access to energy resources and, eventually, the healthcare sector. As opposed to the well-researched link between energy and conflict (see e.g. [14, 15]), the converse relation is still opaque, particularly regarding electrification setups and health. This gap comes at a cost. Understanding how exactly actors on the ground react to conflict is integral to supporting resilience and paving a smooth transition to long-term rebuilding, be it in Yemen or other fragile countries. Such knowledge also represents a step towards promoting 'the local' vis-à-vis often-unfit global perspectives on development, especially regarding renewable energy (see [16]). Missing the energy dimension in war-related health crises may cause the wrong responses. For instance, humanitarian actors or local governments could choose to focus on providing medical equipment whereas energy supply is actually the most constraining factor on healthcare.

Macroscopically, war's destructive nature is likely limit access to electricity. However, we conjecture that the impact will vary between facilities and that (observable) factors — facility characteristics such as size and location but also the form and extent of conflict-exposure — have a structural role in this. Logistical, material, and managerial aspects, which are connected to the aforementioned factors, may impact if and how health facilities adapt to crises. Emerging literature on Yemen's solar boom suggest large inter- and intra-regional differences [1, 17]. Not only might conflict-exposure be relevant but also the type of combat, since airstrikes and ground-level combat differ in persistence, effect, and scope. In this regard, Yemen's solar boom suggests that the conflict may even have had a positive, transformative impact on some certain, previously unelectrified objects.

Therefore, we not only seek to quantify the developments in Yemen, but also to investigate the drivers of electricity supply and the asymmetric effect of different forms of conflict. More precisely, we seek to assess the situation, identify patterns in electricity setup and observables, and test the effect of different forms of conflict on solar energy diffusion. The study therefore has elements both of an explorative analysis and a causal investigation.

We tackle the research agenda using four separate methods. First, we visualise energy supply and conflict using geographic information system (GIS) mapping. Second, we obtain anecdotal evidence on the situation of healthcare facilities from expert interviews. Third, we perform a hierarchical clustering of the facilities and their energy supply to develop and analyse relevant groups and archetypes. Fourth, we use a logistic regression model and generate predictions regarding the effect of conflict on solar energy usage. Our analysis is based on a dataset of 5,183 facilities, mainly from the WHO HeRAMS [18], as well as conflict data from the Armed Conflict Location and Event Data Project [19].

The analysis confirms that the war's effects on hospital electricity supply have been disastrous, albeit diverse. Aside from numerous facilities that were deprived of electricity access and a large group that has never had access to power, there are also numerous facilities that have adopted solar energy or sophisticated hybrid systems due to the war. We find evidence of an asymmetric effect between different forms of combat, which is partially contingent on facility characteristics. These results improve our understanding of conflict, energy, and health and are therefore relevant for a Yemen-related audience and global scholars alike.

The remainder of this paper proceeds as follows: Section 2 provides a brief country profile and recap of events. Section 3 presents our research design, including objectives, methods, and data. Section 4 provides a descriptive assessment of the situation of health facilities in Yemen. Section 5 deepens the analysis by exploring patterns in healthcare power supply using a clustering analysis. Section 6 focuses on the regression results and studies the effect of war on the diffusion of solar energy. Section 7 presents conclusions and policy recommendations.

2. Background

Yemen, located at the southern tip of the Arabian Peninsula, is among the poorest economies in the Middle East. In 2010, following decades of stagnation (see [20]), the GDP per capita was only 1,335 $US, and 35% of its (at that stage) 23 million inhabitants had no access to electricity. Since then, things have taken a turn for the worse. A revolution in 2011 ended in a contested and tense transitional period which was brought to a factual end in 2015. At that time, fighters of Ansar Allah (a Northern rebel group colloquially known as the Houthi movement) seized control of the Yemeni capital [21]. The move led to a military intervention from a coalition of states led by Saudi Arabia officially, per request from the Yemeni government (see [22, 23]).

The coalition is infamous for its airstrike campaign, which has mainly targeted Houthi-controlled governorates in the country's mountainous north(-west). In the period between 2015 and 2016 (our focus in this paper) the conflict has escalated dramatically, including both airstrikes and regular instances of fighting between forces loyal to the coalition-backed government, Houthi brigades, and separatists in the country's south.

Even prior to the conflict, the power sector suffered from weakness and inefficiency. The annual energy consumption per capita stalled at 217 kWh in 2014 — one sixth of the regional average (IEA). By 2010, Yemen`s electrification rate was the lowest in the region and did not exceed 60%. A lack of electrification was especially a rural problem with only 32% of rural communities having access to electricity (IEA). A government strategy from 2009 planned to connect 50% of the remaining regions by 2020 but progress to this end was limited. In total, the national power generation capacity never exceeded 1.5 GW, while actual supply peaked at 1 GW; meanwhile, the load reached up to 2.6 GW, implying a supply gap of 38% [17]. Moreover, the power infrastructure was outdated and poorly maintained; one result of this were distribution losses of up to 27% [12]. Scholars typically quote persistent institutional failure and a lack of financing as root issues behind the weak sector [20, 24]. Yet, complex terrain and frequent attacks on the infrastructure constitute additional hardships.

With the onset of the war, the deterioration of Yemen's power system continued . Many power stations were destroyed or forced to shut down [8]. The World Bank estimates that 55% of power sector assets have been damaged, and 5% have been fully destroyed. Between 2014 and 2016, access to electricity from the national grid fell from 66% to less than 10% [25]. Nationwide, the power supply dropped from 1,500 MW prior to the war to some 200 MW in 2016. This includes the capital, Sana'a, where the remaining supply is estimated at 40 MW [1]. Some responsibility also falls on fuel shortages which have rendered electricity from diesel power stations and generators mostly infeasible.

Surprisingly, there has also been a significant shift to stand-alone photovoltaic (PV) systems — not only among residential users but also among infrastructure providers. Grey literature considers the substantial growth — starting at virtually no applications in pre-war Yemen — to be a bottom-up development led by households and private businesses [1]. It is often driven by necessity; studies consider it a direct result of the war[1] [24]. Estimates of Yemen's solar market volume for the years 2014-2017 reach $US 1 billion cumulatively [27] and a majority of Yemeni households are reported to have some sort of solar supply [1]. Yemen's 'solar revolution' mostly focuses on the country's mountainous north(-west), concentrically using the favourable environmental conditions for PV systems (sun-rich yet chilly) [17]. However, towards 2019, sectoral constraints caused diesel generators to regain popularity despite price spikes [1].

[1] Similar patterns appeared in Gaza, where escalations in the security situation caused a decline in electricity imports and the bottom-up adoption of solar energy systems [26].

3. Study design

3.1. Research structure and objectives

Rather than answering a single question, our study aims at constructing a holistic picture of the energy-health-conflict nexus in Yemen. We equally seek to assess the status quo — i.e. explorative research on the case study, which may assist or even stipulate future work —and to investigate selected causal linkages that are of academic and professional interest. Along the lines of these two goals, the study is led by three overarching topics:

(1) How has the war impacted the Yemeni healthcare sector and its electricity supply?

(2) What drives the electricity supply for (Yemeni) hospitals?

(3) To which extent does conflict have transformative power beyond destruction?

We narrow down the (feasible) scope for this article by deriving more precise research questions from these topics. Some are more descriptive in character, while others are statistically testable hypotheses.

Regarding the first topic, the study asks about the status quo of Yemeni healthcare facilities and their electricity supply. We expect that the war's destructive element has further limited access to electricity — and thus doubled down on the pressure on health facilities. In particular, we seek to quantify the electrification rate among facilities, their energy sources, and the supply shifts resulting from the war. Moreover, we wish to analyse the conflict perspective: how does conflict seem to have influenced these health facilities[2], and are there spatial patterns of energy supply that coincide with conflict? In this regard, we also seek to identify and scrutinise archetypes of facilities in conflict.

Concerning the second and third topics, we consider that the situation (and, more precisely, the electricity supply) is not random. Although it may not have been strategically planned, we conjecture that observable factors have influenced decisions regarding facilities' power supply. We separate these factors into characteristics — environmental variables — and the extent to which a facility is exposed to conflict.

We generally expect that exposure to conflict has a negative impact on energy and health infrastructure due to destruction, recession, increased needs, and logistical challenges. While we have no reason to dispute the deterioration on a macroscopic level, we do however conjecture that the effect of conflict is neither uniform nor monotonous. Yemen's shift to solar energy, for example, has not yet been subject to extensive academic investigation, but grey literature and anecdotal evidence have gathered strong indications of growing electrification

[2] Importantly, our study conceptualises (and models) the energy-health-conflict triangle through the lens of the electricity setup for healthcare facilities within contexts of ongoing violent struggle. In other words, we focus on the impact of conflict on hospital electricity instead of explicitly measuring a triangular relationship between energy, health, and conflict. The paper thus implicitly assumes that — everything else being constant — public health is a mere function of electricity as a productive input. This assumption, although admittedly restrictive, is imperative due to data unavailability and the necessity to bound this paper's exceptionally broad scope. We nonetheless use the qualitative analysis in this paper to include at least some descriptive elaborations on the provision of healthcare itself. Interested readers may also study other academic contributions that concentrate on (and measure) the direct health outcomes of (missing) electrification. They notably include [28] for the case of India, [29, 30] for Senegal, [31] for Ghana and Uganda, and [32] for Malawi.

rates and increasing resilience. We therefore expect that the effect of exposure to conflict will not be constant but instead vary depending on circumstances. In this paper, we aim at investigating such patterns and ask which circumstances are indicative of specific electrification setups.

