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Yemen's solar revolution: Developments, challenges, opportunities

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Energy Access and Development Program

برنامج التنمية والطاقة

Yemen's solar revolution: Developments, challenges, opportunities

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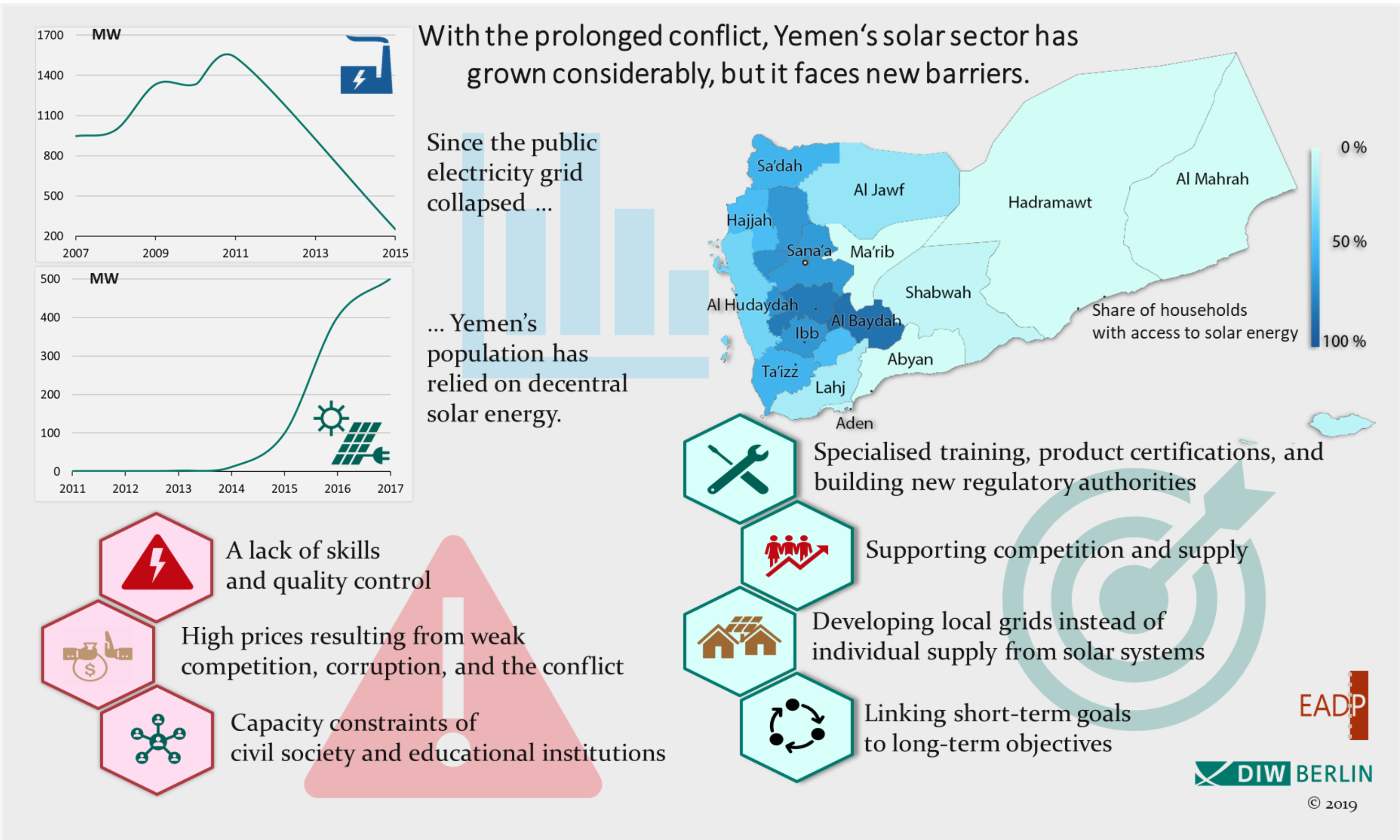
Abstract: Yemen has been involved in a civil war with foreign military intervention since 2014. Throughout the conflict, the majority of the population have been cut off from the public electricity grid. However, as alternatives have been unavailable, the country has turned to decentralised solar energy, giving rise to an unprecedented deployment of solar (home) systems.

This report uses own calculations, new household surveys, and extensive literature research to document Yemen's solar revolution. While the report identifies central drivers for the diffusion of solar energy, it also discovers critical barriers: Since 2017, growth in the solar sector has been stagnating, since bottlenecks in the sector hamper a further diffusion. The article concludes with a set of recommendations for both international and local actors, and it shows how targeted funding and projects can set the course for sustainable development, energy access, and climate change mitigation simultaneously.



1. Introduction

Yemen, located at the southern tip of the Arabian Peninsula, is currently facing the world's 'largest humanitarian crisis' (UN, 2018). United Nations records show more than one million cases of cholera, making it the largest outbreak in history. Yemen's prolonged military conflict has caused three million internally displaced persons and more than ten million people being in acute famine. By the end of 2019, the United Nations expects the total death toll to reach 233,000.

The public electricity grid was among the first casualties of war. Infrastructure attacks and fuel shortages have hit Yemen's electricity supply and cut off the majority of its population from electricity. The fuel shortage made relying on diesel generators impossible (or at least unfeasible), which is why Yemenis have increasingly turned to decentralised solar energy. Within just three years, the solar generation capacity in Yemen has increased roughly 50-fold.

Since 2017, however, various barriers have led to a stagnation of the diffusion of solar energy. Unskilled technicians, missing product quality controls, and the absence of technical standards have taken their toll on the quality of solar energy supply. Hence, and combined with high prices resulting from colluding importers as well as diminished trust in non-profit actors, households are increasingly disappointed. Instead, especially wealthier households turn to private diesel grids–a development not only expensive but also in contradiction with long-term requirements for the Yemeni economy and global sustainability.

This report documents the development of solar energy in Yemen. It uses own calculations, recent household surveys, and extensive literature research, in addition to numerous interviews with local actors to verify and elaborate information. The report analyses the development and role of solar systems in Yemen, and it identifies barriers that hinder their further diffusion. Moreover, the report touches at the vast untapped potential for local grids in Yemen, which could improve energy supply significantly, even when only relying on available capacities. Finally, the report suggests numerous policy options for the international community but for also Yemeni actors and the private sector.

After a brief introduction into the Yemen conflict, we present facts and figures on Yemen's pre-war energy system. After covering the conflict's effects on energy supply, the article presents figures for the solar revolution, before turning to its ongoing challenges. We then elaborate on the potential for local grids and the importance of tackling the energy crisis even during the conflict. Lastly, we argue that the transition towards clean and stable electricity should not be postponed to a post-war scenario, and we present a variety of policy instruments that can alleviate the situation.

