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# Nexus approach to solar technology for energy and water supply for sustainable rural development in Egypt: a review

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**Abstract.** The United Nations Sustainable Development Goals (SDGs) and their interactions in developing countries in general, and in Egypt specifically, form the basis of our review. Issues of energy and water supply, linked to agriculture in rural areas, combine several of the SDGs. The current status and the challenges for solar photovoltaic (PV) electricity production and water supply technologies in rural areas are critically described and an outlook on future developments is provided. The framework of the water–energy–food nexus approach and its relation to the SDGs globally in the MENA region and in Egypt is presented and recommendations are given on institutional governance and research and development to overcome the silo mentality and enhance sector collaboration on all levels as prerequisite to achieving the SDGs. The latest technical developments in PV and water technologies and their opportunities for rural development are outlined. Combined technical solutions are highlighted with examples from Egypt. Specifically, installed systems in various rural locations are presented, and their advantages and shortcomings are discussed. The review provides a context for the studies presented in the Special Section on Solar Energy Solutions for Electricity and Water Supply in Rural Areas, *Journal of Photonics for Energy*, Volume 9, Issue 4. © *2019 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JPE.9.043108]

**Keywords:** solar photovoltaic; sustainable development; rural development; sustainable development goals; solar pumping; drinking water purification.

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## 1 Introduction

Although many international events tackle either the question of energy, specifically the growing importance of renewable energy (RE) for global development, or the development of water efficient technologies and practices that will help conserve our world's scarce and dwindling resources, the two spheres are rarely considered in their specific interconnections that are so important for holistic development approaches. In addition to these linkages, a framework of economic and governance conditions that determine the success of such technologies, specifically in rural areas with their complex problems, needs to be considered for a sustainable rural development. Egypt is a country that is particularly vulnerable to many of the sustainability challenges and climate change effects to which all countries around the world are struggling to respond. The MENA population is expected to double to 720 million by 2050,[1] and the Egyptian population of around 93 million grows by a million people every 6 to 10 months,[2,3] a growth rate of 2.56%,[4] further increasing poverty and the already high youth unemployment. Since the country's landmass consists of 96% desert, 98% of Egypt's population lives on only around 4% of the landmass, mainly on the green sliver of land along the Nile River and in the Nile Delta, and population densities are comparable to those of Indian megacities. This population distribution also means that residents of villages and cities that are located far away from the River Nile constitute minorities that are often not well connected to the services concentrated in the most populated parts of

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Egypt. The vast distances that lie between Egypt's urban centers and the residents of some of its remote rural areas pose a challenge to the transportation of public services, such as 24-h electricity and improved drinking water. The geographical distances and the remote location of some rural communities that may, at times, consist of only a handful of households, lend themselves to stand-alone, off-grid solutions to service power generation based on solar photovoltaic (PV).

Also, the water issue calls for specific attention since the Nile River currently supplies 97% of Egypt's freshwater resources. Climate change related alterations of rain patterns in Ethiopia and Uganda might have a detrimental impact on the amount of water Egypt receives from its main freshwater source. According to a colonial Nile-sharing agreement, Egypt is entitled to 55.5 billion cubic meters (bcm) of Nile water per year. As not all upstream countries are using their own full shares, Egypt currently has access to 59.25 bcm, whereas the national water consumption is 100 bcm/year and rising.[5] A total of 85% of this freshwater is used for irrigation purposes in agricultural production. A reduction of water coming down the Nile, also as a result of damming in other countries, will be a sustainability catastrophe for Egypt. The national sustainability study plans to address the gap between water availability and need by increasing sea water desalination, the reuse of drainage water and treated greywater, and the utilization of shallow groundwater[5]—all solutions that have implications for technical development, especially if they are to be operated in sustainable ways. Remote areas located far away from the Nile are under threat from the over-exploitation of finite groundwater resources, intensifying heat and droughts; the rising costs of fuel and food; the challenge of creating and maintaining viable, sustainable livelihoods under changing environmental and market conditions; and a lack of public services and access to markets. Research on local needs and conditions, development of innovative technologies, adaptation of solutions to the needs of Egypt's remote areas, and the implementation and testing of new technologies could help bring more sustainable development solutions to government authorities as well as to communities across Egypt.

In order to meet the United Nations Sustainable Development Goals (SDGs), Egypt must be able to deliver electricity and water to all of its population. This review explores the intersections between energy and water in the context of solar PV solutions for sustainable development in rural Egypt and specifically considers the lack of services in its remote areas. Innovative, joint technical solutions with examples from the region are presented and appeals made for new governance schemes and collaboration between the different sectors.

## 2 Sustainability Challenges in the MENA Region and in Egypt

### 2.1 *Sustainable Development Goals and the Water–Energy–Food Nexus*

The United Nations plan, "Transforming our World: the 2030 Agenda for Sustainable Development," adopted by 193 countries in 2015, covers a wide range of complex social, economic, and environmental challenges, addressing issues such as ending poverty, combating climate change, and providing quality education for all by 2030.[6] Achieving the 17 SDGs will require deep economic, social, and technological transformations including unprecedented problem-solving approaches at all scales. In many countries, the 17 cross-cutting SDGs are now being integrated into national programs, and signatory countries, Egypt among them, have started issuing voluntary country reports demonstrating their progress toward the goals through concrete actions at the national level.[5]

The SDGs are characterized by strong interactions among them. A complex set of synergies and trade-offs make achievements in one goal without considering other goals hardly possible. Specifically, the environment-based SDGs (SDG 13, climate action; SDG 14, life below water; and SDG 15, life on land)[7–9] are widely recognized as underlying and determining the success of economic and social goals. Poorer countries, which on average are located in hotter regions, are most strongly disadvantaged in terms of economic productivity by increasing global warming and exposure to anthropogenic environmental degradation.[10] The issue of inequality is, therefore, striking in various aspects, starting with the causes for climate change, the greenhouse gas (GHG) emissions: the top 10% of emitters cause 45% of global emissions, whereas the "bottom" 50% contribute to only 13% of global emissions.[11] Considering the projected impacts of climate change on Egypt by 2100, a 3°C to 3.5°C increase in temperature and a 20% decrease in precipitation are expected,[12] already aggravating the water situation as early as 2025 to reach extreme water scarcity levels[13] and severely affecting crop yields and food security, which already poses a challenge to Egypt. The high temperature on the predicted 100 heat days per year, which exceeds the deadly threshold of human thermoregulatory capacity, will extremely affect human health.[14] Additionally, inundation of large parts of the Nile Delta by rising sea levels in the Mediterranean affecting up to 761 $\mathrm{km}^2$ of the Nile Delta accompanied by increasingly frequent storm events, will further rob Egypt of agricultural land, which is already being lost to urbanization by thousands of hectares per year, thus harming agriculture, causing land and groundwater salinization,[15] and displacing millions of people. These impacts make Egypt one of the two or three most vulnerable countries in terms of coastal population and coastal GDP affected, respectively.

Solutions are addressed in SDG 6 (water and sanitation) and SDG 7 (affordable and clean energy).[6] The UN states that, in 2015, 91% of the world's population had access to an improved drinking water source, compared to 76% in 1990.[6] A closer look at the definition of "improved drinking water source" shows that this term clearly differs from the definition of "safe drinking water." Although safe drinking water needs to comply with certain microbiological and chemical standards in order to be considered safe, an improved drinking-water source simply is a construction that adequately protects water from outside contamination, in particular from fecal matter.[16] The water quality of the improved drinking water source, which may be a public standpipe or a borehole, does not influence whether the source is defined as improved or not, as long as it is protected from outside contamination. Even though microbiological contamination and chemical pollution can, and often do, occur in these sources, the World Health Organization (WHO) states: "access to safe drinking water is measured by the percentage of the population using improved drinking-water sources."[16] This misleading definition and measurement reveals that the number of people suffering from inadequate drinking water supply is far higher than 9% of the world's population. The WHO itself states that, worldwide, 663 million people rely on unimproved water sources, whereas at least 1.8 billion people use drinking water sources contaminated with feces.[17] This confirms the conclusion that access to safe drinking water cannot be measured by access to an improved drinking water source. In fact, >80% of wastewater is released into the environment without any pollution removal.[18] Other sources of pollution can be agricultural waste or run-off (fertilizers), power plants, household chemicals, and landfill sites.[19] Thus 2.1 billion people are lacking safe drinking water at home.[20]

According to the above, the statement that nearly 55 million people in the Arab region are without access to an "improved drinking water source"[21] needs revision. It is stated by the Egypt Ministry of Planning that drinking water projects are being extended to achieve 100% provision of safe drinking water to all citizens in urban and rural areas in Egypt by 2030.[5] However, about 85% of water consumption is used for agriculture, and through the predominance of traditional irrigation systems, unrestricted water abstraction, and cultivation of high-water-consuming crops, irrigation efficiencies in the region are as low as 50% to 60% according to the United Nations Economic and Social Commission for West Asia (ESCWA),[1] according to different evaluations. Combined with an overuse of agricultural chemicals, this leads to river pollution with nitrates and pesticides through runoff, specifically in the Nile Delta,[1] which needs thorough monitoring and clean solutions. In Egypt, efforts are underway to transform the irrigation system into a drip system and to reuse wastewater, supported by the private sector, e.g., companies like Sekem, who are pioneers in organic farming and support farmers in the implementation of improved technologies.[5] Thus clear quality guidelines and control mechanisms for drinking water quality, specifically in relation to treatment of wastewater, are needed to encourage re-use for various consumers.[1]