A particular area of interest is the adoption of solar energy. We assume that factors of a managerial nature and related to material and logistical aspects are relevant.

Larger facilities may have a stronger need for (solar) electricity than smaller ones; furthermore, they likely have greater resources in terms of finances and know-how. It may also be easier for them to include solar panels into an electricity mix, e.g. in a hybrid-grid setup. Similarly, we expect that urban facilities have better access to resources than rural ones.

Because the literature frames the diffusion of solar energy in crisis-hit areas as a bottom-up movement born out of necessity, we expect that continued access to power from the national grid will be detrimental to solar energy adoption. Facilities that continue to receive power in an 'easier' way might be less prone to invest in solar panels. Moreover, we expect that even if a facility experiences a war-related blackout, pre-war access to grid electricity may trump the odds of investing in solar energy. We conjecture that hospital decision-makers at such facilities may prefer waiting out the crisis in hope of a returning national grid. Depending on the investment costs and individual discount factor, such behaviour may even be rational, since health facilities that expect to regain national grid power have a higher cost of opportunity for investing in alternative energy equipment. Consequently, we expect that facilities with no prior or current access to grid electricity may be more inclined to adopt solar energy.

Conflict in Yemen, as elaborated above, mainly materialises in two different forms: airstrikes[3] and clashes on the ground. Airstrikes target individual objects through one or multiple missiles and usually result in the destruction of the targeted structure — typically buildings. Ground combat includes various forms of violence on the ground. It ranges from a single party shelling an object to frontline clashes to the use of artillery. Consequently, the effects and duration of ground combat vary immensely. However, ground combat is typically more persistent and spatially spread out yet less devastating than airstrikes.

Since they differ in nature, we hypothesise that airstrikes and ground combat have different effects on the adoption of solar energy. More precisely, we expect that ground operations have a negative impact on solar energy diffusion. On the material level, ground combat may challenge logistics (e.g. roadblocks, increased costs from illegal customs) or damage solar equipment (be it through random shelling or deliberate targeting). On the managerial level, persistent ground operations may make decision-makers more hesitant to invest, since the risk increases and budgets may shrink. Moreover, they may make a region less accessible, making it harder for knowledge to spread or trained technicians to engage with a facility. Conversely, we expect that airstrikes have either no effect or even a positive one. Airstrikes are of a more transitive nature and less likely to interrupt existing systems. If hit, their destruction can have a lasting impact on infrastructure; yet airstrikes do not directly affect the material resources of surrounding health facilities. Instead, on a managerial level, it could be argued that airstrikes make decision-makers

[3] The coalition officially aims at 'restoring peace' by combatting Houthi forces and striking military targets. However, many argue that the controversial airstrike campaign follows other goals and includes civilian targets [22].

more aware of the need to become resilient and independent — thus increasing the tendency to obtain solar equipment.

3.2. Methods

The ambitious and broad research agenda requires an assemblage of methods. Expert interviews and GIS mapping aid us in exploring the situation. Clustering and logistic regressions allow for a deeper analysis of the situation and testing of hypotheses regarding the effect of conflict.

The expert interviews – our only qualitative instrument – help us reconstruct general developments and trends. Since our dataset (see Section 3.4) does not feature indicators to measure healthcare performance, the interviews are also our main tool for assessing how electricity problems ultimately translate into healthcare issues. We use a semi-structured questionnaire to interview a small group of Yemen-based hospital representatives with direct knowledge of the situation. Subsequently, we code the interview transcripts based on the topics and questions in this research (i.e. healthcare performance, electricity supply, conflict situation, and relationships between them). Within each of these general categories, we perform a descriptive coding of the answers. Section 3.3 presents details on the interview process.

The QGIS mapping aids the descriptive analysis of the situation in Yemen. We overlay quantitative field survey data and qualitative insights on conflict, health, and electricity. The resulting maps visualise conflict events, grid coverage, and electricity supply settings per district.

Next, we turn to an agglomerative hierarchical clustering of the dataset, i.e. we create subsets of healthcare facilities with similar values regarding energy, conflict, and further characteristics. The process[4] enables identification of facility archetypes and detection of further patterns in the data. We implement the algorithm using the Python library Scikit [33]. Section 3.4 names the variables. Before performing the clustering, we standardise each variable. We use Euclidean distance and ward linkage as similarity metrics. In the next step, we decide on a depth level within the hierarchy to fix final clusters. In our case, based on the resulting hierarchy, we choose a level of depth corresponding to seven distinct clusters. Aside from looking at the properties of each cluster, we perform a principal component analysis (PCA) to reduce the dimensionality of the clusters to two distinct measures.

Lastly, we perform logistic regressions to test and predict the relationship between conflict and solar energy supply. The setup models the probability that a facility owns a solar panel based on several predictors. Formally, we estimate the following equation

$$\phi_i = \beta' C_i + \gamma'(1\, Z_i) + \delta' C_i Z_i' + \varepsilon_i$$

where, ϕ_i are the log-odds of facility i owning a solar panel, i.e. the logarithmic ratio of the probability that a facility is equipped with solar energy and its complement. C_i and Z_i contain the conflict indicators and characteristics of each facility, respectively. $C_i Z_i'$ contains interactions

[4] The clustering algorithm starts by considering each facility its own cluster and continues to group these clusters iteratively, based on their distance. The initial result of the clustering is a hierarchical structure of all individual sample points.

between conflict and environmental variables. β', γ' and δ' are the respective vectors of coefficients, whereas γ' also contains the constant. ε_i captures the residuals for each observation. We use ordinary least squares (OLS) to estimate the model. Robustness is ensured by estimating a variety of setups: we vary interaction terms, controls, and conflict indicators, including a setup that uses Lasso for selecting appropriate controls. Subsequently, we compute predictive margins to visualise the results.

3.3. Interviews

Table 1: Overview of the variables used in the clustering and the regression analysis.

	Interview #1	*Interview #2*	*Interview #3*
Represented facility	Healthcare group with multiple hospitals and clinics	Healthcare clinic	Hospital
Facility location	Sana'a governorate	Jabal Habashi, Taiz governorate	Dhamar city
Urban/rural	Both	Rural	Urban
Position	Electrical engineer	Facility owner	Operational manager
Years of experience in this position	7	9	9
Pre-war electricity setup	National grid; Diesel generators (in urban hospitals)	National grid, Diesel generator (backup)	National grid
Current power supply	Solar panels(all); Diesel generators and national grid (in urban hospitals)	Solar panels; Diesel generator (backup)	Diesel generators
Conflict situation	Ground combat nearby	Ground combat in neighbouring districts	Airstrikes and ground combat other parts of the city
Impact on power supply	National grid outages; Interrupted/expensive diesel supply; PV panels damaged	National grid blackout; Interrupted/expensive diesel supply	National grid blackout; Interrupted/expensive diesel supply
Impact on healthcare provision	Reduced hours and treatment; Vaccinations unavailable in some smaller facilities	Limited drug availability; Large appliances can only be used exceptionally; Hours cut by 50%	Some treatments cannot be offered; Hours reduced
Stated reason for purchasing solar panels	Unavailability/high price of diesel	Unavailability/high price of diesel; desire for resilience amid roadblocks	N/A
Obstacles of solar energy supply	Limited space in urban areas; Shelling; Limited power	N/A	Power perceived as too weak

We contacted selected experts personally and asked them to participate (anonymously) in an interview for an academic study about the power-supply of Yemeni healthcare providers. The n=3 interviews took place in July 2022 and were conducted on the phone using a brief semi-structured questionnaire.

At the beginning of each interview, the participant was informed about the context of the interview and the interviewer's intentions. They were reminded that the interview is voluntary, that they may abort the interview and withdraw their consent at any time, and that they could decide to remain anonymous. The subsequent questions covered the interviewee's background, conflict-related challenges in healthcare provision, the facility's current power supply and its performance, how the power supply has been affected by conflict, and an open question for further remarks. Each interview took about 30 minutes and was conducted entirely in (Yemeni) Arabic. All participants chose to remain anonymous and asked not to be named.

We used audio recordings of the interviews to prepare translated transcripts and subsequently coded the transcripts. Table 1 contains a summary of the interviews, which is based on the coding. The full transcripts can be found in the supplementary material.

3.2. Numerical data

Our analysis rests on a combined dataset and sample of 5,183 active healthcare facilities in Yemen, covering the entire country. All data concerns the year 2016 unless stated otherwise. Table 2 provides an overview of the variables that we derive from the dataset.

We assemble a dataset regarding the facilities' properties and energy supply from the World Health Organisation's Health Resources Availability Mapping System (HeRAMS) [18] and public governorate-level sources [34, 35]. The data include facility size (minor, medium, or major), setting (rural or urban), location (governorate, administrative district, and coordinates), electricity supply (none, solar, diesel, grid, or various mixes thereof), and national grid access. Noticeably, the latter does not imply that the site receives power from the grid but only that a grid connection was built at some point in time. Facility size was modelled to reflect various indicators such as patient capacity, service provisions, and permanent staff size [36].