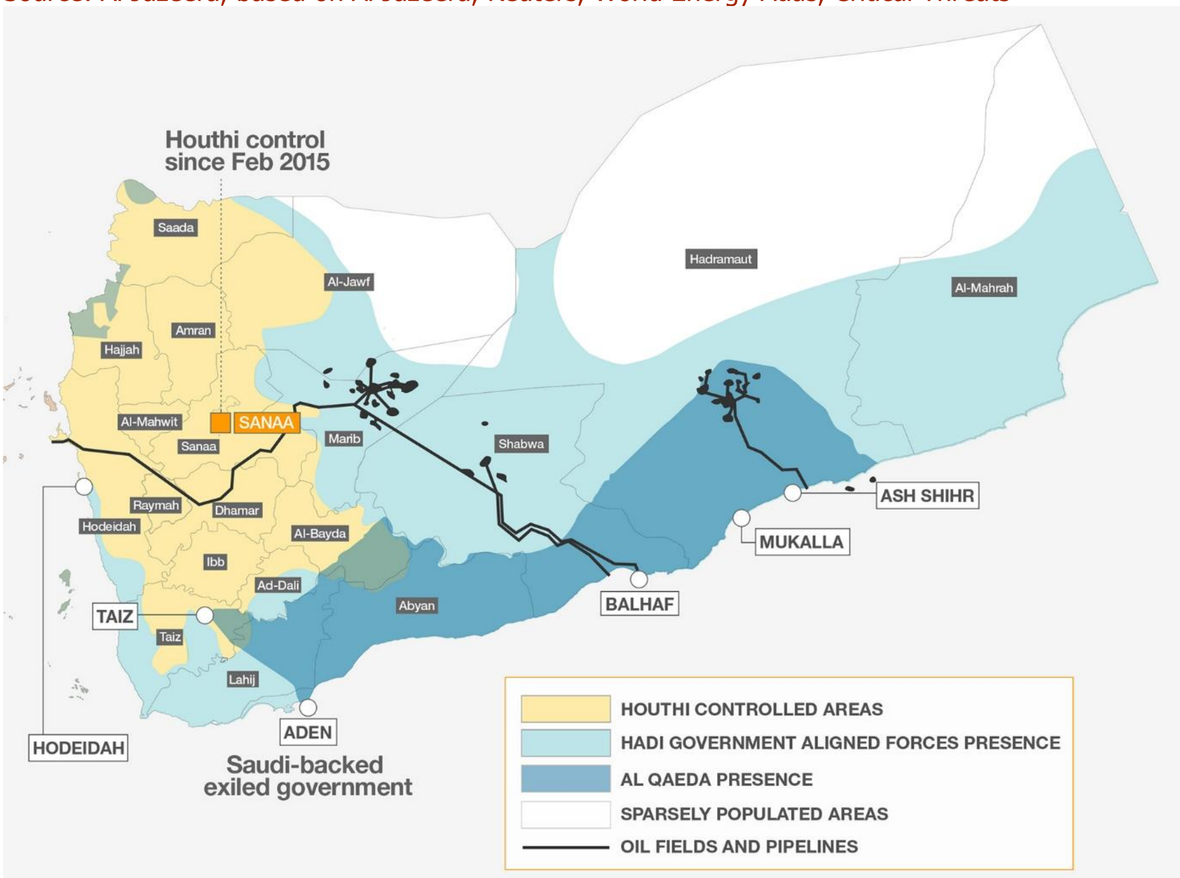
2. Focus: the Yemen conflict

In 2011, after 33 years in power, the Arab Spring led to the overthrow of former president Ali Abdullah Saleh. Subsequently, a transitional government was formed under former field marshal Abdrabbuh Mansur Hadi. Its mandate was to lead the country back to stability, but it failed to distance itself sufficiently from the old regime. An unsuccessful fuel subsidy reform eventually led to the uprising of the Houthis–a northern rebel group with partial support by Iran. The group, which refers to itself as 'Ansar Allah', seized Yemen's capital Sana'a in 2014 and has been the de-facto government of the country's northwest ever since.

Therefore, and officially at the request of President Hadi, a coalition of ten states–led by Saudi Arabia and the UAE–has launched a large-scale military intervention against the rebels. The coalition uses airstrikes in the north but has also ground troops in the south. It continues to maintain a blockade of Yemeni sea and airports and collaborates with local movements and parties. The latter include the long-standing southern separatist movement, which seeks an independent South Yemen. However, Hadi's internationally recognised government has its temporary seat in the designated southern capital Aden, which is why the south is particularly fragmented and tense. Furthermore, large parts of the south and Hadhramawt governorate are under the control of Al-Qaida. Overall, the situation is characterised by a high number of factions and a rapid change of alliances, none of which has an incentive to end the conflict.

Figure 1: Map of the Yemen conflict as of March 2019

Source: Al Jazeera, based on Al Jazeera, Reuters, World Energy Atlas, Critical Threats



Since 2014, Yemen is involved in a protracted civil war with foreign military intervention.

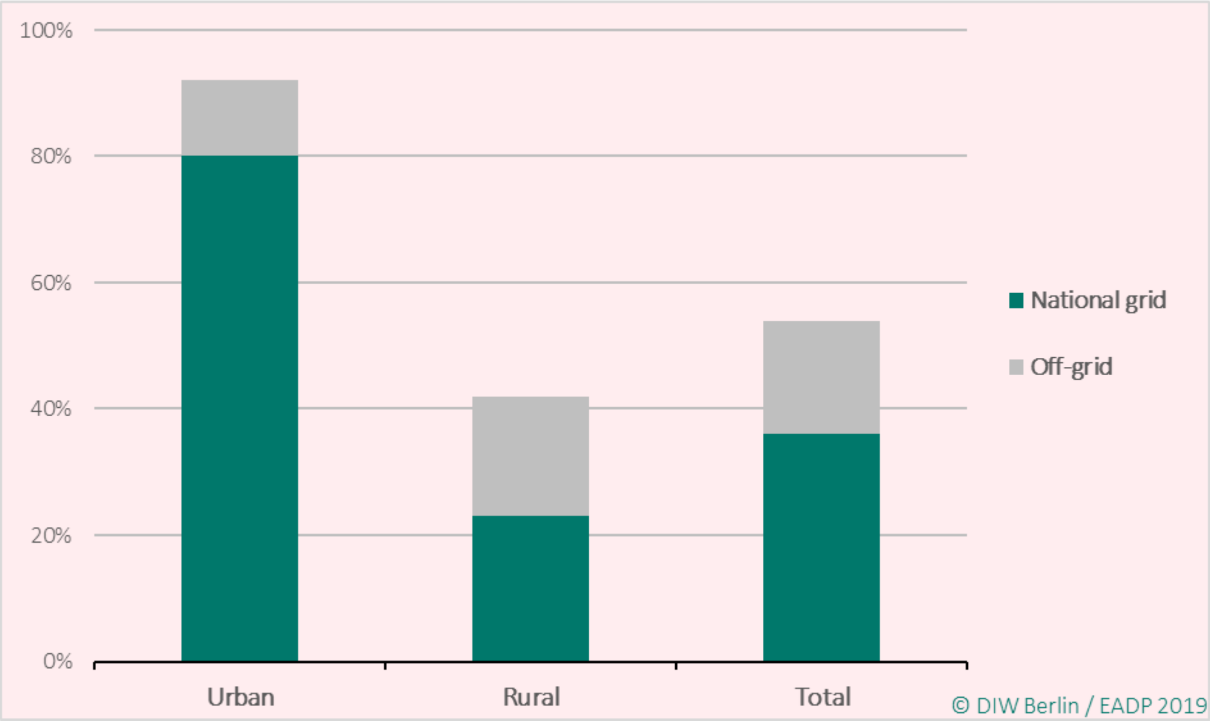
3. Energy poverty in Yemen - even before the war

Although Yemen's energy crisis escalated when the conflict began, it had existed long before the war. Over the second half of the last century, Yemen failed to keep pace with the development in other Arab economies, partly due to the persistent struggle to establish a stable Yemeni state (Dresch, 2000). The predominantly mountainous country on the Gulf of Aden is characterised by sectarian, political, and social divide; and its weak economy has been dependent on volatile workers' remittances and oil exports since the 1970s (Ansari, 2016). Although Yemen's capital inflows have never reached the level of its wealthier GCC neighbours, they have had similar consequences: The lack of absorptive capacities in economy and government has led to embezzlement, nepotism, and excessive security expenditures; infrastructure development has hence been neglected (ibid.).

The electrification of Yemen has therefore been slow and focused on urban areas, whose access is geographically and politically easier. Fig. 2 depicts electrification rates for the year 2003 by type and location. At that time, four out of five urban users were connected to the public grid. The remainder used self-generated power (e.g. diesel generators) or had no access to electricity. However, and although Yemen's rural population accounts for roughly two-thirds of its inhabitants, only 23 % of rural user had access to the public grid, and another 18 % used self-generation. Thus, some 59 % of the rural population (which is about half of the total population) had no access to electricity. Overall, access to the public grid was available for only 36 % of the population.

Figure 2: Share of the Yemeni households with access to electricity in 2003 by the type of electrification

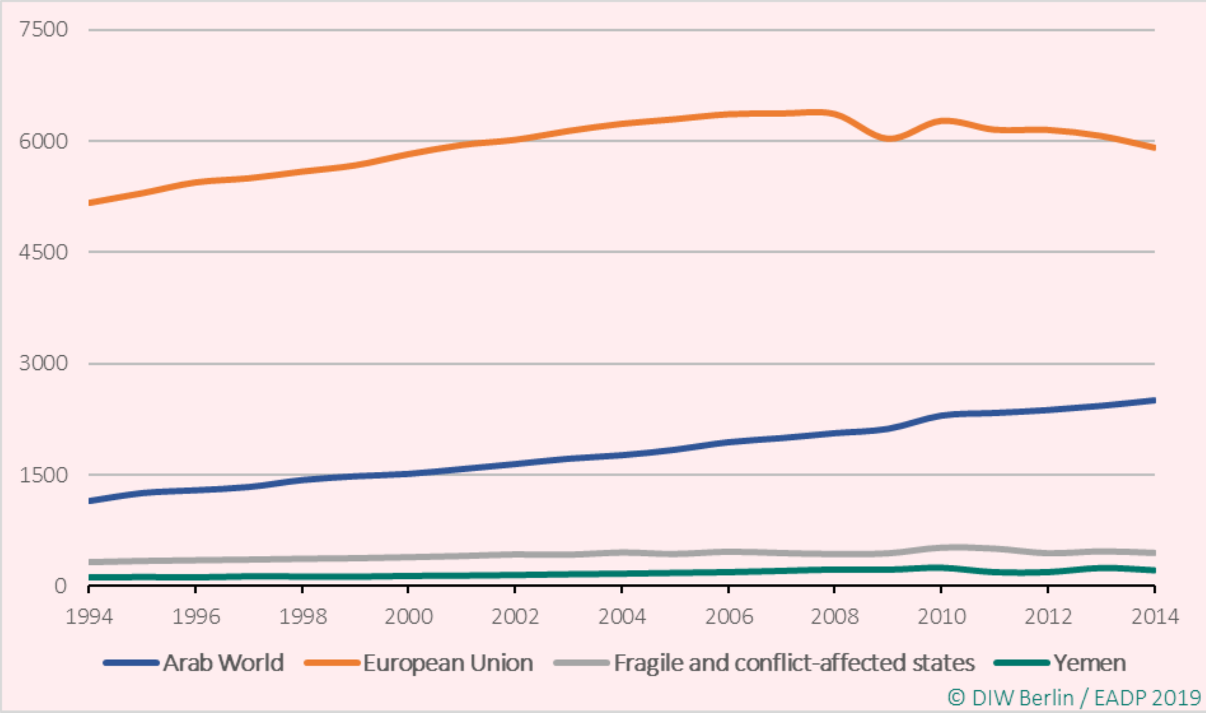
Data: World Bank, El-Katiri & Fattouh (2011)



Even before the war, Yemen's rural population had almost no access to the public grid.

