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Research Article

Investigating energy policies to boost grid-connected rooftop solar PV in Sudan

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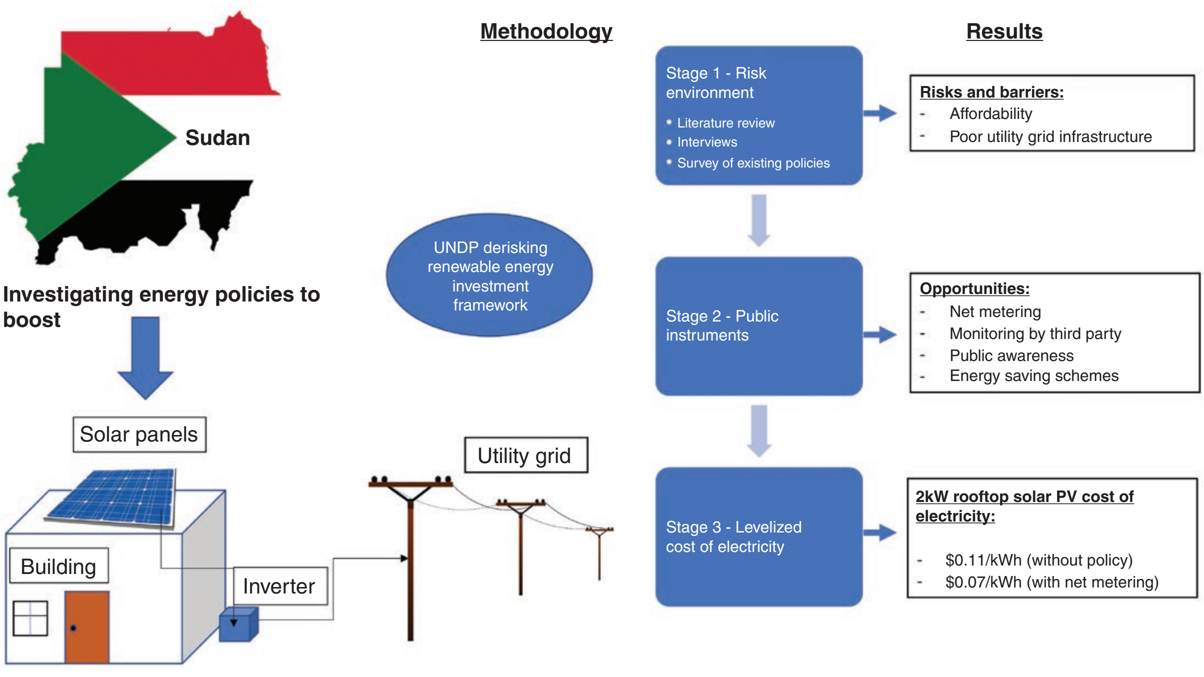
Abstract

Grid-connected rooftop solar photovoltaic (PV) systems can reduce the energy demand from the grid and significantly increase the power available to it. However, rooftop solar PV has not yet been widely adopted in many sub-Saharan African countries, such as Sudan, although they are endowed with high solar radiation and in dire need of additional power. This paper investigates risks and policies to increase grid-connected rooftop solar PV adoption in Sudan. A simplified United Nations Development Program Derisking Renewable Energy Investment framework is adopted to investigate this over three stages. For Stage 1, a list of risks and barriers was produced based on a literature review of solar PV studies in Sudan and interviews with nine stakeholders. Affordability was the risk most often mentioned (eight times from nine interviewees), followed by concerns about poor utility grid infrastructure. For Stage 2, policy de-risking instruments and financial de-risking instruments were listed to overcome the barriers. These include the introduction of net metering, the use of a third-party organization to monitor policy implementation, upgrade of the grid infrastructure, public awareness campaigns and energy-saving schemes. For Stage 3, the levelized cost of electricity was estimated for a typical 2-kW rooftop PV system without policies (0.11 $/kWh) and with a net-metering policy (0.07 $/kWh).