Concerning energy (SDG 7), from the early stages of electricity grids in the late 1800s until today, the total number of people without access to electricity has remained remarkably steady between 1 and 2 billion for more than one century while the global population grew rapidly from below 2 to beyond 7 billion.[22] While there was a rising trend in the second half of the 20th century, over the past decade the number of people without access to electricity has been falling, undercutting the 1 billion mark in 2017.[23] Ninety-five percent of these people live in sub-Saharan Africa or Asia and 80% live in rural areas.[24] This means that for the first time the rate of providing electricity access has surpassed the rate of population growth, though this is not valid for sub-Saharan Africa or Asia, and, yet, every seventh human on this planet still lives without access to electricity and the vast majority of those live in rural areas.[25]

One key challenge is to accomplish the combination of both energy access and sustainability. Most importantly, efforts to reach global electrification need to at least avoid additional emissions of GHGs and ideally reduce overall emissions by substitution of fossil fuel-based systems with alternative technologies. As such, SDG 7 has an immediate and mediate effect on reducing global inequalities: first, by directly providing the poorest with access to electricity, and second, by taking action to mitigate climate change and its associated exacerbation of inequalities. Thus SDG 7 is in-line with the objectives of the Sustainable Energy for All initiative[26,27] and represents a key pillar for sustainable global development, as electricity access is linearly correlated with human development indices such as gender equality, education, poverty, and maternal mortality.[22] In Middle Eastern countries, REs are a target, with Egypt planning to increase the total installed RE from 5% up to 20% in 2020 while, in parallel, reducing existing energy subsidies.[5,28]

The people without access to electricity are largely the same as those who lack access to safe water. The reason for the link between drinking water and electricity systems is that most water purification systems need to be powered by electricity. In parallel, most of the arid and semiarid regions with water scarcity receive high solar radiation, thus providing sufficient sustainable solar energy for the water treatment process. Thus water, energy, and food security are inextricably linked in the Middle East[29] (Fig. 1). To achieve progress, the impact of energy mixes on water, food, poverty, inequality, and their interrelations, therefore, needs to be accounted for, as well as the social and economic impacts, which will influence any success of energy technologies and of energy related sectors.

Considering the relation between SDG6 and SDG7, the use of REs also has an indirect impact on water scarcity and thus on providing access to safe water, through (i) mitigation of global warming and therefore reduction of extreme weather scenarios such as droughts and floods and (ii) the water consumption (bcm/kWh) by power plants, which needs to be considered for the future energy roadmap.

The global energy system is responsible for the withdrawal of 340 bcm of freshwater,[23] in which about 52 bcm is consumed and not returned to the initial source.[30] The water footprint differs strongly for various energy technologies. Biomass and hydropower account for by far the highest water footprint,[31] although it should be noted that the essential environmental impact of this footprint may vary considerably by location due to differing water availabilities. Thermal power stations based on coal and uranium consume a significant amount of water for mining. Yet, cooling accounts for the highest share of withdrawn water, in the order of tens to hundreds of thousand liters per MWh.[32] PVs have low on-site water consumption during operation, e.g., for removal of dust on the modules. However, as estimated in 2013, there was a significant water consumption for the module production of up to 100 gallons per MWh.[32] Yet, it has to be noted that due to the recent fast development in PV technologies, it is likely that these numbers are

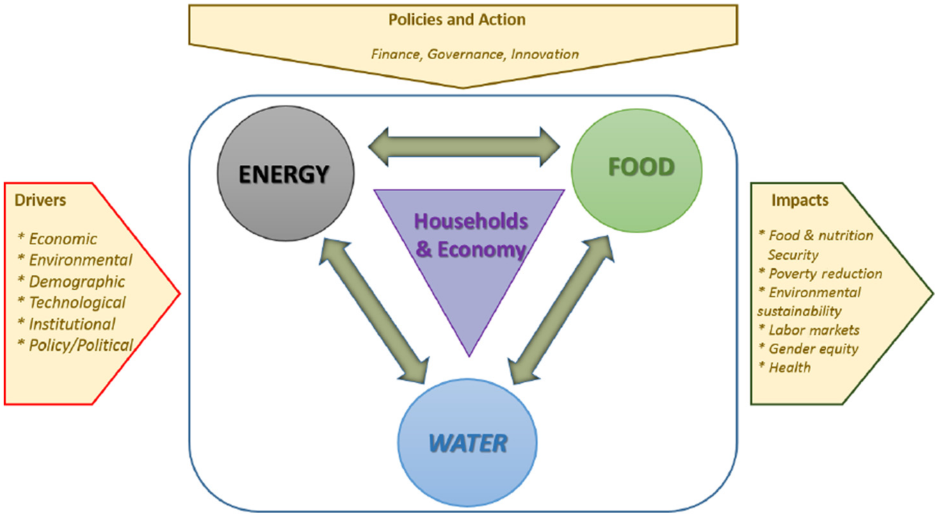

**Fig. 1** The WEF nexus in Egypt.[29]

outdated. It is reasonable to assume that there is a significant learning rate in water consumption, likely similar to the learning rate for reduction in energy consumption of ~12%.[33] Of all major energy technologies, wind energy has by far the lowest water footprint.[32] Therefore, the full life cycle water footprint of energy sources can be ranked as follows, in increasing order—wind power, followed by PV and concentrated solar power (CSP); the highest values are attributed to biomass.[34,35] Additionally, energy generation is vulnerable to climate change associated water stress, which is especially significant for hydroelectric and water-cooled thermal power plants (e.g., coal and nuclear). Overall, REs like wind and solar are the most promising candidates for low-water footprint energy production, especially at the location where the energy is produced.

On the other hand, energy is needed to supply water to people. Worldwide, 120 Mtoe of energy, or ~1% of the total global energy demand, is used every year in the global water sector. Water supply activities, such as water extraction from surface and groundwater and water treatment, account for the largest share of water-related energy consumption (42%), followed by desalination and re-use (26%), wastewater treatment (14%), and distribution (13%) (Fig. 2).[23] A total of 850 TWh (73 Mtoe) of this energy is provided in the form of electricity.[23] Thereby, the water sector accounts for 3.8% of global electricity consumption.

In conclusion, it must be considered that energy generation also depends and has an impact on water availability, whereas water supply depends on energy availability. Therefore, competitive needs and trade-offs are generated between the different water, energy, and food (WEF) sectors, which have to be accounted for in sustainable development planning.[35]

## 2.2 *Governance of WEF Nexus in the MENA Region*

Thus WEF security is among the main challenges the MENA countries are facing.[36] In addition to the above-described environment related challenges, unsustainable production and consumption patterns as well as ongoing socio-political transformations are expected to increase the barriers to implementation of the SDGs. Insufficient governance and institutional structures to achieve sustainable development, lacking public participation and funding and inadequate efforts in human resource development are part of the problem.[1] Thus the SDGs, going beyond the WEF nexus, can only be achieved by a paradigm change, combining efficient governance structures and adapted technological innovations in a sustainable socio-economic framework, to transform economy and society toward a sustainable, "green" future.

Numerous Middle Eastern regional bodies and programs realize the necessity to address the great challenges for the MENA region. Thus considering the interlinkages between the sectors, the nexus approach to WEF sustainability in the Arab region was recently well recognized by the Arab Strategic Framework for Sustainable Development, supporting it as a framework for planning and monitoring to encourage the transition toward a green economy.[37] However, no Arab country has developed a green accounting system as yet.[38] Through start-up green enterprises in areas such as RE and energy efficiency, water, agriculture [including feed and fertilizers

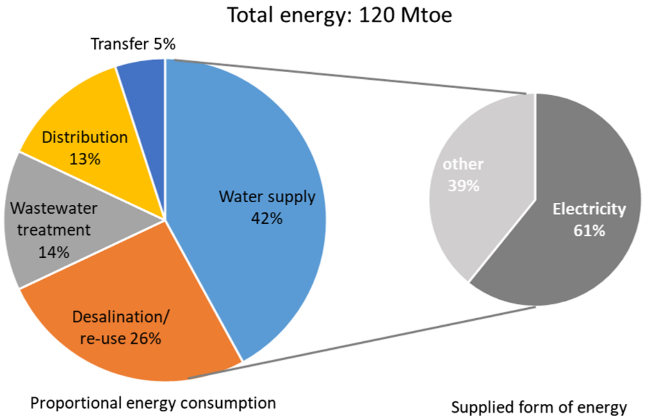

**Fig. 2** The water sector's worldwide proportional energy consumption, which is mainly supplied in the form of electrical energy (data adapted from Ref. 23).