However, even electricity access could not necessarily prevent energy poverty. In a World Bank survey in 2010, Yemeni businesses reported an average of 52 power outages per month. Between 1994 and 2014, Yemen's per capita electricity consumption (Figure 3) was consistently at around 200 kWh. These numbers are not only a fraction of the European average but also only one-tenth of the average figure for the Arab world in 2014, when the conflict began. Yemen's per-capita electricity consumption even undercut the average of all fragile and conflict-affected countries worldwide by one half. Moreover, as Fig. 3 shows, per capita consumption was mostly stable throughout the period; hence, investments in the power sector were merely enough to maintain the per-capita standard for a quickly growing population.

Figure 3: Per capita electricity consumption in kWh per year
Data: World Bank, El-Katiri & Fattouh (2011)



Electricity supply had already been weak before the conflict started, and it had shown hardly any development.

Table 1: Electricity losses in percent of generated electricity
Data: Hadwan & Alkholidi (2016)

Year	2003	2004	2005	2006	2007	2008	2009	2010
Generation losses	6.8	6.5	6.0	5.6	6.8	5.9	6.2	6.8
Transmission losses	2.9	4.1	2.8	4.0	2.6	2.4	3.03	3.8
Distribution losses	26.3	25.0	24.6	25.2	25.8	26.0	26.7	27.4
General losses	33.3	32.7	31.1	32.0	31.8	31.1	32.9	33.7

Yemen's public grid received insufficient investments and attention, leading to high losses.

4. Public service collapse

Already in pre-war Yemen, power generation capacities (Fig. 4) accumulated to far less than 2 GW of total capacity. Until 2005, all power plants had been oil-fired, which is why estimates for the primary energy mix (Fig. 5) depict a dominant role for oil products. Later, the portfolio was expanded by gas-fired power plants, accounting for about one-third of pre-war generation capacities (Ministry of Electricity and Energy).

In the aftermath of overthrowing of the government in 2011, Yemen finally started to stumble. An increased number of attacks on infrastructure were taking their toll on electricity supply, especially in the two subsequent years. The transmission line between the Yemeni capital Sana'a and centrally located Ma'rib became a prominent target. Ma'rib hosts the nationwide-largest power plant, which accounted for roughly one-third of public generation capacities at that time. The power line became the target of 54 attacks by various tribes and movements between 2010 and 2013. Therefore, and as turmoil and missing hydrocarbon exports in that period had made the public budget even tighter, quick fixes largely replaced routine maintenance on the agenda. This decision, however, led to an ever stronger deterioration of the public grid.

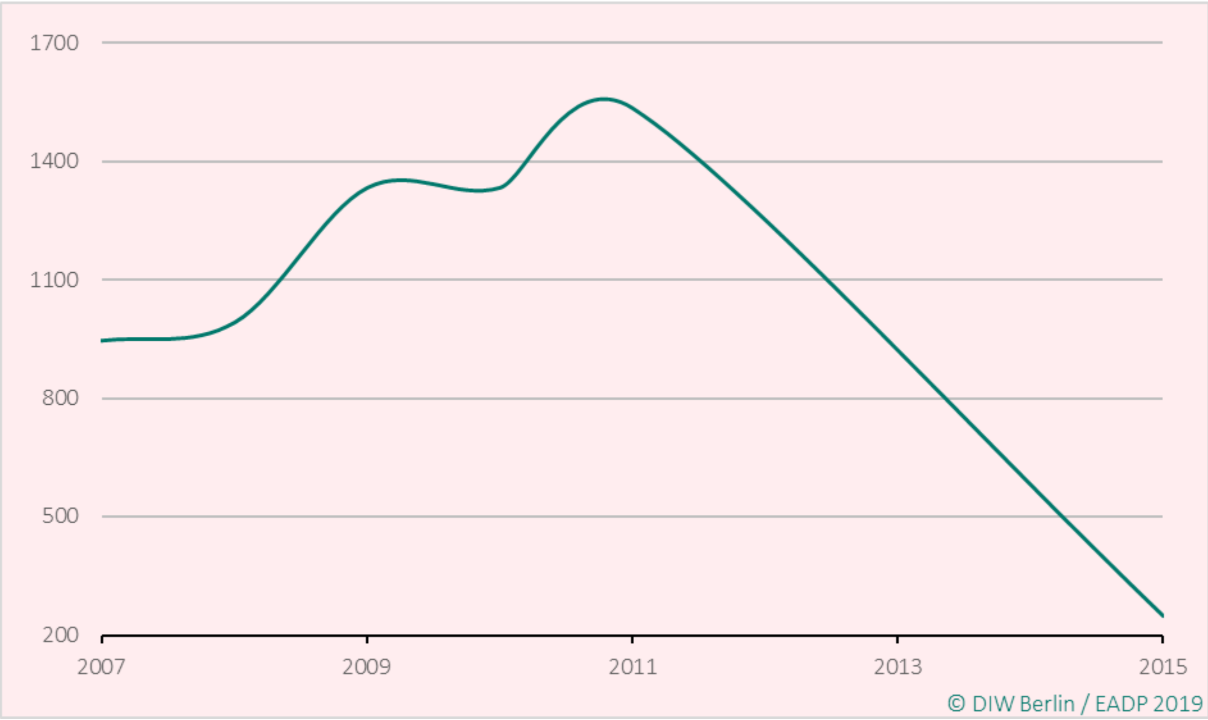
With the conflict, issues in public finance, logistics, and military have led to an escalation of the energy crisis.

In a nationwide household survey, 67 % of Yemeni households mention that public service provision has deteriorated, in part or even massively, over recent years (Yemen Polling Center, 2017). Among these households, 70 % identify the conflict as the leading cause, and another 13 % consider corruption and the absence of the state the primary link (ibid.).

The public grid has suffered from direct damages. Currently, around 55 % of electricity infrastructure (including grid and power plants) is slightly to severely damaged, and 8 % of the infrastructure is destroyed (Al-Akwaa, 2019). As a result, operable power plant capacities have declined (see Fig. 4).

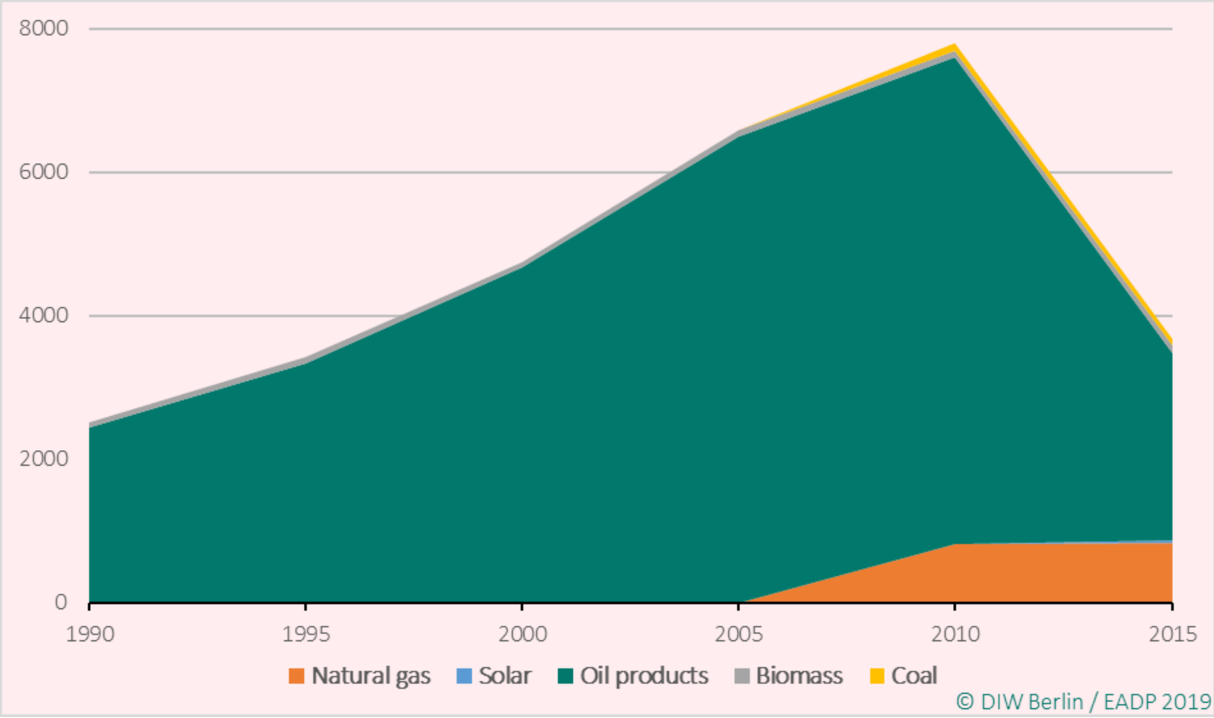
Furthermore, the economic crisis and increased security expenditures have restricted the financial scope of households and government(s). The average daily income has fallen from 4.50 to 1.80 USD, and estimates for the unemployment rate range up to 60 % (UNDP, 2019). Public budgets, which have been weakened by the slump in export revenues from the oil and gas sector (Nasser, 2018), are therefore tight and reserved primarily for military purposes. Infrastructure operation (esp. power-plant fuel) and maintenance have thus been neglected, leading to a restriction of electricity generation.