Furthermore, we use conflict data from the Armed Conflict Location and Event Data Project [19], which builds on data gathered by the Yemen Data Project (Project). The dataset entails records of conflict-related events, each one with the precise date, event type, involved actors, location, (estimated) number of fatalities, source, and narrative description of the event.

We use the data to derive continuous measures of conflict: for each of the 3,906 facilities with recorded coordinates, we compute their distance to any conflict event. For this purpose, we define 'ground' and 'airborne' as two different types of combat. For the former, we consider records relating to the types 'battles' (which includes armed clashes and territorial gains) and 'shelling/artillery/missile attacks'; for the latter, it is 'air/drone strike'. Our central measure is proximity to conflict: For each facility, we compute the distance to the closest instance of either type of conflict. We also compute an alternative measure: the intensity of conflict, given by the number of (airborne or ground) combat events that occur within a radius of 20 km around a facility. Both measures separate data for the years 2015 and 2016.

Lastly, we use information from public authorities [37] to construct a binary indicator that reflects whether a governorate still receives electricity from the grid. We then assign corresponding values to each facility based on their location.

Table 2: Overview of the variables used in the clustering and the regression analysis.

Variable name	Description	Mean (or share for binary variables)	Standard deviation
Facility characteristics			
facility_type	Categorical variable, indicating the facility size (1: minor / 2: medium / 3: major)	1.482	N/A
urban	Binary variable, indicating whether the facility is in an urban area	0.150	N/A
on_grid	Binary variable, indicating whether the facility has a national grid connection	0.319	N/A
on_grid_avl	Binary variable, indicating whether the facility is in a governorate with at-least-partial national grid supply	0.139	N/A
Energy supply			
solar_onl	Binary variable, indicating whether a facility's only electricity source is solar energy	0.168	N/A
solar_inc	Binary variable, indicating whether a facility's electricity sources include solar energy	0.262	N/A
diesel_onl	Binary variable, indicating whether a facility's only electricity source is diesel energy	0.065	N/A
diesel_inc	Binary variable, indicating whether a facility's electricity sources include diesel energy	0.085	N/A
Conflict indicators			
dist_air_2015	The distance between a facility and the nearest airstrike in 2015	19.067	53.218
dist_air_2016	The distance between a facility and the nearest airstrike in 2016	18.495	50.567
dist_ground_2015	The distance between a facility and the nearest instance of a ground combat in 2015	16.163	34.037
dist_ground_2016	The distance between a facility and the nearest instance of a ground combat in 2016	23.453	49.296
intens_air_2015	The number of airstrikes within a radius of 20 km around a facility in year 2015	73.230	159.670
intens_air_2016	The number of airstrikes within a radius of 20 km around a facility in year 2016	73.113	159.091
intens_ground_2015	The number of ground operations within a radius of 20 km around a facility in year 2015	20.888	55.153
intens_ground_2016	The number of ground operations within a radius of 20 km around a facility in year 2016	20.087	62.510

4. Descriptive analysis: the situation of healthcare facilities

Starting with a general perspective on the distribution of combat, we find that most of the 333 administrative districts experienced armed clashes on the ground (see Fig. 1). 47% and slightly fewer 39% were affected in 2015 and 2016, respectively. The map shows that the coastal regions (e.g. Aden, Taiz), which feature oil refineries and strategic ports, were combat hotspots. Furthermore, fighting haunted the country's major cities Sana'a, Aden, and Taiz. Most areas that witnessed clashes in 2015 also did so in 2016 — likely a result of ongoing struggles to keep positions. There is no visually recognisable pattern regarding the evolution of conflict-affected districts.

The health sector has not been spared from this. By late 2016, the armed parties are reported to have damaged 274 healthcare facilities and fully destroyed 79 institutions [38]. However, as both our interviews and sample show, far more facilities have been affected —through the electricity sector.

All interviewees name electricity outages and commodity shortages as the war's main impact. In each case, and despite regular outages, facilities drew power from the national grid in pre-war times. However, only the respondent from Interview #1 — an electrical engineer representing a healthcare group in Sana'a — reports at-least sporadic electricity deliveries post-2015. The respondents in Interview #2 — the owner of a clinic in rural Taiz — and Interview #3 — a hospital operations manager from Dhamar city — confirm that they have not received power from the grid ever since.

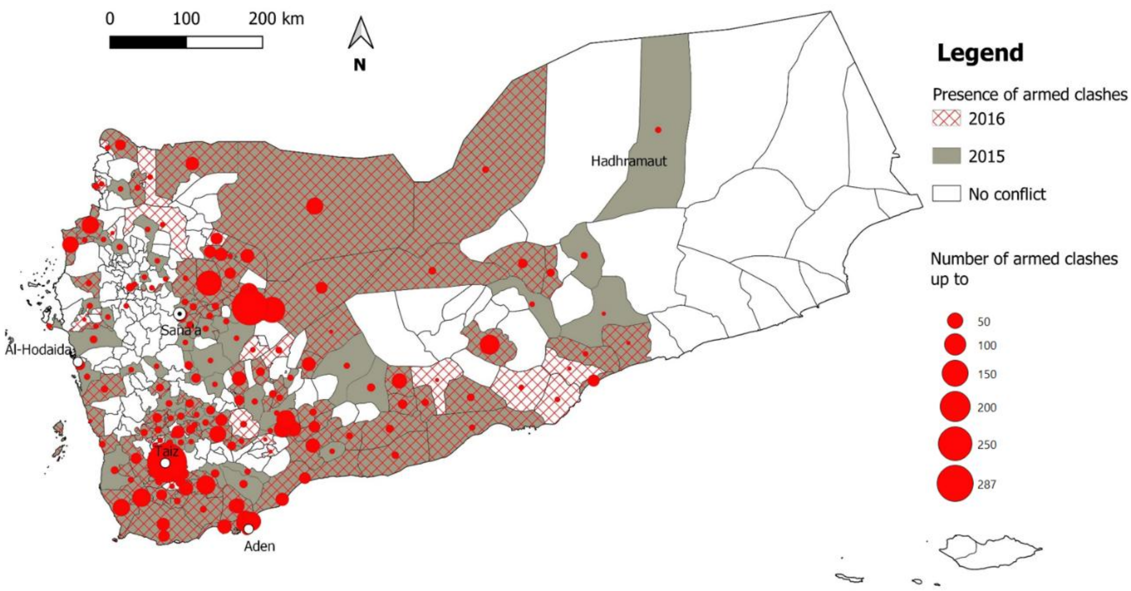

Figure 1: Status of the armed clashes and their events per district in 2015 and 2016.

Electricity shortages have led to stark restrictions in healthcare. All interviews name reduced operations as a consequence. The respondent in Interview #2 even quantifies the hour shedding at 50%: daily operations have typically decreased from 12 to 6 hours daily. This observation matches other studies: A WHO survey showed that only 45% out of 3,507 facilities were fully operational, whereas 38% were partially able to provide essential medical services, and 17% were completely out of use [18]. [39] estimates that the conflict has forced 55% of facilities to partially or completely close. Similarly, the interviewees mention that some treatments cannot be offered (Interviews #1 and #3) or that energy-intensive appliances (such as MRIs) can only be used irregularly (Interviews #1 and #2). Interviewee #1 furthermore elaborated that some rural facilities without backup energy have become unable to provide some vaccines due to a lack of refrigeration. Vaccination rates have seen drastic drops: In 2016, only 59% of children received standard immunisations such as measles and rubella [39]. The only impact named in our interviews that does not stem from a lack of electricity is drug scarcity (Interview #2). According to the interviewee, roadblocks and clashes have made it more difficult (and costly) for rural facilities in war hotspots to access the city to purchase medicine. Measurable consequences of the public health crisis included outbreaks of communicable diseases (especially cholera, dengue fever, and diphtheria), some of them the worst recorded in global history [24].

In our dataset, only 42.3% of the 5,183 facilities have access to some form of electricity, and the number of facilities which receive power from the national grid is as low as 530. Fig. 2 visualises the spatial dimension[5] of healthcare facilities, electrification, and grid access.