(World Council for Sustainable Development WBCSD)], waste management, and other climate friendly technology, this policy change is envisaged to create 30 million jobs in the region, securing a sustainable transition in the Arab world.[37] A recent "roadmap 2050" for global conversion of all-purpose energy infrastructures in 139 countries to REs estimates the creation of 24.3 million more permanent, full-time jobs than jobs lost.[39]

Recently, ESCWA[40] released a Water–Energy Nexus Operational Toolkit—Renewable Energy Module, developing the capacity of ESCWA member countries to address the water and energy nexus for achieving the SDGs. Importantly, other dimensions of the SDGs going beyond water and energy need to complement this approach. However, the current WEF-climate policy landscape in the region is complex and still fragmented since the sectors have to date been developed independently of each other and remain uncoordinated.[1] Policies and actions such as improvements in only one sector influence the water, energy, and food nexus, which embrace both households and the wider economy. Thus the nexus is acted upon by major drivers such as economics, environment, demography, technology, institutions, and policy while impacting food and nutrition security, poverty reduction, environmental sustainability, labor markets, gender equity, and health.[29,41,42] These complex and dynamic nexus interactions take place in a context of transformational processes[21] but are still characterized by a silo mentality with sector-focused governance structures and sector strategies and policies[43] and lack of coordination arrangements.[21] Insufficient governance and institutional setups are the main obstacles in making a transition to sustainable development in the Arab world.[37] This is also reflected in the education system. The 2011 Arab Forum for Environment and Development (AFED) report,[37] therefore, calls for an Arab Sustainable Development Institute to advance "green" transitions and a network of national cleaner production centers to promote research and development (R&D) and disseminate best practices in clean production and processes. AFED[44] demands genuine, integrative efforts across disciplines and institutions, involving government, business, and third sector players, where members share knowledge, collaborate, and rise above, past or beyond official agency boundaries or jurisdictional territorialities.

## 2.3 *Research and Development and Other Prerequisites for SDG Achievement in the MENA Region*

Human resource development and specifically education systems must aim to provide professional and skilled labor that is capable of supporting a transition to a green economy to achieve sustainable development.[44] ESCWA[45] and the Arab High Level Forum on Sustainable Development point at an overall underfunding of science and technology development and a deterioration of education systems in the Arab region, along with an inadequate infrastructure and R&D support systems and call for a stronger regional collaboration between government agencies, research institutions, regional and international organizations, and universities in capacity building and dissemination of knowledge. ESCWA[46] demands commitment with special emphasis on green economy-related scientific, technical, engineering, and social disciplines, prioritizing REs, and waste management. This approach is supported by Council of Arab Ministers Responsible for Environment in the Arab Regional Strategy for Sustainable Consumption and Production published by UNEP,[47] which names as priority areas energy, water, waste management, rural development and poverty eradication, education and sustainable lifestyles, and tourism.

Thus innovative approaches and environmentally sound technologies are key in achieving sustainable development objectives and addressing climate concerns.[44] However, technological and innovative solutions for the nexus are at their early stages of development in the Arab region, as stated in the Nexus Policy Brief 6.[28] There is need for innovative technological research and approaches to the WEF nexus that include economic opportunities such as cleaner production, wastewater treatment, integrated solid waste management (e.g., waste to energy, production of compost from municipal and agricultural waste), and organic and sustainable agricultural projects.[44]

Recent AFED reports on energy, water, food security, climate change, green economy, and sustainable consumption and sustainable development in the Arab region[37,44,48–55] and "Guidelines for Innovation Platforms"[56] provide background and roadmaps for the approach to a "great transformation" for sustainability. In these reports, climate change mitigation and the employment of REs play a decisive role. They are supported by the Strategy for Sustainable Agricultural Development 2005–2025,[57] Egypt's Sustainable Development Vision 2030.[58]

## 2.4 *Toward Realizing the SDGs in Egypt*

As signatory of the SDGs, Egypt has committed itself to realizing the SDGs by 2030.[5] To that end, the Egyptian government launched Egypt's first national sustainable development blueprint, "Sustainable Development Strategy: Vision 2030."[58] The strategy, closely aligned with the UN's SDGs as well as the African Agenda 2063, informs national development steps and processes over the coming decade and will be overseen by a National Committee for Monitoring the Implementation of the SDGs in order to track the country's progress. Acting under the leadership of Egypt's Prime Minister, the committee is composed of members of 17 different ministries and state entities. In 2018, Egypt released a Voluntary National Review 2018, published by the MPMAR[5] with United National Egypt as part of the UN's country-by-country assessment of SDG achievements.

In this report, MPMAR[5] outlines that Egypt's efforts to increase its economic performance under support of international financial bodies include cutting back on national subsidies. Between 2012 and 2018, the Egyptian government decreased subsidies on fossil fuels and food by 34% and 3%, respectively, while subsidies on social security and pensions as well as contributions to pension funds were increased by 11% and 13%, respectively. Despite these measures, the percentage of the population below the national poverty line has grown from 26.3 in 2012/13 to 27.8 in 2015.[5]

Egypt, like most countries in the world, at present relies more heavily on nonrenewable resources than renewables; more than 90% of its power supply is generated from fossil fuels, with only 3% nonhydro REs.[23] In its effort to meet SDG 7, Egypt is working on sustainably diversifying its energy mix. In 2017, Egypt generated 90% of its energy through the combustion of fossil fuels. In order to limit the use of fossil fuels, Egypt plans to reduce oil subsidies of around 2 billion USD (35 billion EGP) in 2017 to zero by 2030.[5] In parallel, the Egyptian government aims to increase the share of RE in the country's energy mix to 22% by 2022.[5] In this energy plan, wind energy will provide 12% or 7.2 GW of energy, hydropower 5.8%, and solar energy 2.2%. By 2027, solar energy is expected to generate a total of 3.5 GWp (2.8 GWp PV and 700 MWp concentrated solar power). With annual insolation rates exceeding 2000 $\mathrm{kWh/m^2/a}$, Egypt has strong potential for solar power generation. By 2035, the Egyptian government plans to increase the share of RE in its energy mix to 37%.[5] However, Egypt also pursues an expansion of coal and nuclear energy plants, a topic Egypt's national report on sustainable development achievements remains very quiet about.

Electricity subsidies are to be phased out entirely over a period of three years starting from 2018/19 and decreased by almost 50% in the first year of implementation alone.[5] The abolishment of energy subsidies will make solar energy more competitive on the Egyptian market. Low monthly electricity costs have been discouraging Egyptians from investing in solar energy technologies, especially in urban areas that are connected to the electricity grid. The government seeks to create further incentives through the full implementation of feed-in tariffs.[5] Therefore, incentives for PV and other RE systems in Egypt include allocation of land with very competitive prices, signature of long-term power purchase agreements, political and governmental guarantees of support, and reduced custom duties at 2%.[59] As a result of the feed-in-tariff applied for grid-connected PV, several foreign investors have invested in PV in Benban, so far the world's largest solar PV park, which is being built in Aswan in the south of Egypt. The solar park, named after a Nile River village nearby, will house 32 power plants when complete and is set to have an installed capacity of up to 2.0 GWp of solar power when completed in mid-2019.[5]

# 3 Challenges of Energy and Water Supply in Rural Egypt

Despite the significant progress being made toward the SDGs, Egypt's sustainable development challenges remain manifold. As Egypt is set to find solutions to many of these sustainability challenges, it is often rural and remote areas where these solutions are most difficult to implement. While the growing use of renewables in Egypt benefits from the removal of subsidies, residents of rural and remote areas suffer the most from the increased prices of diesel and fuel. The surge in fuel and diesel prices not only affects electricity production and pumping in agriculture, but also increases the prices of goods and services, particularly in remote areas of Egypt where transportation costs are added to local prices. The increasing price of diesel and the, at times, unreliable access to fuel and electricity can be a problem in rural Egypt, as it is in many other rural areas around the planet.[60,61] It is here where the effect of subsidy removal is felt very immediately, and where citizens are complaining that rising prices are pushing them beneath the poverty line. Based on interviews carried out in Western Desert oases in December 2018, after the recent rise in fuel prices in Egypt following subsidy removals, irrigation costs for 5 feddan (around 5 acres) of land can be as high as 120 USD per irrigation day—amounting to a cost of up to 240 USD per month for irrigation only.[62] Interviews with local government officials in and around Farafra oasis confirmed that the rising costs of diesel pumping have led hundreds of farmers in the region to abandon their fields over the past few months. As Egypt's sustainability goals include the full removal of fuel subsidies, the price of diesel is expected to rise significantly higher over the next few years, thus further exacerbating the situation for rural farmers.

### 3.1 *Electricity Access in Rural Areas*

Egypt has not yet achieved universal access to electricity in all parts of the country. Egypt's Voluntary National Review[5] states that in 2016, 99.7% of the population had access to electricity. The SDG target for 2030 is 100%. Despite the high electrification rate in Egypt that reaches 99.7%,[5] there are still some remote areas that lack access to electricity, yet other large-scale new agriculture communities are added such as the 1.5 Million Feddan project. All these aforementioned areas lack access to the national electricity grid. As Shouman et al.[63] pointed out, in Egypt "developing an electric grid system to rural and remote areas is often too expensive because these areas are frequently located too far away from existing grid lines."