Figure 4: Operable electricity generation capacities of the Yemeni public grid in MW
Data: Own calculations based on World Bank & Public Electricity Corporation



With the beginning of the war, Yemen has lost most of its operable power plant capacities.

Figure 5: Primary energy mix of Yemen in ktoe
Data: IEA



Fuel shortages and power plant outages led to a collapse of oil consumption.

Fuel supplies have also been disrupted due to the coalition's blockade of air and seaports, leading to repeated and prolonged fuel shortages. (Black) market prices for oil products have therefore increased substantially, which is why even many undamaged power plants have not been in operation since.

Examples also show how parties to the conflict exploit energy (infrastructure) for their military goals. As part of the blockade, imports of electrical equipment (including solar panels and batteries) were temporarily prohibited. Until today, solar equipment is subject to (often informal) transit customs imposed by several parties, depending on the transport route. Previously-mentioned Ma'rib power plant, which is located in the area controlled by Hadi's national government, is still in operation; however, it delivers (almost) no power to the Houthi-controlled capital, which had taken its power primarily from the Ma'rib station prior to the conflict. The Saudi Arabian airstrikes on power plants in the Houthi-held governorates of Hajjah, Sa'dah, and Amran in 2016 pose the most direct examples.

Data from the Yemeni Ministry of Electricity and Energy illustrates the crisis: While southern Aden has an electricity demand of 390 MW and some 190 MW of remaining available generation capacity, the capital Sana'a faces a demand of 500 MW despite remaining generation capacities of only up to 40 MW. The second-largest city, Taiz, as well as the regions Ibb and Al Hudaydah do not have any operating grid capacities despite a demand of 110 and 280 MW respectively. Nightly light emissions in Yemen have therefore fallen by two thirds (Badiei, 2018), and the Ministry of Planning and International Cooperation calculated that the national electricity supply decreased by 77 % between 2014 and 2015 alone.

Areas in which the public network continues to operate have been coping with drastic price increases in addition to the supply restrictions. The country uses a system of increasing block tariffs (see Meran & von Hirschhausen, 2009): Users with a higher consumption pay a tariff, as well as commercial customers pay more than rural users, who again pay more than urban households. In June 2016, the public electricity company implemented a price reform (see Table 2). While the prices for urban private consumers with low demand was were raised by 44 %, tariffs for small rural users increased by up to 122 %. Also commercial users have to cope with an increase of 110 %, but urban frequent users face the highest increase, with 321 %.

Table 2: Prices of the Public Electricity Cooperation before and after June 2016
Data: Ministry of Electricity
Values in USD-Cent per kWh (1 USD-Cent ≙ 2.5 Yemeni Rial)
Price groups of commercial users omitted.

<table>
<tr><th>Sector</th><th>Consumption in kWh (up to)</th><th>100</th><th>200</th><th>350</th><th>700</th><th>>700</th></tr>
<tr><td rowspan="2">Residential (urban)</td><td>old</td><td colspan="2">2.5</td><td>3.6</td><td>4.8</td><td>7.6</td></tr>
<tr><td>new</td><td colspan="2">3.6</td><td>6.0</td><td>10</td><td>32</td></tr>
<tr><td rowspan="2">Residential (rural)</td><td>old</td><td>3.6</td><td colspan="4">7.6</td></tr>
<tr><td>new</td><td>8.0</td><td colspan="4">12</td></tr>
<tr><td rowspan="2">Commercial</td><td>old</td><td colspan="5">11</td></tr>
<tr><td>new</td><td colspan="5">32</td></tr>
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Areas with remaining access to public electricity supply have seen significant increases in tariffs.

5. The solar revolution

Initially, when the public grid collapsed, Yemen's population had responded with an increased use of diesel generators (cf. Fig. 2). However, this became unattractive or even impossible due to fuel shortages (and, thus, price peaks on the black market).

The failure of public services has laid the foundation for an unprecedented rise in solar energy. Various studies (Khogali & Ramadan, 1982; Al-Motawakel et al., 1983; Abdul-Aziz et al., 1993; Hadwan & Alkholidi, 2016; Ajlan & Abdilahi, 2017) confirm that Yemen provides an optimal environment for the use of solar photovoltaic electricity generation. Especially the mountainous north is endowed with moderate temperatures despite high solar radiation and low seasonal variation. Regarding end-users, however, solar energy was still largely unknown when the conflict broke out. With the increasing number of power outages in 2012 and 2013, first households started to invest in solar systems. Still, that time, solar energy remained a niche technology. However, in the absence of power from the public grid or (affordable) fuel supply, solar energy has rapidly gained popularity; and within only a few years, it has become the foundation of Yemen's electricity supply.

Providing exact figures for the development is challenging since the war provides adverse conditions for surveys. However, using a variety of sources, we have estimated the solar capacity in Yemen between the years 2011 and 2017 (Fig. 7). Until 2012, solar installations had been limited to a few households, remote telecommunication infrastructure, and some water pumps. In the years 2013 and 2014, the available capacity grew for the first time, despite remaining on a low level. In 2015, however, it became clear that the Yemen conflict would not see a quick end. Therefore, the solar expansion accelerated drastically towards 2016, when solar energy first became the most important source of electricity in Yemen (cf. Fig. 4).

Figure 6: Photograph of retailer of solar power equipment in Sana'a
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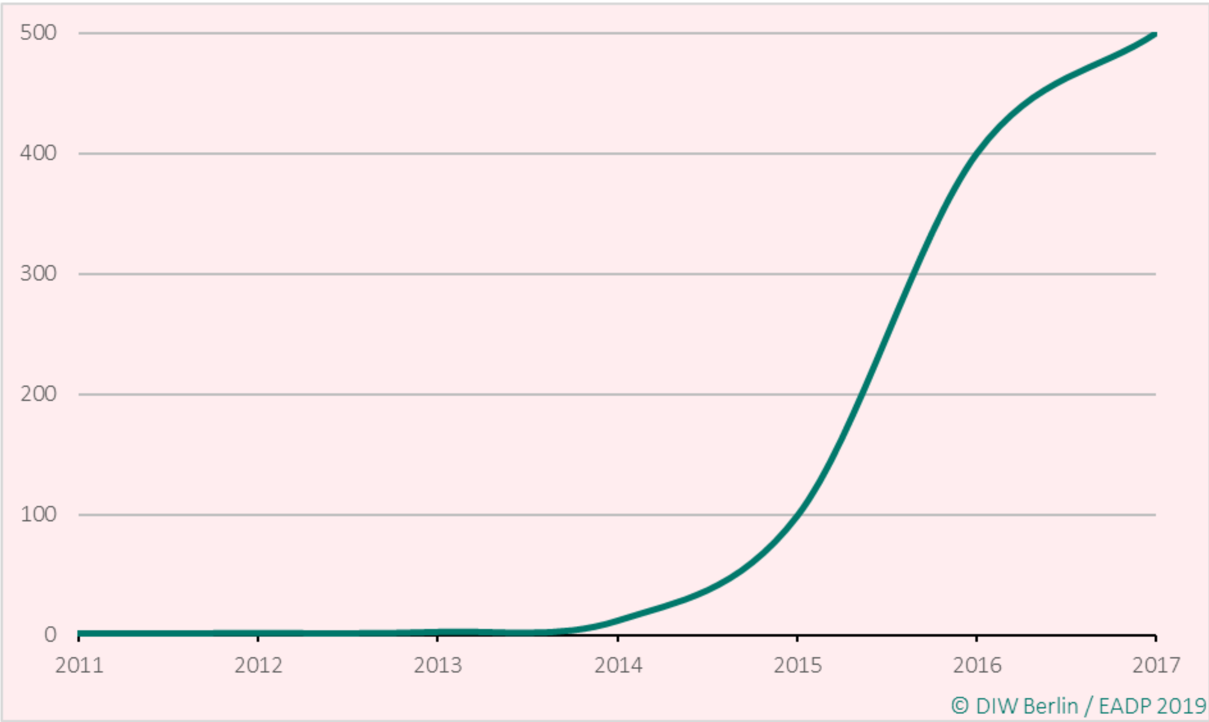
Solar energy retailers can now be found in most commercial areas across Yemen.