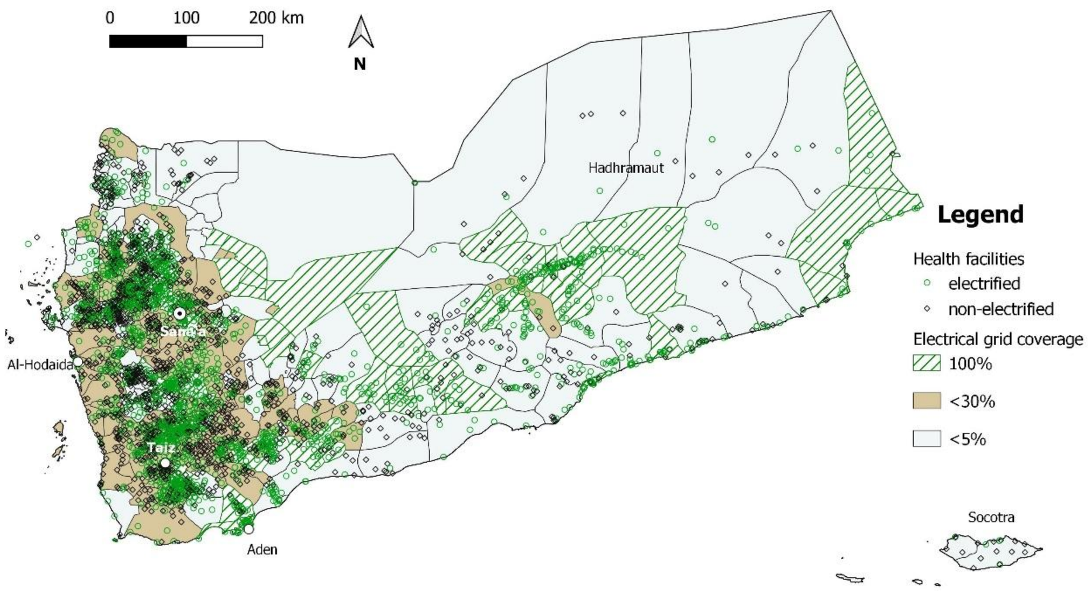

Figure 2: Healthcare facility electrification status and national grid coverage by district across Yemen.

To begin with, the map reveals an unequal distribution of grid access across the country. Only 32% of Yemen's administrative districts have access to the national grid, most of which are urban areas. Full grid access is mostly limited to areas next to central power stations, cities, or politically privileged regions. Regarding the facilities within our sample, most are located in the

[5] This map (and all the following ones) only visualise those 3,911 facilities in our dataset for which spatial coordinates (latitude/longitude) were available.

country's populous west[6] and in districts with a grid coverage of no more than 30%. A substantial amount are even located within districts with grid access rates below 5%. These districts account for 26% of all districts; many of them are marginalised or scattered settlements.

Nevertheless, as discussed previously, a grid connection does not imply a power source. Due to damaged infrastructure and power generation shortages, most regions do not receive supply from the grid even where the grid exists. In our sample, 1,668 facilities have access to the grid but only one third of them actually receive power from it. Furthermore, the map shows the potentially unintuitive fact that neighbouring hospitals do not necessarily have the same electrification status. Within a single district and especially in the country's mountainous north(-west), there can be both units with and without access to a grid — often due to varying topography.

Overall, and as the clustering analysis in the subsequent chapter will detail, electricity access is distributed unevenly across observables. While 77% of urban facilities have electricity, only 34% of rural ones do so. Electrification also increases with facility size: while only 30% of (minor) health units have power, 65% of the (medium-sized) clinics and even 87% of the (large-sized) hospitals are electrified. This result is in line with other studies that have shown that healthcare electricity access in the Global South is more likely for larger-sized facilities [40].

Turning to power supply options, facilities can use national grid electricity, solar energy, diesel energy, or combinations thereof. Diesel systems can take the form of standalone systems and diesel-powered, private mini-grids. Together they power 20% of the facilities in our sample. Solar panels, which power 65% of the electrified facilities in our sample, may be stand-alone (60%) or connected in a hybrid setup (40%). Generally speaking, in this context we define 'hybrid systems' as any electricity supply that utilises more than one of the abovementioned sources (see also [41]). In the sample, a surprising 28% of electrified facilities run on such hybrid systems. Mostly, these are combinations of grid/solar or diesel/solar. Solar-powered mini-grids are a vital option [13] but virtually absent in Yemen.

All three interviewees describe the use of off-grid solutions to stabilise operations. Those are solar panels and, for larger facilities, backup generators (Interview #1 and #2) and diesel generators (Interview #3). It is, however, diesel that has been especially hit by the war. Import controls by coalition forces have strongly limited diesel supply to Yemen, which led to scarcity and exploding prices (Interviews #1, #2, #3). All interviews therefore name diesel as one of their main concerns, contributing to the limitations in health services described above. Interview #2 also highlights how the political collapse of Yemen pushed the role of local authorities, whom many consider to be part of the problem, e.g. by not securing enough diesel for their constituents. Interestingly, while the urban facilities (Interview #1 and #3) often talk from a macroscopic perspective and focus on diesel availability, Interviewee #2 — the rural facility — seems to regard much of the conflict through the lens of increased commodity prices and logistical hardship resulting from the siege of the nearby city. Also, solar panels are not unaffected by the war, since importers need to pay customs to multiple parties, which increases the final price (Interview #1).

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[6] These regions are mostly highlands, which makes grid extensions a difficult and costly option.

Fig. 3 provides a spatial assessment of electricity sources from our sample. Throughout the country, most districts have solar energy as their dominant source of electricity, followed by the public grid, and diesel mini-grids. The map shows a strong solar-and-grid divide between the north(-west) and the south(-east). This divide is mostly congruent with the division of power between Houthi-controlled areas (north/west) and areas under the UN-recognised government (south/east). It also resembles the pre-unification borders between former North and South Yemen. Most districts in the former are endowed with solar energy, whereas the majority of districts in the latter still rely on the public grid. A noticeable exception are arid and remote areas, such as Socotra and the desert of Hadhramaut, which rely on off-grid solutions. In turn, some dense urban areas in the north continue to depend on whatever little supply they obtain from the national grid. As mentioned previously, the divide is also in line with topography and climate: most districts that depend on solar energy are located in the moderate-temperature highland regions, whereas grid-reliant coastal regions in the south and east do not really have a more efficient option than grid extensions.

When combined, the three maps suggest that the reaction to conflict is nontrivial. While armed confrontations have affected two-thirds of the densely populated districts, a significant spread of solar energy systems is occurring amid diffuse electrification. Solar systems appear to be resilient in conflict-affected areas, even more so than diesel. Despite this dramatically expansion of solar systems in Yemen, however, more than half of healthcare institutions are still without electricity. The next subsection expands on these points.

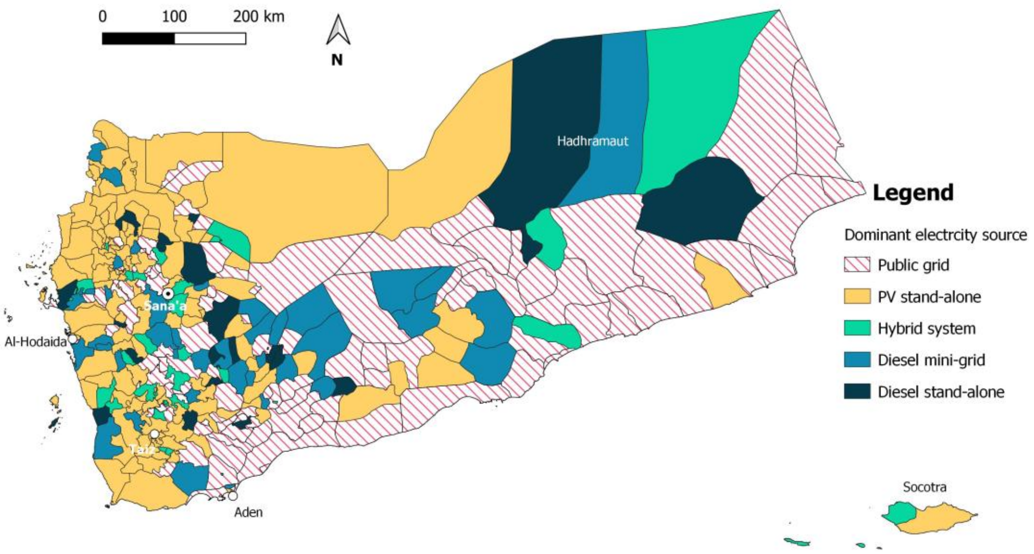

Figure 3: Dominant source of electricity (by plurality) for the healthcare facilities by district.

5. Clustering analysis: patterns in healthcare electricity supply

5.1. Main analysis

This section showcases the results of our clustering analysis. It uses all facility characteristics and power supply indicators given in Table 2. For conflict, we use the proximity-based measure. An alternative analysis using conflict intensity is provided in Section 4.2.

As explained in the methods section, we derive seven distinct clusters, which we analyse to identify further patterns in the data. Our choice of seven distinct clusters corresponds to a cut-off distance of 66.73. We choose this cut-off level, since a higher or lower number of clusters would worsen their interpretability. As the dendrogram (Fig. 4) shows, the agglomeration is rather rapid until this cut-off and then decreases in its speed further up the tree. Furthermore, Fig. 5 depicts the clustered points on a two-dimensional plain generated by two principal components. The scatter plot verifies the goodness of our clusters. The clusters 1, 2, and 3 are located near the origin and show some overlap, but the boundaries between the clusters are apparent. Cluster 5 and, even more so, Cluster 6 are diffuse in the two-dimensional projection, but its members are mostly distinct from the other clusters. Cluster 7 is an island and insulated from the other clusters, showing very high scores on the first principal component. Cluster 4 does show a larger overlap with the clusters 1 to 5.