An important point to make is that the formulation "access to electricity" does not always mean that such access is stable and available at all times. At the Third International Conference on Solar Energy Solutions for Electricity and Water Supply in Rural Areas in 2018, a delegation of project partners of The American University in Cairo, all themselves residents of rural areas, complained about the lack of electricity services. The delegation was represented by residents from the Western Desert oases of Abu Minqar, Farafra, and El Heiz, near Bahariya, as well as a resident of Monufeya governorate located in the Nile Delta, and the El Moghra desert settlement area near the Mediterranean Coast. In the Western Desert, the electricity grid stops in Bahariya oasis (350 km southwest of Cairo) and Dakhla (located around 300 km southwest of Assiut). The oases in between—including Abu Minqar, Farafra, and El Heiz, representing a total population of around 23,000 in total[64,65]—are not connected to the electricity grid. The same applies for people living along the Far Southern Red Sea Coast and in the mountain valleys of the Eastern Desert and parts of Sinai. In remote communities that are not connected to the electricity grid, local diesel generators provide electricity for the community. The daily duration of operation of these generators depends on the size of the community. While Farafra town has a generator that operates 24/7, smaller villages such as El Heiz or Abu Minqar have access of between 6 and 20 h per day. Smaller villages located away from the main road sometimes have to run their own generators for electricity supply. The presence of larger investors, such as big farming companies, sometimes gives local villages more leverage in demanding better electricity services, but smallholder farming communities do not have this kind of bargaining power. Other grievances voiced by residents of rural areas at the conference and in field research[62] include electricity cuts, the failure of RE projects due to misguided planning or mismanagement, the gap between scientific research and solutions, and the accessibility to people living in remote areas, as well as the political support for rural RE transformations.

In Egypt, as in many other countries, electricity and water access are closely intertwined. As Egypt is a country with close to zero rainfall, drinking water is pumped out of the Nile River and its connected canals, from shallow aquifers connected to the Nile River, or from deep aquifers using deep wells. Pumps that draw water out of the ground and/or push it into pipe systems toward household taps run on electricity derived either from the national grid or from a local grid provided by a diesel generator. In remote areas, these systems are often connected, and the dysfunctionality of one system immediately affects the other. Electricity cuts, the malfunctioning of a local generator, or the lack of diesel to operate the generator often mean that an entire rural village lacks access not only to electricity, but also to tap and irrigation water. Although in some governorates, government-owned wells for agricultural irrigation are supplied with diesel by the government, in other governorates, this responsibility was recently shifted over to the responsibility of the farmers. This means that a financial factor also plays an important role in the access to diesel for pumping and thus to water for irrigation.

## **3.2** *Water Access in Egypt's Rural Areas*

The Egyptian government has made significant progress over the past two decades in improving the population's access to clean drinking water. According to a report released by Egypt's Environment Affairs Agency (EEAA) in 2008, between 1990 and 2006, the access to piped water increased from 89% to 99% in urban areas and from 39% to 82% in rural areas.[66] Putting in place the infrastructure to make available safe potable water in Egypt has been heavily financed by the US government. Since the 1970s, USAID has invested more than 35 billion USD into the development of Egypt's water and sanitation infrastructure, reaching, as USAID claims, over 25 million Egyptians.[67] A government sector reform implemented in 2004 initiated the implementation of several new regulations. A Holding Company for Water and Waste Water was founded in April 2004, following an assessment of the drinking and sewage water situation in Egypt. This reform clearly pushed for more private company involvement in the provision of potable water and sewage water services in Egypt. In 2006, the Egyptian Water Regulatory Agency was founded in order to act as an independent agency responsible for reviewing price changes and technical standards, dealing with customer complaints, and promoting public private partnerships. The Holding Company replaced hundreds of thousands of water meters in the Greater Cairo area and worked on several technical improvements for water providers (more details below).

In 2011, Egypt's Holding Company for Water and Wastewater claimed that by 2008, 100% of cities and villages in Egypt would have access to improved drinking water.[68,69] This goal was not reached. According to the HCWW's own numbers, the coverage did not exceed 98% in rural areas in 2012.[69] In 2014, UNICEF[70] found that a total of 91% of Egypt's population had access to tap water at the household level, whereas 12% of the population living in rural areas did not (as compared to 4% in urban areas). The vast majority (5.8 million) of those who did not have access to safe water in 2014 lived in rural areas, compared to 1.5 million living in urban areas.[70] A Centre for Environment and Development for the Arab Region and Europe[71] report based on numbers released by egyptian water regulatory agency[72] states that in 2011/12, Egypt was operating 2593 water treatments plants supplying water through a network of 14,600 km. Looking specifically at the availability of safe drinking water, a requirement under SDG6, Egypt's Voluntary National Review 2018[5] states that 98% of urban and 95% of rural areas have access. According to the report, the Egyptian government is currently implementing 391 projects (236 running and 155 planned), targeting a total of 498 villages in order to bring access up to 100% by 2030. As an example, a study conducted by The American University in Cairo[73] in the North-Eastern Delta in 2015 and 2016 showed that many villages not located far from urban centers presently are not connected to a potable water grid. Although some of these houses at least receive a delivery of 1 cubic meter of water per family per week free of charge from the Egyptian government, others are relying on the purchase of all water required for their households from private vendors.

Despite the progress made in water delivery to households in Egypt, problems with rural access to safe drinking water remain. One part of the problem might be the definition of terms. The WHO[74] defines access to safe drinking water as having access to an improved water source, meaning one that the physical infrastructure of water delivery protects the water from contamination, as well as access to water that complies with national and international safety standards. Progress reports often only address on of these two factors. Therefore, villages that may have improved water infrastructure in place may still not be able to guarantee their residents' access to water that complies with water regulations and standards. As UNICEF stated in the early

2000s,[75] "unfortunately, there are many villages in rural Egypt that continue to rely on water delivery and waste disposal systems that are outdated, unhygienic, and unsafe. As a result, the situation with regard to safe drinking water, household sanitation, and the immediate environment within these communities is far from satisfactory." According to USAID,[67] the goal of providing all Egyptians with access to drinking water, especially for the residents of rural areas, lags behind due to the lack of wastewater infrastructure, water pollution in canals and drains, and the expansion of settlements into areas with polluted waterways. El-Zanfaly[76] confirmed that this problem persists and that the challenge is not always one of access but also one of the quality of both the infrastructure and the drinking water itself. A study published by El Bahnasy et al. in 2014,[66] based on research carried out between 2011 and 2013, revealed that in Menoufia Governorate 1% of the total urban population and 15% of the rural population did not have access to safe drinking water (with a stress on the word safe). The authors conclude that this was due to improperly kept infrastructure and irregular amounts of chlorine added to the water. As a result of this, the authors contend, the majority of the population of Menoufia Governorate were forced to use filtered, bottled, or vended water for drinking or drinking water from privately operated filtration stations run by nongovernmental organizations.[66] This evaluation clearly indicates a lack of trust in the quality of potable tap water provided by the Egyptian government, a result confirmed by a recent study conducted in Upper Egypt.[77]

The general approach taken by the Egyptian government to providing Egyptian villages with clean water has been a "whole village" approach. This means that drinking water and water for other household use are not separated and that household tap water is considered as being of drinking water standard. A result of the "whole village" approach is that the government builds large, expensive stations that are designed to filter and pump large quantities of water into village water pipes. Technologies used for village water purification systems in Egypt include membranes, sand filters, and chlorination (further details in the following section), based on the type of source water. In Egypt's Western Desert, the government pumps up water from the Nubian Sandstone Aquifer, which has a very high-iron content, and chlorine is not added to the water as the bacterial contamination of groundwater is deemed negligible (see Ref. 62). In the Delta, water used for village drinking water supplies is often pumped up from shallow aquifers. In the Nile Valley and Cairo, drinking water stations are mainly drawing water from the Nile.

As this section on the sustainable development challenges in providing electricity and water services for rural areas in Egypt and the MENA region has shown, electricity and water supply are closely interconnected. Therefore, efforts to ensure reliable quality services for both electricity and safe drinking water across all rural areas will have to address and build on technologies that can forge synergies and connections between them.

## 4 Recent Developments in Solar PV and Opportunities for Rural Areas

### 4.1 *Global Developments of the PV Market and Recent Research on Emerging Technologies*

The global PV module production has been growing exponentially and surpassed 100 $\mathrm{GW_p/a}$ by the end of 2018.[78] The overall share of PV in the global electricity supply is still below 2% (0.5 $\mathrm{TW_p}$ installed power), but with two thirds of capital investment for electricity generation, it is among the fastest developing energy technologies.[24,78] In order to reach international climate goals of stabilizing global warming below 2°C, a drastic and fast expansion of PV installations toward tens of terra-watts, i.e., a share of 20% to 45% of the global electricity production, will be required by the middle of the century.[79,80] For the past two decades, PV production has been over-accomplishing, even compared to the most optimistic projections.[81] Thus from a technological perspective, the PV industry is on a trajectory to reach terra-watts production in the near future, making it both a key energy technology[82] and the cheapest energy source for many locations around the world.[23]