Figure 7: Installed solar capacity in Yemen in MW
Data: Own calculations based on IEA, World Bank, Percent for Polling Research, UNSD



Solar energy has experienced an unprecedented rise in Yemen, esp. between 2015 and 2016.

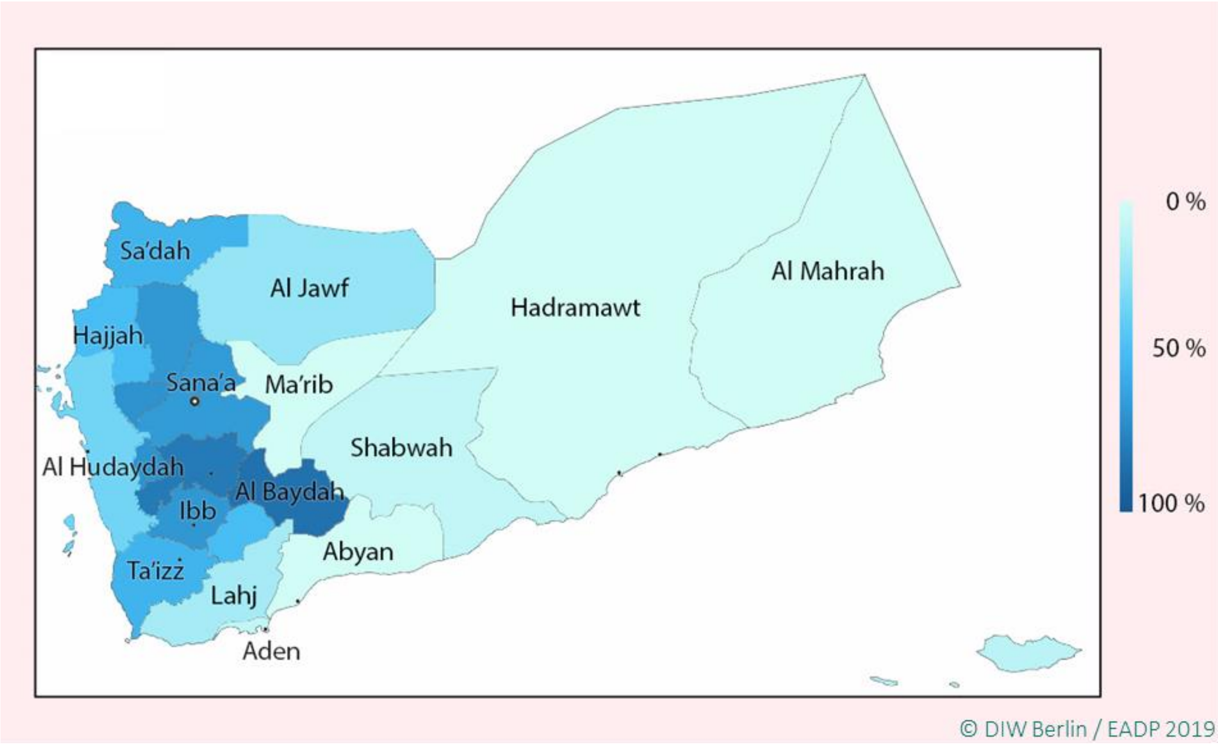
Most Yemeni households are supplied with solar energy. 75 % of the urban population and 50 % of the rural population are estimated to receive solar energy; and the average solar module has a capacity of 150 W (Mahmoud et al., 2017). This makes solar energy the main source of electricity in 13 out of 22 Yemeni governorates (Badiei, 2018). Even some communities that had no access to electricity prior to the war could be electrified during the conflict. The conflict has led to a deterioration in per capita electricity consumption, but it might the electrification rate itself might have increased over the recent years.

According to the Yemeni Ministry of Electricity, the solar revolution has been accompanied by a large-scale exchange of light bulbs. Most households have replaced standard light bulbs with energy-saving lamps. This development is typical (and necessary) for off-grid electricity since older light bulbs consume electricity at a roughly tenfold-higher rate. Thus, older light bulbs would put high pressure on the limited generation capacities of off-grid systems.

The geographical distribution of solar systems is unequal and mostly concentrated in the county's northwest (Fig. 8). This divide is in line with the distribution of remaining public grid capacities. The areas that are most affected by the electricity crisis (largely the Houthi-controlled northwest) show shares of households with solar energy supply above 50 %. In Al Baydah, even 84 %of households receive some form of solar energy. In contrast, the governorates with remaining access to the public grid (most of them also have better access to fuel) only exhibit low shares of solar energy. In these areas, remaining power plants and recently installed (public) diesel generators provide (limited) power supply.

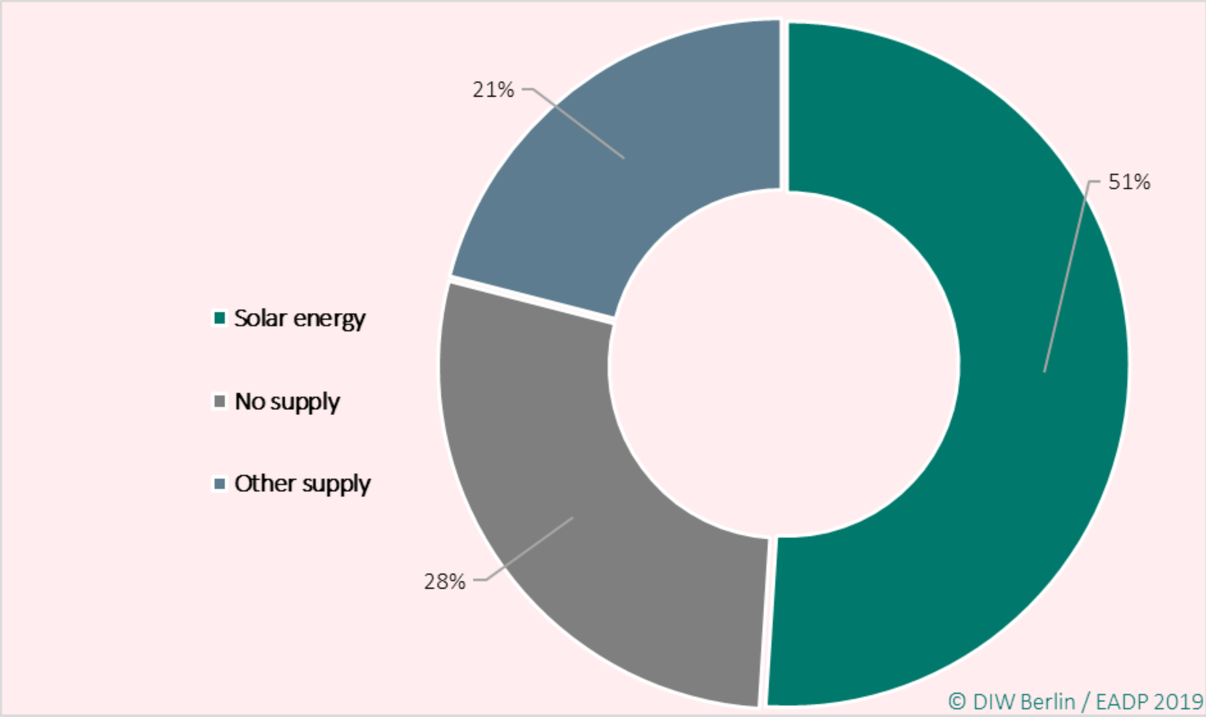
On the one hand, this dichotomy underlines that Yemen's solar revolution was primarily born of necessity. After all, households investing in solar systems have been unable to obtain electricity from other sources. However, it is remarkable that the distribution of solar systems is also roughly in line with external conditions: Solar energy usage is concentrated in the mountainous areas, while coastal and desert regions–which are usually less suitable for photovoltaic technology–exhibit lower shares.

Figure 8: Share of households with solar energy supply by governorate
Own illustration with map from d-maps.com, Data: Percent for Polling Research (2019)



Solar energy is less concentrated in the governorates with remaining access to public supply.

Figure 9: Electrification in Yemen by type of dominant electricity source
Data: Percent for Polling Research (2019)



Solar energy is the primary source of electricity for the majority of Yemeni households.

The rise of solar energy is also relevant to the Yemeni economy. Estimates for cumulative household investments between 2014 and 2016 range between 1 and 2 bn. USD (Mahmoud et al., 2017; Alwly, 2016). The total market potential is estimated at 58 bn. USD, of which 23 bn. USD come from middle-income households and 16 bn. from smaller farms (Mahmoud et al., 2017).

6. The challenges of Yemen's solar revolution

However, as depicted in Fig. 7, a stagnation of the solar revolution started in 2017. Available data for 2018 does not yet allow for a robust estimation of generation capacities, but verbal reports verify a continued stagnation. Currently, most households use their solar systems only to power lamps and televisions. For any other usage, wealthier households have increasingly turned to own diesel generators and private diesel grids, despite high fuel prices on the Yemeni black market.