Graphical Abstract



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Introduction

Solar photovoltaic (PV) systems remain largely underutilized in Africa compared with other world regions [1]. However, many African countries, such as Sudan, are now obliged to increase their renewable-energy capacity to comply with the United Nations Framework Convention on Climate Change and Nationally Determined Contributions (NDC). Sudan's NDC target is to install 796 MW of stand-alone and mini-grid low-emission power generation by 2030, covering residential, agricultural and industrial areas [2]. One way to contribute to this is to increase the presence of rooftop solar PV. The benefit for cash-strapped governments is that capital investment would be mostly covered by the building owner or solar PV developer. Another benefit is that more rooftop solar PV would mean reduced electricity demand from the grid. Also, when the solar panels are connected to the grid, then the energy produced by the panels can be sent to the grid to meet demand elsewhere. This could help reduce load shedding and power cuts, which is still a big issue in Sudan [3]. Another major advantage of promoting rooftop solar PV will be the reduced dependence on fossil fuel generators (such as diesel generators), which means less greenhouse gas emissions and noise pollution.

However, the high initial cost of rooftop solar PV systems relative to fossil fuel generators is a major barrier to adoption. This high cost would likely price out most people in sub-Saharan Africa and Sudan. As a result, some African countries have introduced financial incentives through energy policies, which include feed-in tariffs, net-metering schemes, zero tax on solar PV products and rebates [4].

Sudan has one of the highest solar radiation potentials in the world [5]. However, <1% of electricity in Sudan comes from solar PV [6]. The government has considered various energy policies, including net metering and feed-in tariff [7]; however, these are only in writing and have not yet been implemented.

Several research papers have examined the potential of solar PV in Sudan [8–14] and especially on rooftops [15–17]. These studies highlighted the excellent solar PV energy potential the country has due to its high solar irradiation rates and long hours of sunshine.

The main barriers to the implementation of solar PV in Sudan mentioned in the studies were: the high cost of a solar PV system for the average citizen, the lack of a government financial incentive policy to help homeowners [8, 14] and the need for a grid infrastructure upgrade to allow interconnection of multiple solar PV systems [11]. However, the study by [17] was found to be the only one that specifically focused on the energy policy for rooftop solar PV in Sudan. They found that a feed-in tariff scheme could cut in half the payback time of the solar PV system. To build on this finding, the objectives of this paper will be to investigate risks and barriers associated with rooftop solar PV uptake in Sudan and then propose energy policy instruments to de-risk them.

An energy policy should take into account changes in a nation's environment, socio-economic circumstances and technology development to continue to be effective [18, 19]. The United Nations Development Program (UNDP) developed a four-stage framework for evaluating policies for renewable energy in developing countries. The framework identifies risks and barriers and then analyses various public instruments to help mitigate these risks [20]. This framework is known as the Derisking Renewable Energy Investment (DREI) and has been applied to various developing countries [21]. However, the DREI has not been applied to a sub-Saharan African country before in the literature.

To realize the objectives of this study, the first three stages of a simplified version of the UNDP DREI framework are utilized to do the following:

- Stage 1: Perform a risk assessment to identify barriers to the adoption of rooftop solar PV in Sudan and implementation of energy policies. The risks are identified from the literature and from stakeholder interviews.
- Stage 2: Investigate ways to de-risk these barriers through energy policies and public instruments.
- Stage 3: Levelized cost of electricity (COE)—work out the costs per $ to produce 1 kWh of electricity before and after the policy implementation.

The findings in this paper are not limited only to Sudan but can be of use in other locations too.

1 Literature review of energy policies in Sudan

1.1 Energy policy types

Suitable energy policies are well known to increase the adoption of renewable-energy systems among citizens. This is particularly true for rooftop solar PV systems. Many countries have begun to implement policies such as feed-in tariffs and net metering to act as a financial incentive and allow consumers to sell to the grid any excess energy produced by solar panels [22–24]. For example, a feed-in tariff policy was considered a major reason that Vietnam increased its solar PV uptake from 86 MW at the end of 2018 to 4450 MW by the end of June 2019 [25]. Other countries also had success with policies, although some are more successful than others and this depends on a variety of socio-economic and technical factors [22].

There are various types of energy policies to boost solar rooftop PV uptake. Examples include feed-in tariff, net metering and store on grid as described below:

- Feed-in tariff: Electricity exported from the solar panels to the grid is sold to the utility company at a predetermined rate. The user is compensated for the amount of electricity exported.
- Net metering: If the amount of electricity exported to the grid by solar panels is higher than that consumed from the grid by the building, then this 'net amount' is deducted from the user's utility electricity bill [26, 27].
- Store on grid: Several buildings are connected to a central battery storage system and each building has its own solar panels. Any excess electricity not used by users is then sold to the grid. The cost of the battery system is normally funded by the government or shared between the building owners [28].