We now move on to presenting and discussing the clusters themselves. Table 3 contains an overview of the clusters. Table 4 and Fig. 6 depict their spatial distribution over the districts as absolute frequencies and dominant clusters, respectively. Our first cluster, entitled "Deserted Village Units", contains 1,366 of the 3,906 facilities included in the analysis. It is, hence, our largest cluster. It covers small, rural facilities without any access to electricity. These facilities are close to conflict (especially airstrikes), but not in immediate proximity. The Deserted Village Units have seemingly been forgotten by state and humanitarian actors: they have no grid access, nor any standalone supply by solar or diesel energy. This cluster is not necessarily a victim of the war but of general underdevelopment; the entirely absent energy supply suggests that these facilities were forgotten long before the conflict even started. We suspect that these small facilities are below the radar of international assistance and that there is no funding to obtain solar equipment or power generators. The fact that this is the largest cluster by a landslide shows that a significant portion of healthcare providers — 35% in our sample — are completely off the grid, in all possible meanings.

The "Brownout Stations", our second cluster, are another group of entirely rural and mostly small facilities. The facility covered in Interview #2 is an example of these type. This group of 837 units differ from Deserted Village Units regarding a crucial point. Although they have almost universal access to the national grid, electrification rates remain low, albeit higher than for the previous group. Prior to the war, most Brownout Stations received power from the grid. Now only a quarter do so, in addition to another 10% that rely on a combination of solar and diesel generation. While the Deserted Village Units have never accessed electricity, Brownout Stations have mostly lost access to the grid due to reductions in power-plant supply and infrastructure deterioration. Interestingly, on average, they are further from conflict events than the first cluster.

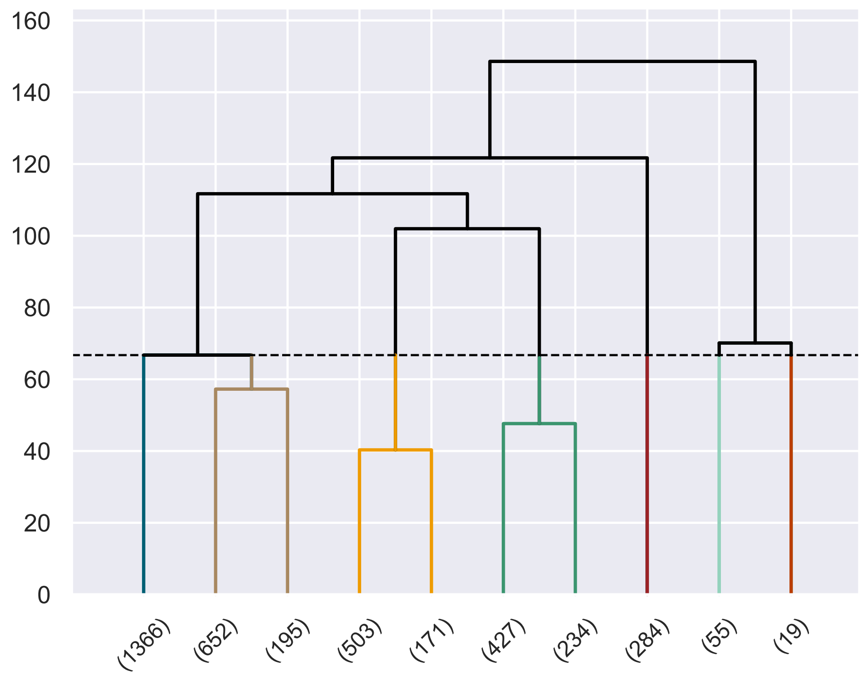

Figure 4: Dendrogram with average distances within the clusters and cut-off level.

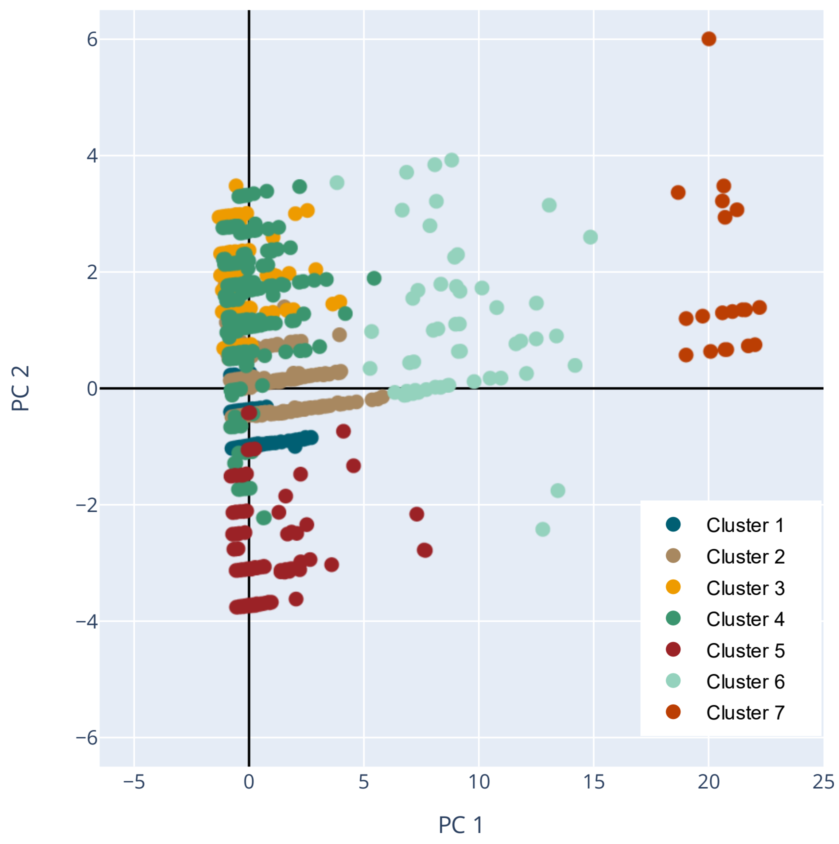

Figure 5: Visualisation of the resulting clusters as a two-dimensional PCA.

Cluster 3 carries the name "Solar Centres" and contains mostly small-to-medium off-grid facilities, which are entirely powered by solar energy. With 674 facilities, it is smaller than the previous clusters but still contains a high number. They are slightly closer to conflict and less rural than the two previous groups, though they remain in a similar range. Almost no facility accesses the national grid. Why then did the Solar Centres adopt solar energy, whereas the first two clusters did not? While the pre-electrified Brownout Stations may have chosen (or been forced) to wait for a return of the national grid, Solar Centres and Deserted Village Units had no access to the grid prior to the war. Their decision-makers want to be as self-sustaining as possible and therefore have no reason to wait. The slightly increased size and conflict proximity may have helped Solar Centres to receive the attention, funding, and knowledge necessary to install solar energy.

The fourth cluster is of similar size (661 facilities) but has very different characteristics. The "War-torn City Hospitals" are a group of almost exclusively urban, medium-to-large facilities that are closest-to-conflict. The urban facilities covered in Interview #1 are an example of this type. Most of these facilities have a grid connection, and many of them even receive at least some energy from the grid. 73% of these facilities have access to power. 51% of War-torn City Hospitals include solar energy in their mix, but not one runs on solar energy exclusively. Instead, the War-torn City Hospitals run on hybrid solutions, mixing on-grid supply, solar energy, and diesel generators. We suspect that importance, access, and knowledge are causative for this sophisticated form of energy supply. Due to size and proximity to conflict, these facilities may receive a lot of attention; they provide medical services to densely populated cities and may treat combat casualties. International assistance has better access and may focus on these facilities, so they may consequently receive more funding. Moreover, these facilities will have better access to the advanced knowledge necessary to construct and organise hybrid energy supply.

Cluster 5 — the "Diesel Units" — represents a smaller group of 284 facilities. All units in the cluster run solely on local diesel power. They are mostly small, rural, and do not possess a grid connection. These units have, on average, the same proximity to conflict as Brownout Stations. However, they differ from these with respect to the lack of a prior grid connection, and diverge from Solar Centres in that they are smaller, more rural, and further from conflict. We presume that the low grid-access rate has fuelled the decision to obtain individual energy equipment. However, the rural setting and the greater distance to conflict might have made diesel supply more attractive — or better known — than solar energy.

A further discussion of the clusters requires a closer look at their geography (Table 4 and Fig. 6). The first five clusters are spatially diverse, though (apart from Cluster 2) they are centred around the Houthi-controlled area of former North Yemen. The Deserted Village Units are the dominant cluster in 40% of all districts. They include much of the country's mountainous west, including some districts bordering the capital and the western coastline. However, the cluster is rare in the country's east. The Brownout Stations, which are dominant in 22% of all districts, are scattered across the country. Yet a sparsely connected belt between the capital in the west and the southern part of Hadhramaut is apparent. The Solar Centres (dominant in 12% of the districts) have their home in the country's northwest and around the city of Taiz. War-torn City Hospitals dominate in another 12% of the country, including major urban areas in the country's west as well as the influential coastal cities Aden and Mukkala. The Diesel Units discussed previously predominate in a series of scattered rural districts throughout the country, which only account for 5% of all districts. The remaining clusters, however, are geographically concentrated. They only appear in the far-eastern governorates Hadhramaut, Al-Mahra, and Socotra, where they set the scene. These governorates have experienced the war quite differently (see Section 4.1): poverty is less severe in the country's east, public electricity supply often remains, and the area is generally more stable.