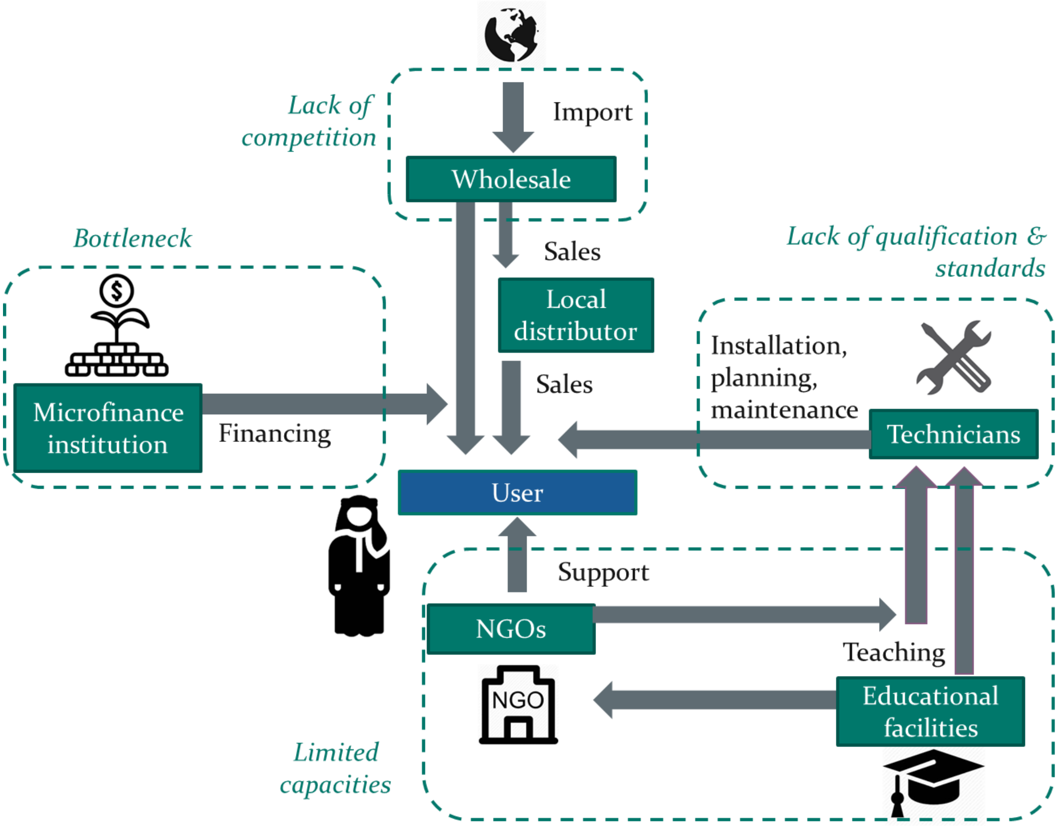
Households complain about weak supply, short lifetimes, and (in exchange) excessive costs for solar systems. In a survey conducted in 2017, only 10 % of households with solar systems stated that their electricity supply was sufficient (Badiei, 2018). The initial euphoria has given way to disillusionment, due to several issues in the Yemeni solar sector (Fig. 10).

6.1. Qualifications, quality, standards

First, retailing and services lack formal qualifications, skills, and quality controls (cf. Badiei, 2018; Mahdi, 2018; Mahmoud et al., 2017).

Yemen knows no formal qualifications in the field of renewable energy apart from some individual university course offerings. Since the solar sector emerged from the war, there

Figure 10: Illustration of the solar sector and its actors



Problems in multiple parts of the solar sector hamper the solar revolution.

had been hardly any opportunity to prepare technicians and engineers through appropriate training or structured programs. Non-specialised or even completely unskilled personnel is responsible for the planning, installation, and maintenance of solar systems. They typically rely on tacit knowledge, which is diffused bilaterally, and personal experience. Moreover, the sector lacks organisational capacities: There are no professional associations or (public) regulatory bodies, which could advocate and enforce binding standards or quality control for products and services.

Solar systems need to be dimensioned and installed for each user individually. This process entails choosing the right system size but also choosing components that fit each other. An undersized system is inadequate, and the user's (intended) consumption cannot be met; an oversized system, nonetheless, is inefficient, because the excess capacities create higher cost where a smaller system would have been sufficient. However, also the wrong choice of individual components turns the system inefficient. If individual components are undersized, they become a bottleneck and limit the entire system (and, thus, worsen power supply). If individual components are oversized, they remain unused by the system despite the higher cost. In both cases of inconsistent components, the levelised cost of electricity ('LCOE', i.e. the ratio of cost to electricity) increases. In other words, the system has a low cost-to-benefit ratio.

Dimensioning solar systems requires specialised knowledge and skills as well as the use of appropriate computer software. Similar remarks apply to their installation, which requires a proper physical mounting, adequate safety precautions to protect components and users, and an optimal inclination of the panel towards the sun. Moreover, additional equipment (such as batteries) needs to be connected and placed in an adequate environment. However, the practice in Yemen differs: Components are not dimensioned professionally but instead selected based on personal experience, and a quick assembly substitutes a professional system setup.

After-sales services, such as maintenance and repair, are crucial for the system's proper functioning and longevity yet no standard in Yemen. Customer service is not commonly included when purchasing or installing a solar system. Instead, users often consider themselves responsible for maintenance. The improper handling of solar equipment (also a potential result of unskilled technicians), however, influences lifetime and performance.

Solar modules require some light maintenance, such as regular cleaning, but especially batteries prove to be troublesome. Batteries require (dis-)charging schedules that are tailored precisely to their characteristics. Liquids (usually acids) must be regularly maintained or even replaced. Moreover, batteries must be placed in locations that meet specific external criteria that match their characteristics; most batteries tend to be very sensitive concerning the temperature. Incorrect handling will result at least in a drastic loss of storage capacity over time. Therefore, the average Yemeni off-grid battery has a lifetime of only 16 months (Ministry of Electricity), although five years are considered the international standard.

Most Yemeni solar systems experience a drop in performance after six months; hence, professional maintenance, proper instructions for the users, and adequately programmed control units are essential. This issue can, however, also be traced back to inferior and defect products.

The current market is mostly dichotomous: First, there is a quality market in which mainly commercial customers and professional retailers offer brand products with included after-sales service (e.g. maintenance). Second, there is a market for the general public, in which private households purchase goods of inferior quality and from non-specialised retailers. Even car batteries and old rechargeable batteries remain popular energy storages. Households make this decision unaware of the strong performance losses that result from inferior products and missing services. This decision is in contrast with survey results that indicate a preference for stable electricity supply over low prices (Baharoon et al., 2016). Hence, it is reasonable to assume that the market for low-quality products will decline with sufficient awareness of the importance of quality.

Moreover, missing quality control itself is a crucial issue. Apart from low-quality equipment, defective and fake products have entered the value chain (often via retailers). There are even cases brought to attention in which framed paper was sold as solar panels (see Fig. 11). Therefore, it necessary to make users aware of the role of product quality. Nonetheless, there is also a direct need for governmental or non-governmental product control (e.g. by an industry association).

Such steps are even more important, as products and incorrect handling pose a safety risk. In particular, handling batteries bears physical hazards, including life-threatening dangers due to short circuits, explosions. and leaking acid. No figures are available for the number of victims of solar systems accidents, but numerous cases are locally documented.

Figure 11: Photos of damaged and fake solar equipment in Yemen
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The lack of maintenance skills and quality control leads to dangerous malfunction of solar equipment.

6.2. Civil society & competition

Universities, vocational schools, and NGOs are important actors, which can teach and transfer specialised knowledge, create awareness, and support the sector's capacities. However, in addition to the slow development of curricula and training facilities, limited financial and personnel capacities impair their work. As state budgets are limited and irregular, teachers at all levels of education have received little or no salary since the war has begun. Yemen's still-young third sector receives international assistance, but financial flows into and within the country as well as active support are often not transparent (as elaborated below). There is only limited assurance that they will arrive where they are most needed and can be used most effectively.

Since the Arab Spring, Yemen's civil society has proven resilient, despite its (unprepared) operation in complex terrain. During Ali Saleh's autocratic rule, which was characterised by power games and nepotism (Ansari, 2016), civilian actors had only played a minor role. Its growing influence in the wake of failed governments is, therefore, opposed to the complicated environment. Civil actors need to move amid military governments, rapid social change, and an often-mafialike private sector.

Still based on the structures mainly laid by Ali Saleh, Yemen's state and economy suffer from large-scale corruption. It manifests in a far-reaching patronage network of government, military, noticeable tribesmen, and religious influencers; however, businessmen (an identity often overlapping with the previous groups) have been crucial to and profiting from the situation (see Ansari, 2016; The Sana'a Center for Strategic Studies, 2018; Nasser, 2018; Hill et al., 2013). Entire economic sectors in Yemen are often monopolised, driving local prices up.