An increasing number of African countries have now adopted energy policies to increase rooftop PV uptakes, such as feed-in tariff and net-metering schemes [24]. However, many other countries are still without conducive policies for rooftop solar PV. Perhaps the largest barrier to rooftop solar PV in Africa is cost. The large start-up cost of the solar PV system and the low annual incomes of most of the sub-Saharan African population make it difficult for many to afford these systems [29].

The cost of a solar PV system per kW differs by country and region but, in general, the global weighted average is $1230 per kW [30]. However, the gross domestic product (GDP) per capita in sub-Saharan Africa was estimated to be only $1501, as of the year 2020 [31].

Demand-side management and energy efficiency were found to have a significant impact on the cost of a PV system. In a case study in Bamako, Mali, changing appliances to more energy-efficient types (light bulbs, refrigerator and computer) reduced energy consumption in a household by 76% and solar PV cost by 67% [32].

Although most energy policies focus on reducing the financial burden of purchasing a rooftop solar PV system, they sometimes miss out on other risks. For example, a risk present in Africa and Sudan is the quality of imported solar PV products. Since most solar PV equipment is imported from overseas, the quality is not to the required standard and the product fails soon after use [33]. This reduces people's desire to invest in solar PV and can hinder the uptake that the energy policy was intended to stimulate.

1.2 Energy policy status in Sudan

1.2.1 *Solar PV status*

In Sudan, the Ministry of Energy and Mining is now the body responsible for developing plans and policies related to electricity generation, transmission, distribution and pricing, implementing renewable-energy technologies and improving the efficiency of energy consumption [7].

The electricity usage in Sudan has faced high growing demand: the peak demand reached 3300 MW in 2020 and the energy consumption grew from 6026 GWh in 2010 to 14 766.7 GWh in 2020, showing an average growth of 10% per year. The residential sector consumes the largest share of the total generated electricity, which is estimated to be 64% [34].

Most of the electricity in Sudan comes from hydropower, but this power source is susceptible to drought that can drastically reduce its output [35]. Only 5 MW of solar energy was commissioned by the Ministry of Energy and Mining in Al-Fashir in 2019. Currently, solar PV contributes <1% of the electricity generation in the country, as shown in Fig. 1.

Sudan is endowed with abundant solar resources. Unfortunately, these resources are largely untapped. The country

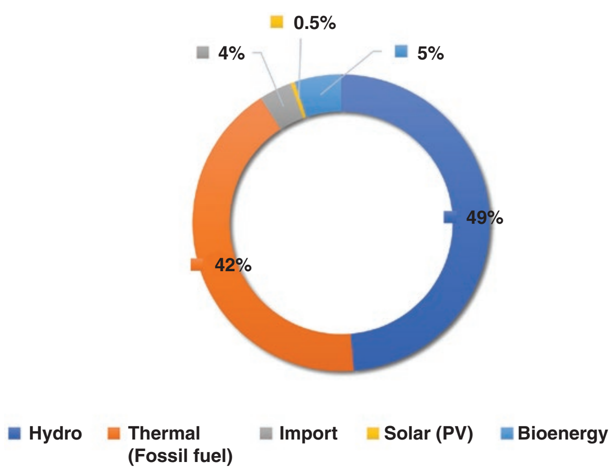

Fig. 1: Energy generation capacity in SudanAdapted from [6].

has an average annual global horizontal irradiation value of between 2000 and 2500 kWh/m^2 [36]. Sudan has been ranked as the second-highest country in Africa for the solar PV potential [5] (Fig. 2).

The Renewable Energy Master Plan (2019–2033), produced by the government, includes an additional generation capacity of 13,454 MW by 2033, including an aggregate solar capacity of 1920 MW [7]. Furthermore, the Government of Sudan aims to increase electricity access through grid-connected rooftop solar PV and set a national target of 9000 units with capacities ranging from 0.7 to 1.5 kW during the period 2020–24 [7].