Table 3: Clusters with data from the sample

No	Cluster name	N	Average distance to conflict (in km)		Share of facilities (in %)									
					Facility size			In governorate with public grid supply	In urban area	With a grid connection	With electricity supply from			With available electricity
			Air	Ground	Minor	Medium	Major				Solar only	Solar included	Diesel only	
1	**Deserted Village Units**	1,366	10.2	15.6	84.9	14.7	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	**Brownout Stations**	847	19.0	18.1	72.4	25.7	1.9	23.0	0.0	90.1	0.0	18.2	0.0	33.1
3	**Solar Centres**	674	8.6	13.8	42.1	45.9	12.0	7.6	22.1	0.2	100	100	0.0	100
4	**War-Torn City Hospitals**	661	7.8	7.5	13.8	53.4	32.8	37.7	92.9	83.5	0.0	51.29	0.0	73.1
5	**Diesel Units**	284	18.7	19.0	63.7	28.5	7.8	13.4	13.0	3.2	0.0	0.0	100	100
6	**Isolated Variety**	55	286.6	181.7	69.1	20.0	10.9	100	36.4	47.3	3.6	14.6	3.6	54.6
7	**Offshore Healthcare**	19	534.1	486.6	36.8	47.4	15.8	100	15.8	15.8	10.5	21.1	0.0	26.3

Table 4: Number of facilities by cluster and governorate

	Cluster						
Governorate	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Abyan	41	61	5	17	13		
Aden		1	1	37	9		
Al-Dhala	75	25	11	6			
Al-Hodaida	162	15	83	35	31		
Al-Mahra		1			3	43	
Al-Mahweet	96	36	10	12	25		
Al-baida	82	11	11	29	12		
Amran	124	72	67	62	8		
Capital Secretariat		2	31	104			
Dhamar	75	93	35	30	25		
Hadramout		191	19	108	26	12	
Hajjah	94	16	132	24	14		
Ibb	110	96	53	74	26		
Lahj	63	80	17	23	22		
Rimah	69		19	3	5		
Sa'adah	69		36		11		
Sana'a	123	60	26	22	16		
Shabwa	45	48	6	22	17		
Socotra							19
Taiz	138	39	112	53	21		

The two smallest clusters “Isolated Variety” and “Island healthcare” (55 and 19 facilities) have no relation to the conflict. Cluster 6 contains the units close to the Omani border and Cluster 7 only features units on the Island of Socotra. In terms of the clustering, it is not so much their electricity supply but rather their (increasing) distance to conflict that makes them unique. Isolated Variety contains rather small and rural facilities, of which nearly half have access to electricity by various means. The share of solar energy is low and comparable to that among the Brownout Stations. Socotra’s Island Healthcare is a mixed group of mostly mid-sized facilities. Only one-quarter has access to electricity, of which many include solar energy alongside on-grid supply.

In summary, we obtain five large clusters of units spread mainly throughout the country’s west and centre, and two small clusters located in the country’s east, far from the violent interaction. The largest group are the Deserted Village Units, i.e. they are small, rural, and were never electrified. The Brownout Stations are generally similar but many of them have lost electricity access due to the war and they cover much of the country’s mid-east. The Solar Centres instead are a cluster of slightly larger and closer-to-conflict facilities, which are entirely powered by solar energy and mostly located in the country’s north-west. War-torn hospitals — the mid-to-large urban facilities that are most affected by the war — are electrified by hybrid setups. The group of Diesel Units Off-grid Units is further distant from the conflict and possesses no grid-access.

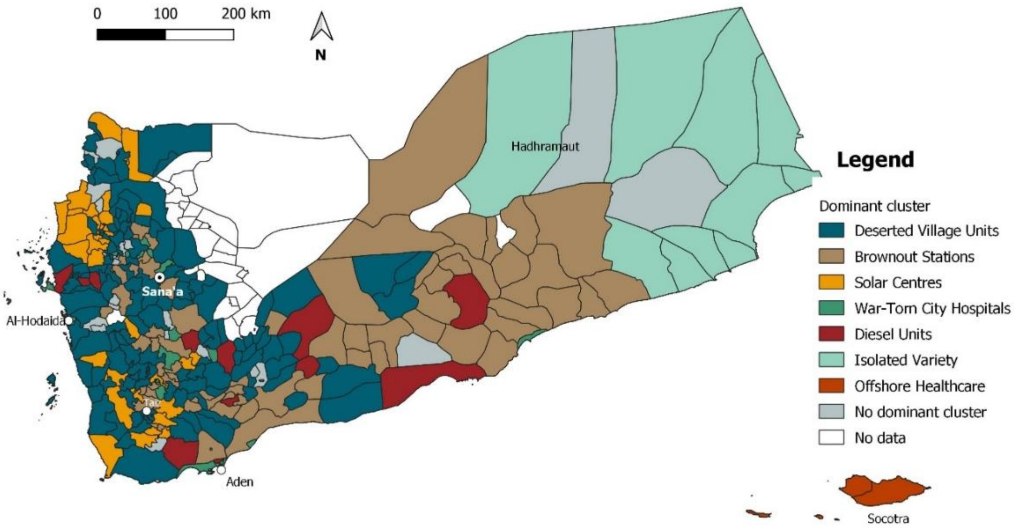

Figure 6: Map of the dominant cluster (by plurality) per district.

5.2. Alternative clustering

We repeat our clustering with intensity as the conflict indicator. This process validates the robustness of our results while also generating additional insights. Table 5 presents the new results and Fig. 7 visualises how the clusters change between both versions.

Overall, the clustering proves mostly robust with respect to the change in conflict indicators. We are able to match 4 out of the 7 seven clusters to direct counterparts in the proximity-based clustering. These clusters — the Deserted Village Units, the Brownout Stations, the Solar Centres, and the Diesel Units — experience only little change. This group accounts for more than 70% of the facilities.

A central reason for this behaviour is the dominance of power-related variables: the uniqueness of those clusters is primarily defined by their idiosyncratic electrical (and environmental) setup, such that conflict is not their defining quality. The Deserted Village Units are characterised as purely rural facilities without any access to power in the present or past. Solar Centres and Diesel Units are groups of mostly rural facilities that run only on one particular technology. Another observation is that the ranking of conflict proximity between the clusters matches the ranking based on conflict intensity for those groups. In other words, for these clusters, the difference between a proximity-based measure and an intensity-based one is small.

The Brownout Stations stand out slightly, since the Cluster has an altered composition. The alternative cluster is formed by the Brownout Stations (roughly two-thirds of them) and War-torn City Hospitals which have no national grid available (plus a neglectable number of Deserted Village Units). The resulting cluster is similar but arguably more refined in its properties: the

Brownout Stations as facilities that have access to a grid that has become unavailable. Whereas one-third of those facilities managed to take their fate into their own hands and obtain solar panels or diesel generators, two-thirds remain without electricity.

We can, however, also identify three new, alternative clusters: the Peaceful Enclaves, the Air-raided Capital Hospitals, and the Bullseye facilities. Generally speaking, these three clusters are mostly defined by conflict intensity. Since conflict intensity is less geographically distributed than conflict proximity, the clustering process is less spatially-motivated than was the case for Isolated Variety and Offshore Healthcare.

The Peaceful Enclaves contain former Brownout Stations and War-Torn City Hospitals in addition to some facilities from Isolated Variety and Offshore Healthcare. These facilities exhibit the lowest conflict intensity — though many of them are in high proximity to conflict — and are mixed in size, in areas where the national grid still operates. They mostly have access to electricity from the grid. Solar energy and diesel play virtually no role for the Peaceful Enclaves since they continue to rely on the public grid.

The Air-Raided Capital Hospitals are, for the most part, a subgroup of the War-Torn City Hospitals. Almost all facilities are in the country's major cities Aden and Sana'a. They are urban facilities of medium-to-major size that live in areas where the national grid continues to operate, despite being in conflict hotspots (especially airstrikes). Their urban location is likely connected to the high number of airstrikes. Similar to the War-Torn City Hospital cluster, nearly half of the facilities own solar panels.

Lastly, the cluster of Bullseye facilities faces the highest overall conflict intensity — spread over both years and both forms of combat. Their composition displays few patterns: they contain facilities from almost all original clusters. No facility has grid availability, and they are mixed regarding position, size, and grid access. Approximately half the facilities have access to energy, most of them using solar energy.

Comparing these three clusters to the other four yields a surprising insight: The clustering suggests that both the most peaceful and the most violent locations usually have access to electricity. Instead, the facilities in between these extremes seem to struggle with energy access. One apparent reason is that all three clusters contain many facilities in urban locations. Cities often retain some form of national grid access. However, especially the Bullseye facilities are outside of such areas — rather, solar energy has become their central means of electricity provision. Another reason might be that these facilities are the most relevant for (and probably funded by) domestic and international actors.

Table 5: Alternative clusters with data from the sample.