Also solar equipment is affected. Competition in the sector (especially import) is oligopolistic, limited, and observers report price-fixing between importers. Wholesale prices are usually about one-third higher than international average (although import costs, which vary with time and location, play a significant part). Price spikes are frequent and caused by a lack of competition but also import bottlenecks. Profit margins can be as high as 300 % (Al-Daqimi, 2018) and are a massive burden for households; this was especially the case in 2015 (Mahdi, 2018). Furthermore, local authorities set import permits and duties (in practice) on an arbitrary basis, which comes in addition to the well-established practice of bribery.

Figure 12: Photo of a store with solar equipment in Sana'a
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Collusion, high profit margins, and informal customs duties drive up prices for solar equipment.

Concerning the bottlenecks in the microfinance sector, we refer to the numerous other reports which deal with this topic in more detail, e.g. Badiei (2018), Mahmoud et al. (2017), LFS Financial Systems (2014).

The international community supports Yemen with humanitarian aid and development cooperation projects. Between the years 2014 and 2018, a total of 23 bn. USD was declared aid. However, Yemen faces a growing number of corruption scandals that involve both local NGOs and international organisations. These scandals range from nepotism to direct embezzlement. Various UN organizations–most recently even the World Health Organization and UNICEF (see WHO, 2019)–the King Salman Humanitarian Aid and Relief Center, the Saudi Program for the Development of Yemen, and the UAE Red Crescent are accused of failing to provide proper documentation of their use of funds and of embezzling aid money (Aljazeera, 2019). Particularly in the areas controlled by the Houthi-government, an unusually high number of projects are declared unfeasible or failed during the implementation phase, after budgets have been spent (ibid.)

Social networks have put growing pressure on funding bodies and NGOs. Activists use the Hashtag #YemenNGOBLackHole (Arabic #وين_الفلوس) to call for transparency, accountability, and an end to ongoing embezzlement. However, this process is Daedalian due to the deeply rooted corruption, the limited experience of civil actors, but also the missing attentiveness of donors. This climate of embezzlement not only restricts aid results, but it also harms the sensitive tissue of trust between population and aid organisations–a development that can cause lasting damage to internationally organised peace and development missions.

7. From individualism to some collectivism

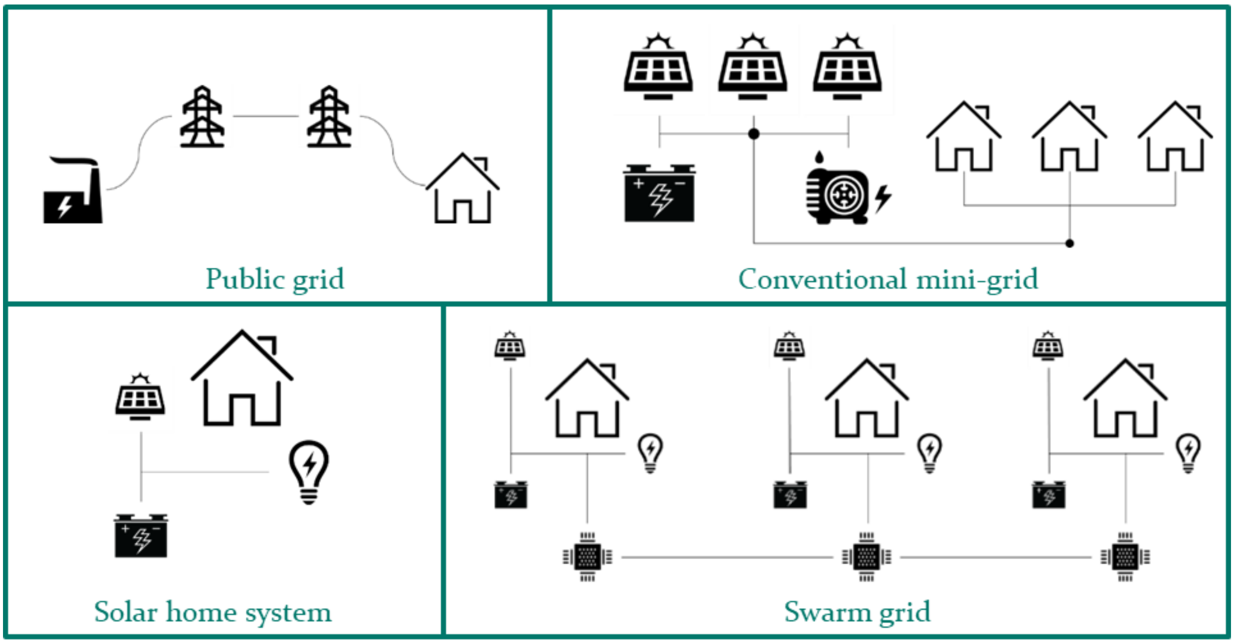
The conventional paradigm of electricity supply is a centralised, public grid. Electricity is generated in large-scale power plants (typically run on fossil fuels) and then transported to users via a long-distance transmission grid and local distribution network. Decentralised electricity, on the other hand, considers supplying electricity from smaller generators and near the user. This includes diesel generation, but solar energy has had the largest impact. Due to sharp reductions in costs but also a different cost structure itself, solar modules are particularly suitable for decentralised use. While other generation technologies, such as coal-fired power plants, are only efficient in large-scale applications (so-called economies of scale), solar systems can already be used efficiently on a smaller scale.

Power supply off the public grid is generally referred to as off-grid systems. In contrary to popular opinion, studies have proven that off-grids are no temporary workarounds, but they are the first-best electricity supply for many (primarily rural) regions worldwide (IEA, 2017, Bhattacharyya & Palit, 2014).

Individual supply from a solar (home) system is the most popular off-grid approach. The systems consist of (at least) a solar module, a control unit, and a battery. They do not require significant investments but fail to deliver a strong performance. A network requires multiple users to flatten aggregate demand peaks. As solar (home) systems have only a single user, they have to be oversized to meet the user's individual short-term peak load. The levelised cost of electricity ('LCOE', the ratio of cost to electricity used) is, therefore, overly high (see Table 3). Thus, self-supply with solar systems is inherently inefficient.

However, individual supply from solar (home) systems is by no means the only solution for an off-grid system (see Fig. 13; Hoffmann & Ansari, 2019). Instead, combining multiple users in local grids leads to synergies. By mixing different users with individual demand profiles, existing capacities can be used more efficiently; thus, LCOE is lower.

Figure 13: Illustration of different off-grid approaches



Solar systems are simple and do not require large investments; yet, they are the most inefficient off-grid approach.

Table 3: Simulated indicators for different electrification approaches in the case study Bayhan A'mas Aljabal

Data: Hoffmann & Ansari (2019)

Indicator	Individual supply (solar system)	Swarm grid	Conventional mini-grid
Share of successfully supplied electricity demand	12.4 %	81.7 %	97.6 %
Levelised cost of electricity in EUR-ct. / kWh	52	29.4	23.1

Linking existing solar systems in a swarm grid leads already to a fourfold increase in electricity supply.

Mini-grids, in which electricity is generated for a whole community and distributed through a local network, are the most efficient solution. Mini-grids can easily be designed to work with AC generation (e.g. wind power, diesel) and consumption (e.g. washing machines). Although mini-grids attain lower LCOE than any other off-grid approach (see Table 3), they require high investments.

Swarm grids are another, novel approach to electrification. With the help of intelligent control units, existing stand-alone systems are interconnected to a network in which neighbours can trade electricity with each other. Although the system fails to achieve the performance and efficiency of a mini-grid (cf. Table 3), it requires less capital, builds on existing structures, and contributes to social development (see Schill et al., 2017). Swarm grids already exist in Bangladesh, but they have so far been limited to DC designs (e.g. Koepke & Groh, 2016; Groh et al., 2015). DC, however, limits performance and usability significantly when compared to AC solutions.

Almost the entire solar capacity in Yemen is installed in solar systems for individual supply. Mini-grids, on the other hand, exist in the form of private diesel grids, in which the owner invests in a larger generator and sells electricity at a profit to neighbouring users. In the last two years, wealthier households have often shifted to this option. They aim at receiving better electricity supply than what their solar systems can provide (or, at least, what they believe it to be able to provide), despite high prices for power from the diesel grids.

Simulations for Yemen (see Tab. 3) confirm the vast potential that is lost by restricting the use of solar energy to individual supply. Commercial users, who often have a more balanced load profile and use most electricity during the day, may be able to use stand-alone systems efficiently. However, the load profile of private households is usually incompatible with the generation profile of a solar system. Apart from illumination and electronics (televisions, mobile phones), households often need high power but only for short periods. Typical examples include vacuum cleaners, electric kettles, or washing machines. Therefore, individual supply has to be oversized to meet the household's demand. This comes at substantial cost and in addition to the expenses for storing the electricity from peak-sun hours (usually at noon) until nightfall, when users demand most electricity.

Hence, instead of switching to diesel grids, existing solar systems should be interconnected and form local networks. Such integration can provide a four-fold higher electricity supply at less than half the levelised cost (see Table 3). Thus, solar-powered grids can help households to improve their quality of life at even lower cost.

The precise model for such a grid depends on location, social cohesion, local institutional quality, political objectives of the principal/donor, and financial possibilities. Mini-grids are easier to administrate and a more mature technology, but grid and generator ownership is a pressuring issue. In small, homogenous communities, existing standalone systems could simply be merged into a mini-grid. For larger and more inhomogeneous communities, local authorities could purchase existing solar systems and supply users with metered electricity from the new grid.