Several research papers have looked at the potential of solar PV in Sudan [8–14]. Osman and Alsokhiry looked at the potential of combined wind and solar PV systems in the northern state of Sudan. They found both renewable energy sources to be viable, especially with wind more so in the northern areas [38]. Some studies specifically looked at rooftop solar PV potential in Khartoum [15–17]. Both studies confirmed the payback time would be reduced for the system if an energy policy, such as a feed-in tariff, were implemented. All these studies mentioned the excellent solar PV energy potential the country has due to its high solar irradiation rates and long sunshine hours. These papers were selected for their relevance to Sudan and solar PV. In general, the literature review was limited to this.

There is currently a literature gap related to energy policies for solar PV in Sudan. Only one study was found to focus specifically on energy policy in Sudan [17]. They looked at the potential of a feed-in tariff system for a 5-kW rooftop solar PV system in Khartoum. They estimated the payback time for the system to be 18 years with no feed-in tariff. With a feed-in tariff policy, this dropped to 9 years. This showed the significant financial benefit of such a scheme. This study will focus specifically on the energy policy for solar PV in Sudan and identify all the major barriers that prevent rooftop solar PV adoption.

1.2.2 *Energy policy plans*

In 2010, the Government of Sudan established the Renewable Energy Department to introduce renewable-energy policies that are appropriate for the country's context and accelerate the dissemination of renewable-energy technologies with a focus on solar power. Sudan then committed to implementing the 2014–2030 Arab Strategy for Sustainable Energy produced by the League of Arab States [39], which proposes the following policies (among others):

(i) a feed-in tariff for small and medium renewable-energy systems;
(ii) a net-metering system whereby consumers generate electricity via their rooftop solar PV systems and sell their surplus to the national grid; and
(iii) setting standards for connecting renewable-energy plants to the national grid while adopting precise specifications for renewable-energy equipment and systems.

The government has also considered introducing a net-metering programme to encourage and accelerate the installation of rooftop solar and solar home systems (SHS) [7]. An SHS plan was initiated by the government in 2014, which aimed to install 100-W or 200-W solar PV systems in rural off-grid communities. The first phase saw the successful installation of 100 SHS systems. The target is to install up to 1.1 million by 2031 [7].