Today, mono- and multicrystalline silicon solar cells make up 95% of the global PV market. The rest is essentially covered by so-called "thin film" technologies such as cadmium telluride and copper indium gallium selenide solar cells.[83] Although silicon PV production requires much energy for the growth of highly pure Si crystals, in research, alternative PV concepts are being developed based on liquid-processable PV absorbers such as in dye, organic, quantum dot, and, recently, perovskite PV. Here PV inks can be used for printed PV, which has a clear advantage over silicon PV in the ease of production, as the photoactive material can be deposited by fast printing techniques like roll-to-roll, screen-, or inkjet-printing. Such a production can drastically reduce the module price. If printed on lightweight substrates like foils, such devices have advantages for remote areas by ease in transportation. This also provides more degrees of freedom in terms of implementation. For example, flexible PV could be used in nonpermanent settlements on tents and tarps. Yet, finding suited foil barrier materials for long-term encapsulation against air is a major challenge. The drawback of these emerging technologies has long been the relative low-power conversion efficiency, which has stagnated below 12%. Recently, organic and quantum dot PV efficiencies of 15.6% and 16.6%, respectively, have been reported, however on very small scales.[84] In parallel, the young technology of perovskite PV has shown rapid progress in the past ten years. Today, the record efficiency for small-scale laboratory cells is 23.7%.[85] In terms of laboratory efficiencies, perovskites are thereby already ranking among traditional technologies like silicon and thin film. The long-term stability of these emerging PV technologies is a major obstacle for commercialization as the employed organic or hybrid organic–inorganic absorbers and contact layers are prone to degradation upon exposure to oxygen and humidity. Yet, for perovskite PV, there has been a steep learning rate. The most promising path today is the incorporation of inorganic carbon counter electrodes. Although the highest certified stabilized efficiencies of 12.6%[86] are still relatively low, for graphite-based perovskites, lifetimes of up to one year have been reported, as well as the first fabrications of perovskite minimodules for outdoor test applications.[87,88]

## 4.2 *Photovoltaics and the Electrification of Rural Areas*

Efforts to extend access to electricity can be made either directly by the affected person or community, or by governmental or private actors such as ministries, utilities, corporations, or NGOs. The availability of provided electricity can range from a few hours per day to continuous coverage. Electricity access can be enabled either through connection to a centralized electricity grid or through a range of solutions for distributed, mainly off-grid, electricity generation from community-based minigrids, over single-household or even single-application power solutions. There is a power-law inverse relationship between electricity cost and scale of electricity supply technology. This means that, in an ideal scenario, due to economies of scale, grid connection would be the cheapest solution to provide electricity access.[22] Yet, there is a range of hurdles for the establishment of grid connection. First, whether it is economic to install a new transmission line and extend the grid power capacity depends on the size of the community to be connected and the distance to the next transmission line.[89,90] If the community is too small, legal force or financial incentives for utilities to provide grid access are needed. Still, even for those living within reach of a power line, the implementation of grid connection is often impeded due to high initial costs to the consumers, utilities, or government, as well as legal hurdles.[22] Finally, many of those connected to the grid suffer from unreliable electricity and frequent power outages.

In many cases, off-grid solutions can be a more feasible option for access to reliable electricity. Historically, the implementation of off-grid solutions has been realized by diesel generators. Yet, this technology is associated with health issues and a severe global warming potential. Diesel generators represent one of the most expensive methods of electricity generation, for example, due to fluctuating fuel costs and transportation. Therefore, diesel must be highly subsidized in many African countries, consuming a large portion of the national GDP.[90] Fortunately, in recent years, prices for RE technologies have drastically declined, enabling the rise of solar powered off-grid solutions. PV electricity generation is especially attractive in regions with high insolation rates. These regions tend to also have the highest need for electrification. PV is an energy technology that is very flexible in terms of configurations of power capacity, from a few watts to megawatts, and therefore ideally suited for off-grid solutions on all scales. Moreover, PV has the advantage of very low-running expenses and low-global warming potential. On the downside, electricity is only produced during the daytime, necessitating additional storage such as batteries for continuous power supply. The worldwide installed capacity for off-grid solar systems has been rising exponentially to 2.8 GWp in 2017. Thereof, 0.8 GWp was installed in Africa (0.4 in Algeria alone), 0.6 in India, 0.4 in Yemen, and 0.4 in China.[91] While these developments were supported by subsidies, with declining prices for solar modules and batteries, off-grid solar solutions for reliable electricity are becoming more and more competitive with the grid, especially in tropical locations like sub-Saharan Africa.[92] Yet, barriers to implement solar off-grid electricity are often nontechnical, such as the need for relatively high up-front investment capital or a reduced relative profitability if diesel is subsidized by the local government.[22] Sustainable economic options for technical solutions are therefore needed to support the deployment of PV use (see also Wydra et al., this issue).[93]

For system integration, conventional applications are open land or rooftop PV installations, but the combination of land use for both agriculture and PV electricity generation is gaining more momentum. Though the concept was first proposed in 1981,[94] many so-called "agrivoltaics" pilot installations on open fields and PV-greenhouses have only recently been implemented. Especially in places with limited land availability, agrivoltaics has strong potential for providing energy with efficient land use for the agricultural sector. In arid climates, the shading by the PV panels can contribute to more efficient water use.

The most basic benefit of electricity is access to clean lighting and the replacement of harmful kerosene lamps. Electric lighting has a positive effect on child education and productivity of workers as it extends the amount of time they can devote to work or study.[95] This can already be enabled with simple solar powered lamps. Another benefit of electrification is the ability to charge mobile phones. Mobile phones have rapidly evolved to play a key role for enabling social, economic, and informational participation. In 2016, the number of worldwide cell phone subscriptions has surpassed the number of humans in the planet, with 0.75 subscriptions per inhabitant in the SSA countries.[96] PVs may also play a role in more advanced electricity systems providing power for workshops and businesses. Solar power can contribute to a reliable electricity supply in healthcare facilities, improving the health services ranging from provision of electrical light, ensuring cold-chains for vaccine cooling, and powering for life-saving electrical equipment.[97] Finally, solar powered water pumping and purifications can have positive effects on agricultural activities and sanitation, as will be discussed in the following section.

In many countries, PV already is or is about to become cost competitive with traditional fossil fuel-based power sources, with prices clearly falling below the threshold of utility scale prices.[98] For even more advanced PV production scenarios, in the future, PV industry landscapes might change toward a production scenario with lowest manufacturing prices like in the global glass industry where transport costs account for a considerable share of the entire costs.[99] This would enable the creation of new jobs in the countries where the PV panels are both produced and installed. In arid climates, the day-night fluctuations of PV can be cushioned by electrification of complementary sectors such as expansion desalination infrastructure.

## 5 Solar Applications for Electricity and Water Supply in Rural Areas in Egypt and the Region

### 5.1 *Solar PV for Electricity Generation*

There are several off-grid PV applications currently operating in Egypt, including telecommunication stations, rural electrification, groundwater pumping, street lighting, water purification, and water desalination units. An off-grid or stand-alone PV system, either working on DC or AC mode, consists of the PV modules, charge controller, solar batteries, and an inverter in the case of AC mode. Such systems are installed in Egypt in several areas as indicated in Table 1.

One of the most widely implemented applications for off-grid or stand-alone PV systems are groundwater pumping for irrigation in the new reclaimed desert lands. The brackish groundwater is pumped from wells about 200-m in depth using multistage submersible pumps. The required power for these pumping systems is about 75 HP and the rule of thumb for the required peak power of the PV modules is 75 kW. In most of the already installed systems, the PV peak power is equal to the HP of the pump. This design allows for about 5 h of daily operation at peak load of the pump.

**Table 1** Installed PV systems in Egypt, updated from El-Hefnawi.[100]

| | PV power (kWp) | Installer | Location |
|---|---|---|---|
| Water pumping | 18 | Solarex | East Oweinat |
| Water pumping | 25.3 | A.E.G | Wadi Elnatron |
| Water purification | 7 | A.E.G | |
| Seven telecommunication systems | 0.24 each | BP | Hurghada, Abu-Ghossoun, Matrouh, Siwa |
| PV/wind diesel hybrid | 7 | Ecosun | Wadi Elnatron |

Hybrid PV systems are one of the most promising applications of PV technologies in remote areas, where the cost of grid extension is prohibitive and the price of fossil fuels are continually increasing. Hybrid PV systems are RE systems that combine at least one other RE source, such as wind or hydropower. The ultimate goal of a hybrid system is to achieve complementarity between the RE sources in order to reduce the amount of energy storage capacity needed. However, such systems are rarely seen in the Egyptian market due to their sophisticated design and operation.

Currently, it is always desirable to have flexible systems, with consequently modular structure. These systems are achieved via coupling all consumers and generators on the AC side (AC coupling systems). The structure of such supply systems requires, in addition to the power conditioning equipment (inverters and charge controllers), a control and supervision unit, which is responsible for implementing a specific operation control strategy and for securing the entire system components. In small and medium power systems ranging from 3 to 30 kW, this control unit is often integrated into the key component (bidirectional battery inverter), which simplifies system operation and decreases the investment costs. This configuration also helps to reduce the cost of the entire system, especially the costs for the cabling on the DC side and the subsequent distribution on the AC side. Such topology is implemented in Wadi Elnatroun using the SMA inverters shown in Fig. 3.

An additional benefit of hybrid PV systems installed in AC topology, which are sometimes called minigrids or microgrids, is that they allow for future integration with the national grid, in case of future extension to the area. However, since micro- and minigrids require sophisticated control systems and well-trained personnel, these systems are currently underexploited in Egypt. A detailed analysis of the RE potential in these rural areas is needed in order to design an optimal hybrid system.

AC coupling systems can also be fully integrated into the already existing diesel-generated systems in isolated areas. The generator then can be operated as an emergency back-up, in case of deficit energy from the RE sources or low-battery state-of-charge. The minimization of the operating hours of the generator should be set as an objective function during the design phase of the project in order to minimize the nonrenewable fraction of the generated energy.