No	Cluster name	N	Average number of conflict events within 20 km		Share of facilities (in %)										
					Facility size			In governorate with public grid supply	In urban area	With a grid connection	With electricity supply from			With available electricity
			Air	Ground	Minor	Medium	Major				Solar only	Solar included	Diesel only	
1	Deserted Village Units	1307	40.5	9.6	85.3	14.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.1
2	Brownout Stations	1041	65.6	16.8	47.8	40.4	11.7	0.3	33.3	88.8	0.0	33.4	0.0	36.3
3	Solar Centres	632	49.4	10.5	44.6	44.0	11.4	4.4	18.4	0.2	100.0	100.0	0.0	100.0
4	Peaceful enclaves	369	5.2	2.5	69.1	23.3	7.6	100.0	32.0	66.7	0.0	11.9	0.0	66.7
5	Diesel Units	273	35.0	6.7	65.6	27.1	7.3	11.4	9.9	0.0	0.0	0.0	100.0	100.0
6	Air-raided capital hospitals	176	642.9	67.3	0.6	55.1	44.3	100.0	98.9	80.7	15.3	57.4	5.1	96.0
7	Bullseye	108	711.5	353.4	39.8	36.1	24.1	0.0	38.0	38.0	17.6	50.0	3.7	53.7

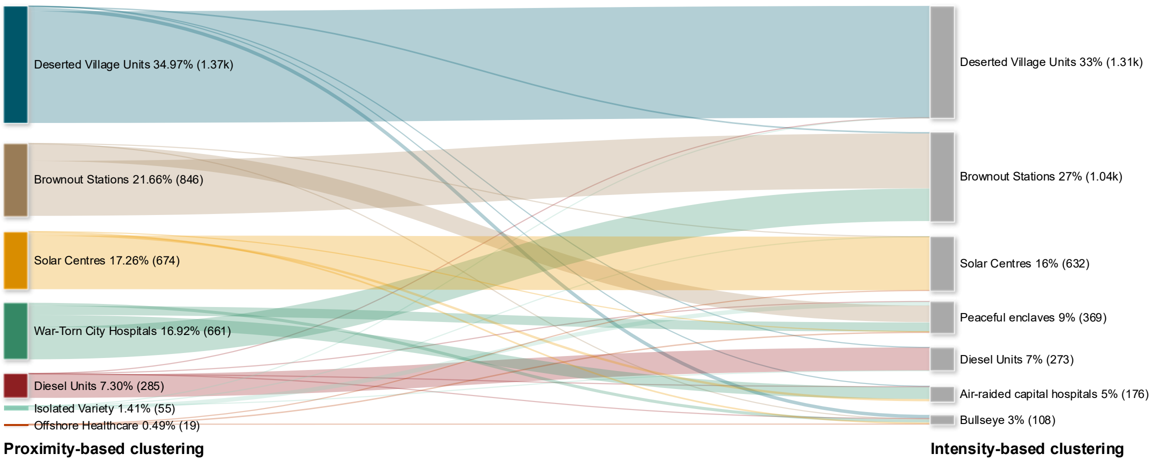

Figure 7: Sankey diagram visualising the movement of facilities between proximity-based clustering and intensity-based clustering.

6. Regression analysis: the effects of conflict on solar-energy diffusion

Lastly, we turn to our regression analysis and the question as to how conflict affects the diffusion of solar energy. We start with the regression results before presenting predicted probabilities.

We estimate a total of five different specifications. Model (1) is a baseline that features dummies for central facility characteristics (size, grid access, availability of on-grid electricity, and rural/urban location) and the distance to airstrikes and ground combat. Model (2) extends the baseline model with an interaction term between urban and the two distance measures. Model (3) adds interaction terms between urban and facility size(s) to the baseline setup. The remaining two specifications are further robustness tests. Model (4) adds conflict intensity as an alternative indicator to the baseline. Model (5) is a more drastic alteration: we use a double-selection lasso[7] logistic regression (see [42]) to flexibly include district-specific dummy variables. We force the algorithm to include all variables of Model (4) and choose among the 333 district dummies as possible controls. Table 6 contains the estimated coefficients and t-statistics.

Starting with facility characteristics, the regressions offer a robust picture. Size, location, and grid access are significant predictors for the probability of owning a solar panel. The sign and magnitude of each effect is unanimous across all model setups. As expected, smaller facilities have a significantly lower chance of owning a solar panel, and the effect is roughly four-times stronger for the smallest facilities compared to medium-sized ones. Similarly, both access to the grid and continued power supply from the grid further decrease the probability of solar panel ownership. However, this effect is contested by the lasso regression: when district controls are included, both effects become insignificant. Given the high granularity of district controls versus the relatively small number of observations, it is equally possible that grid access has indeed no

[7] Lasso is used for situations with a very high number of potential controls. The algorithm uses a penalty function for automatised variable choice. The double selection nonetheless allows estimation of robust standard errors (which enable causal inference). We implement the regression in STATA using the command *dslogit*.

effect or that the district controls conceal their effects. An urban facility is more likely to own a solar panel — an expected result that only fails to materialise in Model (3), where interaction terms likely sabotage the actual relationships. Model (3) also suggests that the urban/rural control does not moderate facility size, meaning that the effect of the facility's size does not depend on whether it is in a rural or an urban setting. Notably, the regressions suggest that size has a far stronger effect than location. The lasso estimation selected 78 district controls, which implies that the power supply has strong geographical variation beyond the specified characteristics.

The results meet our initial hypotheses: facility size and an urban location increase the likelihood of owning solar panels, likely because of better access to resources and a stronger need for services. Surprisingly, these results contradict the opinions of our expert interviewees, who saw solar panels as more suitable for smaller, rural facilities (Interviews #1 and #3). We interpret the divergence between interviews and regression as a sign that access to resources eventually outperforms suitability — even if small rural facilities are more suitable, they have less opportunities to obtain solar equipment.

Implicitly, the interviews also support our conjecture that knowledge plays a significant role. The electrical engineer (Interview #1) stated that solar panels are better suited for small rural facilities, since they can cover all demand and have ample space. Yet he does not reject their usage for larger facilities; in fact, the hospitals that he covers own solar equipment and use it in hybrid setups. The operational manager (Interview #3) emphasised that his facility owns no solar panels because it considers them too weak to power their devices — a statement that is false, provided that panels are sized correctly or used in a hybrid setup.

The results for grid access and availability are partially inconclusive, but the tendency to decrease probability is in line with the interpretation that solar energy diffusion results from a lack of alternatives. This finding is in line with our interviews, which named affordability (Interview #1) and lacking alternatives (Interview #2) as reasons to adopt solar energy.

The conflict-related results are robust throughout the different specifications as well. All five setups yield a significant negative effect for the distance to airstrikes and a significant positive effect for the distance to ground combat. In other words, the setups show that the probability of owning a solar panel increases with the proximity to airstrikes but decreases with the proximity to ground combat. Model (2) furthermore suggests that the respective effects are stronger for rural facilities than they are for urban ones. Models (4) and (5) substantiate the results' robustness further. The finding translates to conflict intensity: an increased intensity of airborne (ground) combat increases (decreases) the probability significantly. The result prevails even when district controls are introduced.

The findings meet our hypotheses and are in line with the interview responses. Ground combat — shelling, in particular — can damage solar panels (Interview #1), block roads to merchants (Interview #2), and lead to forced displacement (ibid.). Our interviewees agree that airstrikes are more devastating but ultimately less relevant for solar energy adoption (Interview #1 and #3). However, they also give no indication as to why airstrikes ultimately increase adoption likelihood. We also cannot fully exclude the possibility that some form of cofounding drives the positive relationship — airstrikes could appear more often in prominent and well-financed areas, in which solar panels may also be more widespread.

Postprint / Accepted manuscript: Al-akori, A., Ansari, D., Cader, C., Brahim, W., & Blechinger, P. (2023). Conflict, health, and electricity: An empirical assessment of the electrification of healthcare facilities in Yemen. *Energy Research & Social Science*, *95*, 102905. / https://doi.org/10.1016/j.erss.2022.102905

Table 6: Logistic regression results.

Variable	(1) solar_inc	(2) solar_inc	(3) solar_inc	(4) solar_inc	(5) solar_inc (Lasso)
medium	-0.770***	-0.771***	-0.929***	-0.688***	-0.732***
	(-5.46)	(-5.48)	(-3.30)	(-4.82)	(-4.37)
minor	-2.424***	-2.432***	-2.536***	-2.331***	-2.485***
	(-15.58)	(-15.64)	(-9.12)	(-14.75)	(-13.64)
on_grid	-0.261**	-0.254**	-0.258**	-0.239**	-0.126
	(-2.86)	(-2.78)	(-2.82)	(-2.61)	(-1.11)
on_grid_avl	-0.408**	-0.398**	-0.412**	-0.704***	-0.399
	(-3.03)	(-2.94)	(-3.06)	(-4.49)	(-1.80)
urban	0.572***	0.593***	0.413	0.552***	0.455***
	(-4.95)	(-4.92)	(1.35)	(4.72)	(3.36)
dist_air_2015	-0.00816***	-0.0144***	- 0.00802***	-0.00606**	-0.0171**
	(-3.41)	(-3.62)	(-3.36)	(-2.63)	(-2.72)
dist_ground_2015	0.00767*	0.0152**	0.00754*	0.00633*	0.0200**
	(-2.45)	(-3.13)	(2.41)	(2.12)	(2.97)
urban × dist_air_2015		0.00982*			
		-2.13			
urban × dist_ground_2015		-0.0128*			
		(-1.99)			
urban × medium			0.245		
			(0.75)		
urban × minor			-0.199		
			(-0.45)		
intens_air_2015				0.00118***	0.00170***
				(4.01)	(3.49)
intens_ground_2015				-0.00284***	-0.00671***
				(-3.40)	(-5.03)
district (dummy controls)					78 controls selected
Constant	0.743***	0.718***	0.869**	0.640***	
	-4.9	-4.72	(3.17)	(4.10)	
Observations	3906	3906	3906	3906	3799
Pseudo R-squared	0.173	0.174	0.175	0.177	N/A