Swarm grids offer an outstanding opportunity to circumvent the issue, as ownership remains with the users, while the grid provides them with the opportunity to trade. However, two different challenges emerge: Compared to mini-grids, swarm grids require more sophisticated engineering (especially if it operated with AC). Moreover, administration and operation will usually require intense local capacity building (especially for cleaning and billing electricity trades). However, for cases in which both challenges pose no barrier, swarm grids offer the most direct method to exploit already existing solar potential.

8. Advocating for electricity access - even during the war

Although the three central humanitarian fields–food, water and health–are often given priority, similar consideration should be given to energy. Having stable access to electricity improves the quality of life significantly, and it contributes to stability and prosperity.

Electricity is the basis of modern life; hence, households without access are left behind, and commercial activities are hardly possible. This has a direct impact on well-being but also on economic growth, (un-)employment, and (social) development. There are even immediate benefits, while conflict is still ongoing. Stable telecommunication services contribute to security (e.g. civilians can warn each other of imminent air attacks) as well the coordination of humanitarian aid. Medical services, pumped water, and hygiene require energy, which is why energy shortages can quickly worsen the humanitarian situation. Education is crucial despite (maybe even because of) war, which is why the electrification of schools must be an integral concern.

Also for (international) security, guaranteeing energy services is relevant. Political science recognises public service provision as one of the fundamental pillars of any state (see Brinkerhoff, 2007). Failure in the provision of services creates a legitimacy vacuum, which will lead to either chaos or non-state actors quickly filling the vacuum. For example, al-Qaida on the Arabian Peninsula has rapidly gained legitimacy among the local population due to its rapid rebuilding of electricity and water supply (Al-Awlaqi et al., 2018).

Furthermore, a secure energy supply is not only important for the economy, but also for climate change mitigation. Decisions for the energy system determine developments over decades and restrict the scope of future decisions. The energy sector occupies numerous interdependent markets, has deep roots in the economy, and is always associated with social interaction. The lifetime of energy plants and infrastructure can exceed 30 years. Therefore, user behaviour, economic integration, and the choice of technology are often rigid and make change difficult–even if economic and ecological conditions have already changed.

Thus, it is essential to seize opportunities to modernise energy systems as early as possible. Violent conflicts are a forced disruption of all systems within a country, including the energy system. Decentralised solar energy can provide energy during war, but it can also become the foundation of a post-war energy system.

The latter will be a key challenge. Due to insufficient power plant capacities and necessary grid expansions, an end to the conflict will improve electricity supply but by no means raise it to a sufficient level (Hoffmann & Ansari, 2019, Development Champions Forum, 2019). The post-war energy system will, therefore, have to integrate decentralised solar energy as an essential component. This can happen through either local grids or integration into the public electricity grid.

Hence, focussing on the local level is an integral step for both infrastructure development and lasting peacebuilding. Despite limited capacities during the conflict, local authorities are often to thank for maintaining everyday life in Yemen and offer the best opportunities to create stability after the conflict and beyond a central state (see Development Champions Forum, 2019, 2018). Thus, projects and support should and can observe two principles in this context: the sustainable use of local structures and linking short-term goals to long-term objectives.

9. Conclusions and recommendations

Due to the collapse of Yemen's energy system, its population has turned to solar energy. Fuel shortages and infrastructure damages have rendered both public grid and individual diesel generation unfeasible or uneconomical. Many users have, therefore purchased solar (home) systems, which provide decentralised electricity. The solar generation capacity has thus increased almost 50-fold in just four years, and solar energy now constitutes the main source of electricity in the majority of Yemeni governorates. However, the probability of owning a solar system is higher for urban households than for rural ones. Also, while up to 85 % of households in the mountainous areas around the capital own solar panels, other governorates in Yemen's east and south have only small shares of solar systems.

The Yemeni solar revolution is threatening to stagnate. Users are complaining about weak supply performance, low lifetimes, and (in exchange) high costs for solar systems. In this regard, the report identified a lack of qualified technicians and quality controls for products and services as well as the absence of competition among importers as crucial challenges.

Therefore, we present the following set of recommendations for both the international community and actors within Yemen:

- A comprehensive **programme to enhance specialised skills and ensure the quality of products and services** is urgently needed. Institutionalised qualification measures and training for technicians and engineers as well as international standards must replace tacit knowledge and personal experience as the modus operandi. Otherwise, the wrong (or missing) dimensioning, installation, and maintenance of solar systems could cause considerable performance losses and life-threatening malfunctions. Targeted courses, capacity building, and international collaborations with vocational schools and universities are important tools. However, the establishment of regulatory bodies and professional organisations (either state or non-state) is essential: Product and service standards need to become de-facto standards or even enforced by law. The scope for action ranges from softer (bottom-up) measures, such as product and retailer certifications, to hard (top-down) instruments, such as mandatory product tests and professional licenses. Irrespective of the eventual choice, international actors, civil society, and state actors need to act as partners to couple international know-how with local capacities.

- Both households and existing development cooperation projects direct most of their attention to standalone solar (home) systems for individual supply. However, and although a fully independent power supply comes with benefits, standalone systems are inherently inefficient, especially for private households. As a result of recent years, users own a considerable generation potential that is currently not fully used. By bundling capacities in local grids, the supply quality could increase considerably, even when using only capacities that already exist. Actors in Yemen (primarily national and local authorities) should therefore understand the opportunities from developing local networks since electricity supply can be significantly improved even with restricted budgets. In this context, existing examples such as Bangladesh, Rwanda, and Morocco should be examined more closely. New projects, including those of the international community, must **go beyond supporting standalone systems and, instead, consider more efficient local grids**. Combining existing capacities alleviates the energy crisis in the short-term and creates a stable, long-term foundation for infrastructure in a post-war Yemen.
- Projects of the international community should aim at **increasing competition among importers** and, to a lesser extent, retailers as well as capacity building along the solar value chain. Action is necessary to avoid bottlenecks and market inefficiencies, which result from excessive prices and harm households. Compared to the other goals we propose here, achieving this one is significantly less trivial: On the one hand, subsidising the purchase of solar equipment carries the risk of increasing profit margins in the sector rather than actual market supply. On the other hand, interests of sellers and government(s) overlap (e.g. customs duties on imports) in addition to entangled power relations. Therefore, measures must be chosen carefully and in coordination with relevant stakeholders. The most direct option would be founding a non-profit company for the import and distribution of solar products under direct control of an (international) donor. Such action would balance the market by increasing supply and, thus, creating pressure other competitors to lower their profit margins. A more restricted, but also easier approach would be to increase market transparency, for example by setting up online platforms on which buyers can compare prices between distributors across the country.
- Projects should **make use of existing structures in Yemen** to enhance project effectiveness but also to support long-term capacity building for local actors. Local authorities, who are often upholding daily life despite the conflict, are a notable example. These local authorities can (and may) also play a central role in a (presumably decentralised) post-war Yemen. However, regarding the involvement of the private sector, there is a crucial trade-off: On the one hand, developing a resilient and independent private sector is essential for building a stable Yemeni economy. Moreover, at the moment, the private sector has better capacities than the public sector. However, the Yemeni private sector has also a vivid history of being inclined towards rapid monopolisation and price-fixing. Such collusion causes (or reinforces) adverse power structures and market inefficiencies; and poorly designed action may even consolidate them for the long run. Thus, the involvement and support of the private sector should be an integral part of projects, but it needs to go hand in hand with monitoring market

developments. Actors need to be ready to intervene and ensure the development of free and fair markets.

- Humanitarian and development actors (both financing and implementing agencies) should **take the current debate on corruption seriously**. Intended impacts fail to materialise if funds disappear, and the absence of fair competition among implementing agencies may lead to inefficacy and marginalisation of social groups. A loss of confidence in the domestic third sector and the international community will damage other missions that need robust collaboration, such as peacebuilding.
- For private companies, Yemen's solar revolution bears an enormous market potential. Within only four years, households have invested between 1 and 2 bn. USD, and the future market volume is estimated at 58 bn. USD. Product manufacturers but also relevant service providers can **position themselves in a growing market while expanding electricity access** at the same time.
- Although food, health, and water are crucial, similar **attention should be paid to stable and clean electricity**. Providing energy access does not only make an essential contribution to the population's wellbeing but is also necessary for economic development and the implementation of humanitarian aid.
- Supporting the solar sector can simultaneously **set the course for poverty reduction, social and economic development, and climate change mitigation**. As Ansari & Holz (2019) have recently shown, integrating these targets is vital to enabling the global energy transformation. Otherwise, the energy system risks falling back into old patterns, which are neither in line with climate targets nor least-cost options. Failing to alleviate the technical struggles households face, for example, will create long-term damage to the public's trust in renewable energy. Instead, implementing the recommendations proposed here will support the wellbeing of households and enable Yemen to enter a path of clean and affordable electricity. In this respect, long-term objectives of sustainable development can be easily linked to short-term goals.

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