### 5.2 *Solar PV Pumping Solutions for Irrigation and Agricultural Production in Rural Egypt*

Egypt, like much of the MENA region due to its arid climate, relies almost entirely on irrigated, rather than rain-fed, agriculture for food production. Therefore, pumping represents an integral part of farming in Egypt. Water has to be pumped out of the Nile into canals, out of canals into fields, and up into desert areas that have been developed into agricultural production areas as part of Egypt's desert reclamation and expansion policy. Water is pumped into pressurized irrigation systems such as drip and sprinkler irrigation systems, and, often, into and/or out of drainage canals. Most pumping related to irrigated agriculture in Egypt is managed by diesel pumps, as is the case with many other countries that rely fully or in part on irrigated agriculture.[102,103] Some of these diesel pumps are large, firmly installed pumps, others are small, moveable pumps moved around between different irrigation areas and sometimes shared by multiple farmers in different

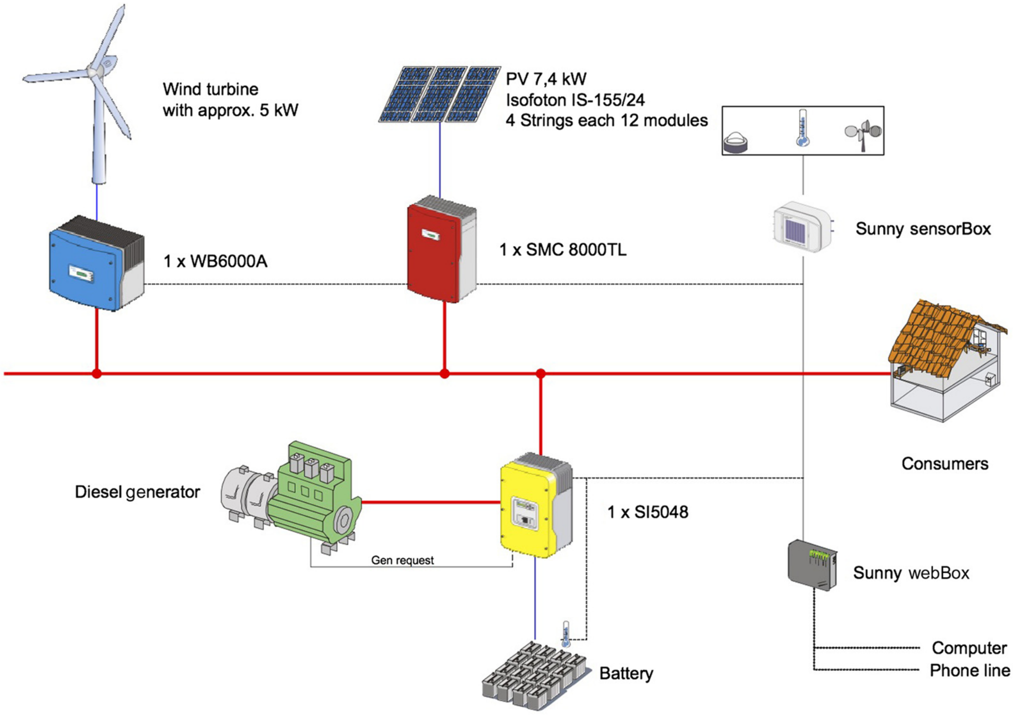

**Fig. 3** Hybrid PV/wind/diesel installed in Wadi El Natroun (source: Ref. 101).

locations.[104] Especially, older pumps are often dysfunctional and in need of frequent repairs (Fig. 4). The pumps' smoke usually causes local pollution and strong diesel smells.

There are a variety of RE solutions for water pumping that have been researched and tested worldwide, including solar PV pumping systems, solar thermal pumping systems, wind energy water pumping systems, biomass water pumping systems, as well as a number of hybrid systems.[105,106] Solar PV technologies for pumping have been significantly improved since the 1970s,[107] after some initial tests conducted in the mid 1960s.[61] Aliyu et al.'s[60] overview of current research showed that solar pumping systems are installed in 18 countries around the world, with a third of the locations being in Africa. For the MENA region, solar PV pumping solutions are a particularly viable option for more sustainable pumping solutions due to the high incidence of sunshine.[60] In Egypt, as in many other regions of the world,[106] solar PV systems for water pumping are the most common RE powered pumping solution. Wind pumping systems, which take second place overall[106] were tested in various parts of Egypt in the 1980s but are less common today. According to Gopal et al.,[106] "the solar thermal and biomass water pumping systems are less popular due to their low-thermal energy conversion efficiencies."

**Fig. 4** Examples of small, movable diesel pumps in rural Egypt that are prone to failure and in constant need of repairs. (a) Movable pumps and (b) stationary pumps (source: authors).

Research on the technical feasibility of solar pumping in Egypt started in the early 1980s.[108] As of 1982, The American University in Cairo ran the first research farm on reclaimed desert land in Egypt whose ∼10 acres of farmland were drip-irrigated using a 10-KVA solar PV powered DC pump. The system shown in Fig. 5 also provided electricity for the laboratories and administrative building by means of an inverter, which was very large and noisy at the time. The panels still operational and still used in small-scale development initiatives in rural areas.

Since these early days of solar PV pumping in Egypt, the feasibility of a variety of technological solutions of solar pumping has been researched and tested in different areas of rural Egypt. A study conducted by Gad[109] calculated technical performance of a system consisting of a four-module PV array (with 72 PV cells in each module), a pump controller and a 12 VDC submerged pump, pumping from a well with total head of 30 to 40 m in St. Catherine on Egypt's Sinai Peninsula. The author concludes that such a system is capable of pumping 24.06 $\mathrm{m}^3/\mathrm{day}$ in summer and 12.12 $\mathrm{m}^3/\mathrm{day}$ on a winter day with clear skies, operating at a PV array efficiency of between 13.86% in winter to 13.91% in summer. Technology developments in solar PV pumping have resulted in solutions being available for pumping "anywhere in the range of up to 200 m head and with outputs of up to 250 $\mathrm{m}^3/\mathrm{day}$."[103] Reviewing the most recent studies on solar pumping from around the world, Aliyu et al.[60] confirmed that suction heads are an important efficiency factor and that it is rare for current PV pumping systems to exceed pumping heads of 200 m.

Research continuously goes into optimizing the performance of solar PV pumping solutions. PV pumping solutions with tracking systems that automatically tilt the panels toward the sun can increase the system's performance by 25% to 50%.[61] Because of the significant amount of energy required to facilitate such tilting automatically, most systems in Egypt are manually tilt-able for an optimal adjustment of the PV array toward the sun throughout the day. Abo-Khalil and Ahmed[4] simulated solar PV pumping systems consisting of a vector control of induction motor with a centrifugal hydraulic pump fed by DC–DC converters with maximum power point tracking in order to match the crop water requirements of different crops grown in Toshka, a newly developed desert area in southern Egypt.

Solar PV systems have several advantages over internal combustion engine pumps, such as their long lifespan, their minimal maintenance requirements, the fact that no fuel is required for operation—thus also eliminating the need for fuel transportation—their low-operational environmental impact, and the fact that installation is relatively straightforward.[103] In most solar PV systems, the weakest links are batteries due to their relatively short life span. As irrigation takes place during the day in most farming systems, batteries are often not required for pumping systems.[103] However, the inability to pump at night can also represent a drawback in areas where cultivated areas suffer from water scarcity or where additional irrigation is needed during certain

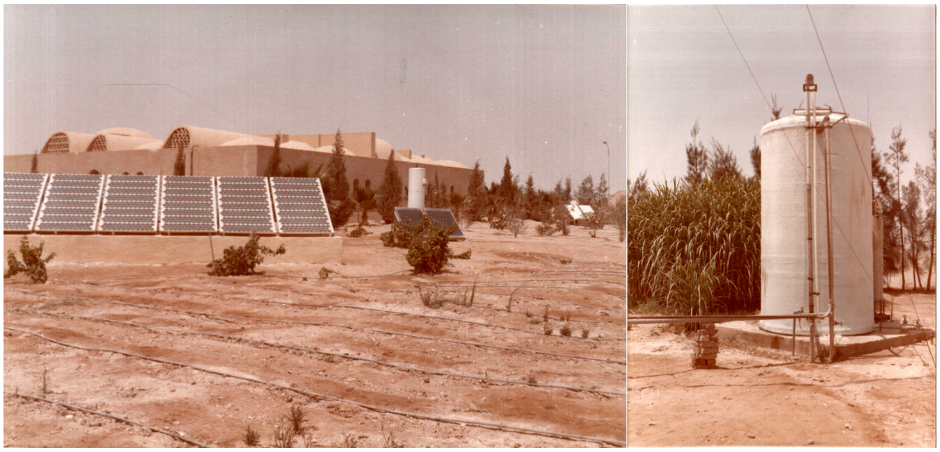

**Fig. 5** The beginnings of solar pumping for agricultural irrigation in Egypt at Desert Development Center's research station in Sadat City in 1982. (a) Complete system and (b) tank with irrigation pump (source: CARES, formerly the Desert Development Center, The American University in Cairo).

periods of the growing cycle, for example, during the summer months. While in some countries the inactivity of solar systems during off seasons is a problem,[103] Egypt enjoys several growing seasons a year and water wells are usually in operation year-round. However, as Elrefai et al.[110] showed, based on a case study of solar PV pumping without batteries tested in Egypt's Western Desert, the maximum daily water output volume occurred during the summer months, which coincides with the time of higher crop water requirements. Gad and El-Gayar[111] presented a solar PV pumping system for Egypt's Western Desert that includes a battery bank in order to ensure maximum pumping capacity during cloudy days and in the dark. Batteries, however, present cost and sustainability challenges. Other performance limitations such as dust accumulations on panels, which is a particularly relevant problem in desert areas, can be solved by spraying water on the panels.[107] This, however, can also pose a problem in areas that suffer from extreme water scarcity.