Reference: large, off-grid, no on-grid supply, rural
t statistics in parentheses
× implies an interaction term
* p<0.05, ** p<0.01, *** p<0.001

Fig. 8 makes the findings tangible by showing the probability that a facility owns solar panels as predicted by Model (2). An average urban facility located directly next to an airstrike has a predicted chance of 37% of owning a solar panel, while a facility 40 km distance from airstrikes has a chance of only 33%. For a rural facility, the same comparison yields predicted likelihoods of 28% (no distance) and 18% (40 km). Urban facilities are hence not only more likely to have solar supply, but the reduction in the chance of having a solar panel is far more severe for rural facilities. Regarding ground combat, the same pattern appears, though in the opposite direction. The average urban facility hit by ground conflict has a 35% chance of owning a solar panel, while a facility that is 40km distance from conflict has an only slightly increased chance of 37%. However, for a rural facility, moving 40 km away from the battle increases the chance from 20% to 31%. The confidence intervals show that the differences between urban and rural facilities are significant except for the case of facilities that are far from ground conflict. The behaviour could reflect that shelling in rural areas is more likely to hit and impact solar panels than is the case for urban facilities. Similarly, combat in a rural setting is more prone to displace the population. As such, the presence of ground conflict may be more severe for rural decision-makers than it is for urban ones.

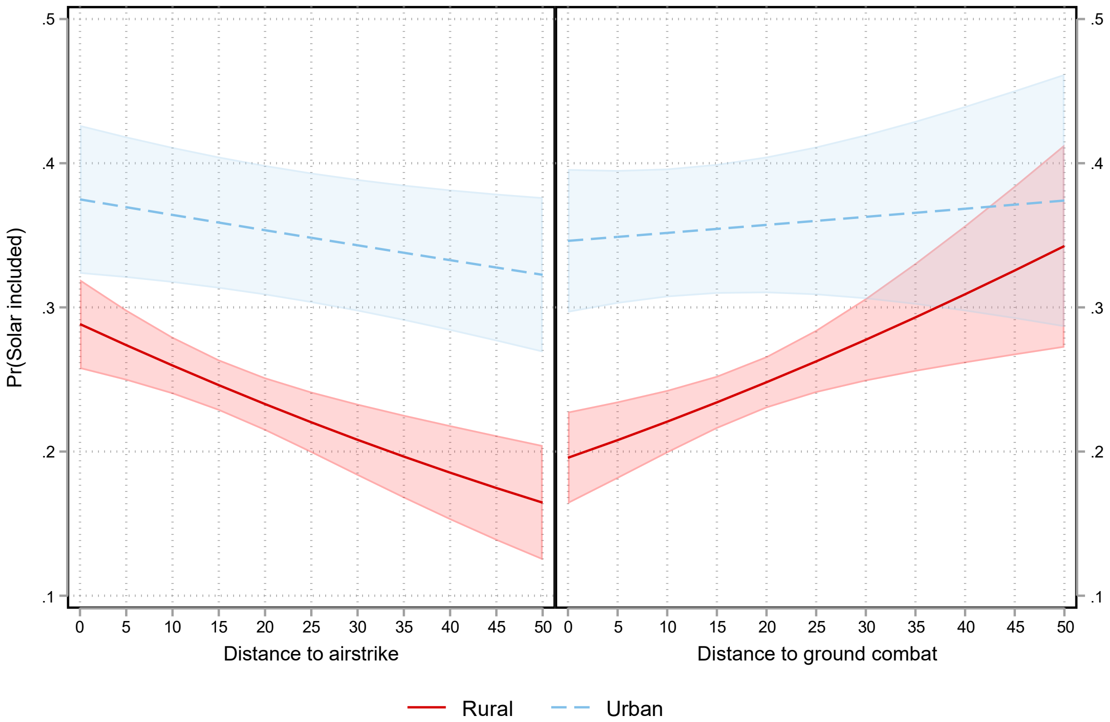

Figure 8: Adjusted predictive margins and 95% confidence intervals for Model (2) by location and distance from air and ground combat with remaining variables at means.

7. Conclusions and policy recommendations

In conflict-affected countries, critical infrastructure is often a victim of violence. While energy and health can be individual targets of destruction, the possibility of providing healthcare is also an implicit target whenever electricity provision is affected. Therefore, this study has focussed on the question of how conflict affects energy and thus health. We looked at Yemen, where ongoing violence has wreaked havoc on both sectors. In particular, our study has been a review both of the situation for Yemeni healthcare facilities and underlying patterns regarding the effect of violent conflict on electricity supply choices in general.

Our analysis has shown that the lack of electricity is major obstacle for healthcare and especially manifests in reduced operational hours for facilities, limited treatment options, and problems in vacation campaigns. As such, the electricity and diesel crisis has been a major contributor to the public health crisis. Only a minority of Yemeni facilities have access to electricity — 42% in our sample. Their spatial distribution is uneven, and their energy mixes vary greatly. Facilities in the more conflict-dense west of the country are less likely to be electrified than in its more stable east. We identified two large clusters of rural facilities (mostly) without electricity, the “Deserted Village Units” and the “Brownout Stations”. These two groups alone represent more than half of the facilities in the sample. While the former have never been electrified as a result of overall underdevelopment, almost all of the latter received power from the grid prior to the war. They represent healthcare facilities that lost access to electricity during the war.

However, our analysis has also shown that the effect of conflict is non-monotonous. The “Solar Centres”, which amount for 17% of the facilities, are off-grid units that purchased solar equipment and now run entirely on solar energy. They represent Yemen’s ‘solar revolution’ and showcase the transformative power of violence. Together with the small group of “Diesel Units” which run exclusively on diesel gensets and private grids, they represent rural facilities that have electricity, many of which were not electrified prior to the conflict. Compared to the two first groups, Solar Centres are less rural, spatially concentrated, larger, and closer to conflict. We therefore suspect that better access to resources and knowledge, partially due to heightened interest and support from international assistance, contribute to the difference. Our alternative clustering into “Bullseye facilities” and “Peaceful enclaves” suggests that the most and the least affected facilities often have access to electricity, while those in between both extremes are more likely to be left behind.

Logistic regressions helped detail the (complex) role of conflict in solar energy adoption: while exposure to ground combat decreases the probability of obtaining solar energy, this is not the case for airstrikes. Ground combat can easily damage panels, is more persistent, and can create displacement — all of which are factors that prevent decision-makers from upgrading their power supply. Generally, we found a strong rural-urban divide, which was accompanied by a gradient in facility size (small/rural vs. large/urban). Large, urban facilities next to conflict events (‘War-torn City Hospitals’) are more likely to be electrified. Surprisingly, their energy mix is quite sophisticated (hybrid systems), whereas all other previously discussed rural groups tend to rely on a single (if any) source of electricity. This sophistication is another example of how conflict has forced affected actors to leapfrog towards new technologies. Yet, our interviews strongly emphasise that the growth in solar energy results from its relative affordability (compared to diesel) and the absence of other sources of electricity.

Readers should bear in mind that most of our analysis is a snapshot of the situation in 2016, since when the conflict has transformed. Solar energy usage grew considerably between 2017 and 2018 so the numbers in our analysis may underestimate development. Our interviews, in which two out of three cases contained solar panels, further highlight this process and give an updated picture.

Naturally, as a case study, there is no direct proof as to whether our results are generalisable and apply to other countries as well. Nonetheless, many of our empirical findings can be explained theoretically, and the energy system of pre-war Yemen shows few structural differences to similar countries with weak electricity systems. We therefore believe that the results also apply to similar regional cases, such as Libya, Gaza, and Afghanistan.

For development practitioners in Yemen and elsewhere, our results hold several implications. Given the over proportionally large effect that even small amounts of electricity have for an unelectrified facility, decision-makers should consider the fact that the largest groups of facilities still have no electricity whatsoever, and many of them never had any. They are mostly rural, not directly located next to conflict though in its sphere, and seem to be below the radar of agencies. Local organisations and actors should be used to reach those off-the-grid areas more effectively. Knowledge and technical knowhow remain central issues and potential levers for supporting development. Our interviews have shown that decision-makers are not yet fully aware of the substantial merits and availability of advanced solar setups (e.g. hybrid grids in urban areas or solar mini grids in rural ones). They require detailed planning, established reference cases, and experienced engineers. Targeted assistance may help to harness existing potential and improve the situation drastically.

By no means should these results be understood as a romanticization of war —eventually, the number of facilities whose electricity supply degenerated exceeds those mentioned cases. However, we advocate for a research agenda that further investigates the forceful moment that arises from conflict towards energy. This investigation has been able to show that the effect of conflict on energy (setups) is non-trivial, may depend on the means of violence, and can potentially stimulate leapfrogging and the adoption of new technology. Better understanding these dynamics may help in shaping energy pathways in fragile and conflict-affected countries and shifting towards improving both livelihood and sustainability in affected communities.

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