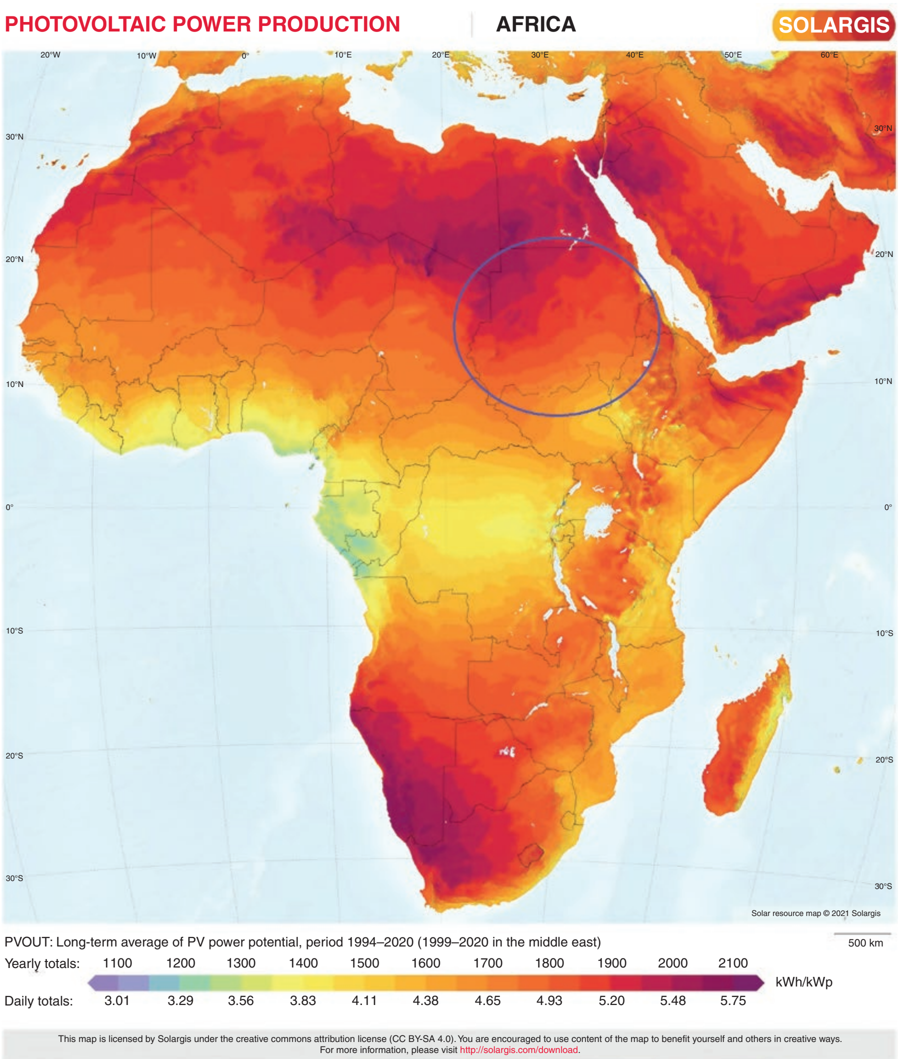

Fig. 2: Solar photovoltaic power potential in Africa with Sudan circled in blue [37]

Demand-side management and energy efficiency programmes can also be effective energy policies to help reduce demand from the grid [18]. The energy efficiency regulation in Sudan is contained as part of a draft law on electricity that is awaiting ratification. The draft law addresses the following aspects of electrical energy efficiency regulatory measures and procedures: (i) the conduct of users of energy efficiency licences; (ii) the introduction of energy efficiency in government institutions and government companies; (iii) the promotion of energy efficiency in buildings; (iv) performance of mandatory energy audits; (v) registration of energy audit services companies; and (vi) procedures for authorizing the use of energy efficiency labels [7]. The Ministry of Energy and Mining has also launched an energy efficiency plan for the period from 2020 to 2035. Some goals include replacing 1.3 million tungsten light bulbs with LED ones. This is estimated to save 87.6 GWh in energy [7].

1.2.3 *Current policies*

Although the Sudanese government has been planning, drafting laws and goal-setting for solar PV energy policy, no feed-in tariff or net-metering policy has yet been implemented. Policies and laws have been drafted to help enable such a roll-out in the future; some of the current ones are:

- Power Purchase Agreement (PPA) law—the renewable-energy PPA legal basis was issued within the 2010 Procurement and Contracting Law. This sets the path for companies or individuals to sell renewable energy to the Ministry of Energy and Mining, although no rates have been set or projects implemented.
- Tax exemptions—according to the Sudan Investment Promotion Law of 2013, all renewable-energy equipment and systems are exempt from customs duties, which apply to various pieces of solar PV equipment imported into the country.
- Cuts in fuel and electricity subsidies—the government has been increasing main grid electricity prices and reducing its electricity subsidy from 95% to 69% [40]. This aims to save money for the government and encourage people to invest in renewable-energy technologies.

Sudan is a signatory to climate change agreements, which allows it to finance its development projects through international funds such as the Green Climate Fund [41]. There are also opportunities to finance energy policies such as net metering or feed-in tariffs through carbon credit revenues based on the amount of greenhouse gas emissions avoided by the system [42].

2 Methodology

The DREI framework method was chosen for this paper because it was not previously observed in literature other than by UNDP itself. The UNDP case studies are limited to a few countries with none in sub-Saharan Africa. Therefore, this paper presents an opportunity to demonstrate and showcase the potential of this framework for Sudan and other similar sub-Saharan African countries.

The original framework contains more complex requirements, but this paper adopts a more simplified version to simplify the assessment. The three stages utilized in this paper are:

- Stage 1—Risk environment

  This stage involves identifying the main barriers and risks to the uptake of rooftop solar PV and energy policy in the country, as well as the underlying causes and impact. These were found in the literature and through interviews with stakeholders.

- Stage 2—Public instruments

  This stage presents the energy policies, in the form of public instruments, to help mitigate the risks identified in Stage 1. They are split into two sections: financial de-risking instruments to help ease the affordability of the solar PV system and policy de-risking instruments to help with the roll-out of the solar PV system and policies.