An important factor in the widespread use of RE technologies is their economic viability, cost, and affordability. Chandel et al.[107] concluded that "solar water pumping is found to be economically viable in comparison to electricity or diesel-based systems for irrigation and water supplies in rural, urban, and remote regions" with payback times of 4 to 6 years for some systems. Studying solar PV pumping solutions in India, Shinde and Wandre[103] concluded that "in general PV pumps are economic compared to diesel pumps up to ∼3 kWp for village water supply and to around 1 kWp for irrigation of maximum solar radiation." Diesel systems are characterized by a lower capital cost and thus lower initial investment but higher operation and maintenance cost, whereas the opposite is true for PV systems. PV systems require high capital costs, but farmers save on operation and maintenance costs, especially given the longer life span of the technology.[60,63]

Several authors have assessed the economic benefits of different pumping systems, including diesel systems, hybrid systems, and PV powered pumping systems in Egypt. Shouman et al.[63] showed that compared to diesel systems, PV pumping systems can have significant long term cost advantages for farmers in terms of net present cost and cost of energy. The cost of energy was calculated at 0.12 $/kWh for the PV system, 0.269 $/kWh for the hybrid PV-diesel system, and 0.321 $/kWh for the diesel system, and this was before the latest subsidy removals in 2018. Researching the merit of PV-diesel and wind-diesel hybrid systems in Egypt's Western Desert oasis of East Oweinat, Kamel and Dahl[112] showed that both types of hybrid systems can cut diesel consumption by 23%. Mahmoud et al.'s[113] study on the potential of PV powered water pumping for sustainable development in the same oasis of East Oweinat concludes that PV powered systems ensure a cost of water unit pumped that is much lower than that of diesel powered systems. Moreover, the water cost seems to be dependent on PV cell prices than on their lifetime periods. Campana et al.,[114] looking at the new approaches to optimizing solar pumping systems in general, demonstrated that the optimal configuration of the system does not only play an important role for smooth continuous operation but can also lead to a "substantial reduction of PV array size and consequently of the investment capital cost and the payback period." The study has shown that a reduction of 18.8% in capital costs is possible taking into account the price of PV modules, forage, and the water source as determinant factors.

Research based on over 30 interviews with farmers in Bahariya, Farafra, and Dahkla oases in Egypt's Western Desert conducted by The American University in Cairo shows that solar PV powered pumping systems have been the most popular solution for newly drilled wells, even for groups of small farmers, over the past few years.[62] The majority of newly drilled wells, whether drilled by medium to large agricultural investors or informal wells that irrigate smaller plots, are powered with solar PV systems. Farmers in the area around Bahariya oasis pump from the Nubian Sandstone Aquifer from depths between 150 and 200 m with static water levels ranging between 1 and 30 m, most commonly using submersible pumps.[62] The drop in price of solar PV equipment in recent years through the inundation of the market with products from China has made these technologies significantly more available for the residents of rural areas. In recent years, solar PV shops offering solutions for both electricity generation and pumping have sprung up across even remote towns and villages of rural Egypt. In 2018, a 5- to 7-hP solar PV pumping system with panels, frame, inverter, pump drive, and pump (and without batteries) cost an equivalent of around 6000 USD in rural Egypt. For a farm that operates on a flood irrigation system, as most small farms in Egypt do, such a pump is sufficient for irrigating around 10 acres of land.

This does not, however, include the cost of drilling the well, which would double the above-quoted price.[62] Even though this is a significant investment for small farmers, these farmers often decide to make this investment either individually or in small groups, in order to avoid the long-term operational and maintenance costs of diesel powered pumping systems (see also Wydra et al., this issue). An increased availability of PV pumping systems through several companies that have opened in the oases over the past few years, sourcing PV panels, pump drives, and pumps from China, have made this pumping solution significantly more accessible for farmers in these remote areas. Figure 6 shows some examples of such rural setups in Egypt.

The decreasing cost of solar PV panels has contributed to a rise of solar powered electricity and pumping applications worldwide.[103] The potential of low-PV prices for the sustainable development of irrigation in rural areas is significant. Shinde and Wandre[103] estimated that "India's potential for solar PV water pumping for irrigation to is 9 to 70 million solar PV pump sets, that is, at least 255 billion liters/year of diesel savings." Kamel and Dahl[112] confirmed that "the lowest initial capital cost is apparently the main factor that energy planners are concerned about."

Sontake and Kalamkar[61] pointed to challenges in maintaining solar PV pumping systems in rural areas, given the complexity of the technical system components. According to Jaskolski et al.,[62] in rural areas of Egypt, particularly the handling of pump drives that often have English, Korean, or Chinese language systems can be an issue for farmers with limited educational levels, knowledge, and training in rural areas. The malfunctioning or failure of a system often stems from the inability to repair a broken pump drive. In rural areas, capacity building for users and vocational training opportunities are needed in order to build up a local and regional workforce of solar PV technicians that can perform installation and maintenance work. In their review article, Sontake and Kalamkar[61] introduced a number of technological approaches to solar pumping that are designed with minimal maintenance and with the conditions of rural areas in developing countries in mind.

From a sustainable development perspective, the reduction of $CO_2$ emissions through applying solar PV pumping solutions is particularly important. Aliyu et al.[60] reviewed the emission reduction potential calculated in the various studies. For a solar PV powered water pumping system of 3.4 kWp tested in Inner Mongolia, Yang et al.[115] recorded a total emission reduction of 129 $\mathrm{Mg\,CO_2\,ha^{-1}}$ over an expected lifespan of 20 years. Out of this amount, 43.5% of the total emissions were contributed by the PV panels, 89% out of which is due to the construction phase of these panels. Comparing hybrid solar, wind, and hydro water pumping system with a conventional system, Ramos and Ramos[116] recorded $CO_2$ savings of 1030 Mg, whereas Ould-Amrouche et al.[117] were able to reduce $CO_2$ emissions by 4.2 t per year when using a 1000-PV systems on the basis of kW pumps. Rehman and Sahin,[118] comparing $CO_2$ emissions for diesel pumps and solar PV operated pumps, mentioned the potential to save 24,069 tons of GHGs annually by replacing a 7-kW diesel generator system with a variety of solar PV systems. Given these demonstrated savings and the need to align pumping practices with SDGs and commitments to limit climate change, solar pumping solutions have a huge potential for rural areas in Egypt and elsewhere.

**Fig. 6** Examples of solar PV pumps installed in the oasis of El Heiz, in Egypt's Western Desert (source: authors).

## 5.3 *Solar Energy for Water Purification Globally and in Egypt*

In the following, only solar-powered water treatments are considered where PV panels generate electricity or solar thermal collectors provide heat for desalination technologies. Direct solar desalination systems, solar photocatalysis, and solar disinfection[119] as well as environmental impacts of desalination technologies[120] are reported elsewhere. In solar powered desalination, various combinations of systems for electricity or heat production from solar energy and for water treatment are possible. In terms of desalination technology, 69% of facilities worldwide rely on energy-intensive reverse osmosis (RO), 18% on multistage flash distillation (MSF), 7% on multieffect distillation (MED), 3% on nanofiltration, 2% on electrodialysis (ED), and 1% on other.[121] The water qualities treated are 61% seawater [20,000 to 50,000 ppm total dissolved solids (TDS)], 21% brackish water (3000 to 20,000 ppm TDS), 8% river water (500 to 3000 ppm TDS), 6% wastewater, and 4% pure water (<500 ppm TDS).[121] Earlier large-scale desalination plants employ mainly thermal desalination, such as MSF and MED, where sea water is heated, evaporated, and the steam then condensed to receive freshwater. For small-scale water purification on the household or community level, technologies using metallic iron ($Fe^0$)-based filtration systems without the need of energy input are being tested.[122,123]

In Egypt, various model plants with parabolic trough collectors (PTC)[124] with solar collector areas of 61,680 and 93,050 $m^2$ were installed in combination with MSF technology for seawater with capacities of 5000 $m^3/d$. For MED, seawater is delivered to several cells for vaporization and condensation, and a quite low top brine temperature (55°C to 120°C) is needed. Solar powered systems such as PTC are being used on different scales in Egypt and Jordan,[125,126] with 42 MWe power generation and 24,000 $m^3$ seawater cleaning capacities in Jordan, including thermal storage in molten salt tanks. In MSF, seawater is vaporized at low temperatures in a vacuum, under which the boiling point of water is low therefore requiring less energy, though energy is still needed to heat up the seawater. In comparison, in RO systems, the intake of seawater is only one third of that needed for the same output in MFD systems, thereby reducing energy costs for pumping and disposing the spent brine.[124] In RO, high pressure is used to filtrate saltwater or brackish water against an osmotic pressure through a semipermeable membrane, removing ions, molecules, and larger particles. Small-scale and pilot-scale plants have been investigated since the 1980s,[127] and the World's first Solar PV powered seawater RO plant was built in 1982.[128] Compared to MED and MSF, RO is the most energy-efficient process, and, depending on the feed water type, higher (6 to 8 Mpa) or lower (0.6 to 3 Mpa) feed pressures for seawater or brackish water, respectively, are needed, where energy can be provided by PV systems. Gargh and Joshi[128] provided a review of PV powered brackish and seawater RO desalination plants.

Various small-scale and pilot-scale plants integrating solar PV and RO to clean brackish groundwater have been built in Jordan[129] and Tunisia.[130] These plants performed successfully, e.g., a PV-RO plant built in 2006 in Tunisia, providing 3.26 to 12.8 $m^3/d$ freshwater from brackish water in a Sahara Desert village, with an energy consumption of 1.64 to 3.13 $kWh/m^3$,[129] as well as a pilot plant in Jordan, with a specific energy consumption of 16 $kWh/m^3$ brackish water. A pilot plant producing 30 $m^3/day$ using RO powered by off-grid solar is being implemented by the company Mascara NT in 2019, and stand-alone containerized mobile desalination units are commercially available.[131,132]

Forward osmosis (FO), a newer desalination technology, is a membrane process based on the natural osmotic pressure gradient rather than hydraulic pressure to force water to permeate through the membrane: on the other side of the membrane, a "draw" solution with significantly higher osmotic pressure than the saline feed water is used, optimally composed of ammonium salts formed from the mixture of ammonia and carbon dioxide gases.[133] This process has relatively low-energy requirements since the major energy consuming step is only the draw solute separation, and thus, has lower costs than RO. Recent developments combine hybrid FO–RO systems for wastewater reuse and seawater desalination.[134] These hybrid systems can be used to recover high-quality water from a wastewater stream and to dilute seawater before RO treatment, which reduces the energy needs of the desalination. However, this process needs more research in up-scaling and technical optimization, specifically facing the challenges of membrane fouling in RO membranes.[135] Energy savings of up to about 70% could be possible, considering that the natural osmosis to desalinate seawater requires $\sim 1\ \mathrm{kWh/m^3}$ of water produced.[136] Thompson and Nicoll,[137] comparing FO and RO, reported a specific energy consumption of $4.9\ \mathrm{kWh/m^3}$ for an FO and $8.5\ \mathrm{kWh/m^3}$ for an RO plant at Al Kahlouf, Oman.

CSP is considered specifically suitable in integrated CSP desalination systems for middle- or large-scale desalination[138] and is matter of ongoing studies but not yet commercially realized. Here steam can be used for the MED treatment and surplus for provision of the population with electricity. In simulation studies in Israel and Jordan, a $24{,}000\ \mathrm{m^3/d}$ desalination plant was powered by a CSP plant of 42 MW electricity generation capacity, supplying the MED plant with steam and electricity.

Solar thermal collectors are also employed for membrane distillation (MD) systems to heat the untreated water, creating a temperature gradient between two reservoirs separated by a hydrophobic membrane with pore sizes of typically $0.2\ \mu\mathrm{m}$. The membrane acts as a barrier for the liquid impure water but allows water vapor to pass through such that the water vapor is condensed as potable water on the backside of the membrane. The specific thermal energy demand is 90 to $250\ \mathrm{kWh/m^3}$ of water and the specific electrical energy demand is around 0.5 to $1\ \mathrm{kWh/m^3}$. MD can be designed for small-scale water purification systems, which is beneficial for applications in regions with low-population density and infrastructure.[139] A pilot MD installation in Alexandria purifies 64 liters of brackish water per day.[140] Currently, the largest systems produce $5\ \mathrm{m^3}$ per day, and 50 to $100\ \mathrm{m^3}$ per day can be regarded as a realistic perspective. The latter technologies are suitable for rural areas close to the sea with large-scale agricultural production, to be implemented by the government. Sustainable solutions for small-scale farmers are presented by Wydra et al. (this issue).

ED for water desalination depends on electric power and is, therefore, predestined for combination with a PV system. Conventionally, saline or brackish water is subjected to a high-density electric field whereby salt ions are driven through an ion-selective membrane, separated and concentrated. Studies are available on small- and lab-scale plants in Spain[141,142] with a PV field and battery to power pumps, valves, and programmable logic controllers control units and direct supply of the ED by other PV fields without a battery, which is not possible in PV powered RO. ED technology is usually not used for large-scale seawater desalination but mainly for various qualities of brackish water, due to the high price of electrodes and membranes and their relatively short lifetime. For brackish water, an average of 0.4 to $4.0\ \mathrm{kWh/m^3}$ provided by PV is needed,[143] which is lower than that for RO with PV. This system is highly viable, economically.[119]

Comparing the energy requirements of desalination, the lowest values were identified for FO (3 to $8\ \mathrm{kWh/m^3}$), followed by RO (4 to $6\ \mathrm{kWh/m^3}$), MED (15 to $58\ \mathrm{kWh/m^3}$), and MSF (21 to $58\ \mathrm{kWh/m^3}$),[144,145] specifically due to the fact that FO and RO do not require additional energy for heat. However, McGovern and Lienhard[146] and Shaffer et al.[147] considered RO as more energy-efficient for seawater desalination than FO and suggest FO for other purposes.

Most of the technologies discussed above currently are at a model stage and not yet commercialized. Considering that prices of large-scale solar-based plants are already reduced to 1.4 cent/kWh already in some regions, desalination based on solar energy will in the future be economically viable. This view is supported by "the Global Clean Water Desalination Alliance—$H_2O$ minus $CO_2$," launched in Paris as a collaborative global climate initiative, one of the few climate initiatives dealing with the water–energy nexus and climate change. The Alliance's action plan could see a decrease in emissions from 50 MT $CO_2$ up to as much as 270 MT $CO_2$ per year by 2040, and the Global Clean Water Desalination Alliance predicts 80% energy for desalination plants deriving from renewable sources by 2036.[148]

In addition to desalination, solar PV has applications for other forms of water treatment as well. One model for drinking water disinfection through chlorination consists of a PV powered, autonomous apparatus including a water pump, in which the application of a DC current in an electrolytic cell mediates the conversion of naturally dissolved chloride to chlorine gas.[149] This process is incorporated into a complete treatment system comprising pumping, filtration, disinfection, and water quality monitoring. The apparatus removes iron and was recently optimized for arsenic removal,[150] as shown in the setup in Fig. 7. Energy is provided by a 24-VDC solar PV —battery system with about 600 Wp and 60 Ah. The system has been installed in oasis villages across Egypt's western desert, as shown in Fig. 8.[151]

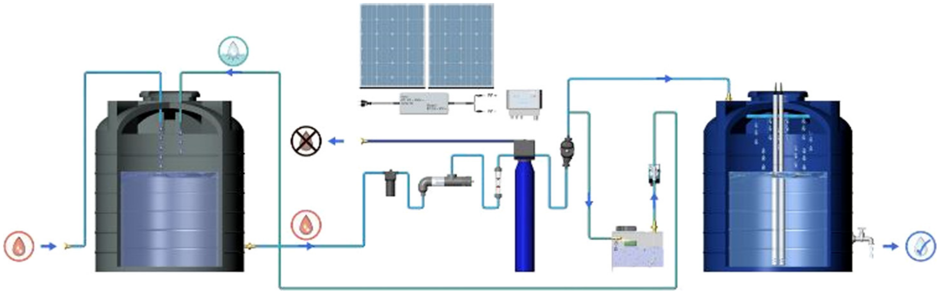

**Fig. 7** Schematic overview of the water purification system using anodic oxidation, developed for rural areas by German startup AUTARCON (source: Ref. 149).

**Fig. 8** Water purification system working on solar energy and using anodic oxidation for drinking water purification installed in Egypt's Western Desert (picture source: Kohler for AUC, 2018; authors, 2016).

## 6 Conclusion

This review has explored the applications of solar PV for electricity generation, water pumping, and drinking water supply in order to reach the United Nations Sustainable Development Goals. Through the example of Egypt, we highlighted the benefits of PVs for sustainable development in rural arid areas and outlined the connectedness of electricity and water, concluding that solar PV has a great potential to fulfill these purposes in rural areas of Egypt and worldwide. However, it is not sufficient to only review the current technical solutions but also to consider the challenges confronted with when implementing them on the ground, as well as the wider implications of the technologies for improving livelihoods and contributing to the achievement of the SDGs. Thus we also have widened the scope on the sociopolitical, geographical, and economic, as well as ecologic context within which this complex question is embedded. Today, PV panel technology is mainly driven by developments in the world market due to economies of scale governing the module price. However, we discussed that in the future, emerging PV technologies such as light weight, low-cost perovskite PV may become important for niche applications in remote areas. Moreover, a combination of PV and agriculture as in the concept of agrivoltaics can contribute to efficient combination of electricity generation and water use in agriculture.

Current technologies for PV powered water pumping and purification have been discussed. We argue that the major obstacles for a wider implementation of PV in rural areas are not only related to technical issues regarding the PV device or electricity storage solutions or to viable financing models, but are connected to broader economic and governance challenges, specifically the collaboration between the water, energy, and agriculture sectors on all levels to identify synergies and avoid trade-offs while pursuing the fulfillment of the SDGs. Although there has certainly been progress in implementing the SDGs, there is still a long way to go in achieving universal sustainable fulfilment of basic human needs for electricity and clean water. Thus we hope this work will contribute to widening the perspective of researchers to encourage the development of future solutions for combined electrical and water supply in remote areas.

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