- Stage 3—Levelized COE

  This involves estimating the COE in $ per kWh before and after the public instruments (policies) are applied. There are two COEs compared: one is the rooftop solar PV COE without policy implementation and the second is the COE value with policy implementation. These are compared to the baseline COE from the grid taken from the literature. Equation (1) was used to calculate the COE for the solar PV system [43]. The breakdown of the COE calculation is found in Appendix 1 (available in the online Supplementary Data). For the COE with policy implementation, the amount of energy exported to the grid by the solar PV system was deducted from the cost of the solar PV system. A rate of 0.015 $/kWh was used as the typical cost of grid electricity in Sudan based on grid utility prices in January 2022 and the report on average usage [6]. The parameters for COE are shown in Table 1.

Equation (1) is used to calculated the COE [43]:

$$\text{COE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where I_t represents the investment cost (in the year t), M_t represents the Operation and maintenance costs (in the year t), r represents the discount rate, F_t represents the fuel cost (in the year t), E_t represents the annual electricity output and n represents the economic life of the system.

Equation (2) provides the potential energy from PV [44]:

$$E_{out} = 365 \quad P.r.\ H \quad (2)$$

where E_{out} represents the energy generated (kWh), P represents the solar power installed (kWp), r represents the system performance ratio (0.9) and H represents the daily PV power potential (5 kWh/kWp for Khartoum [36]).

Research was conducted in the existing literature and through interviews with key stakeholders to help compile the Stage 1 and Stage 2 data. The data were used to identify the risks and public instruments to be implemented. Nine local stakeholders were interviewed in total, as shown in Table 2, including three different solar PV contractors based in Sudan. Stakeholders were selected to represent the people involved in the various stages of a rooftop solar PV project, from installation to end use. A summary of the methodology used in this paper is shown in Fig. 3.

The first three interviews were conducted in person and in Sudan in January 2020, with open questions. The last six interviews were conducted via a questionnaire sent to the stakeholders through e-mail in early 2022 and 2023. These questions consisted of multiple-choice and open questions. In all interviews, a question was asked about the barriers to the adoption of grid-connected rooftop solar PV and opportunities in Sudan. Transcripts of the interviews can be seen in Appendix 3 of the online Supplementary Data, and the interviewee names have been kept anonymous to maintain confidentiality.

3 Results and discussion

3.1 Stage 1—Risk environment

Following a review of the literature and stakeholder interviews, the main risks and barriers were compiled and are shown in Table 3. From the literature, the barriers to rooftop PV deployment in Sudan mentioned most often were the high capital cost of the solar PV system, the lack of public awareness and poor grid infrastructure. These were mentioned in various studies and are summarized in Fig. 4 and Table 3.

Table 1: COE equation parameters explanation

Parameter	Description	Reference
I_t—investment cost (in the year t)	$2993	Quote in Appendix 2. The costs are derived from the average costs of a solar PV contractor based in Sudan (light energy ltd). See Appendix 1 for a breakdown
M_t—Operation and maintenance costs (in the year t)	$60	A value of $30 per kW is assigned based on research by [43]. Operation and maintenance are expected to be minimal due to no moving parts in the system
r—discount rate	10%	Average value [43]
F_t—fuel cost (in the year t)	$0	No fuel use
E_t—annual electricity output	3523 kWh	Expected value from a 2-kW system in Khartoum. This was calculated using Equation (2)
n—economic life of the system	20	The expected average life of a solar PV system

Appendix 1 and Appendix 2 can be found in the online Supplementary Data.

Table 2: Stakeholders interviewed and their main responsibilities

Stakeholder interviewed	Main responsibilities
Government: - Interviewee A—senior electrical engineer, Sudanese Electricity Holding Company (SEHC), Ministry of Energy and Mining - Interviewee B—Director Renewable Energy, Ministry of Energy and Mining - Interviewee C—engineer, Ministry of Energy and Mining	- Setting-up of energy policy for end users - Providing guidance and standards to contractors - Responsible for grid transmission infrastructure
Solar PV contractors: - Interviewee D: project manager (Contractor 1) - Interviewee E: CEO (Contractor 2) - Interviewee F: project manager (Contractor 3)	- Installation of rooftop solar PV systems to end user's building - Maintenance and repairs - Connection of solar PV system to the grid network
End users: - Interviewee G: solar PV owner and researcher - Interviewee H: academic lecturer - Interviewee I: homeowner, non-governmental organization	- Purchase of rooftop solar PV system - Register on the energy policy scheme with the government ministry - Liaise with the contractor to install the system and monitor performance

A summary of the responses of the stakeholders interviewed on the main barriers to rooftop PV in Sudan is shown in Fig. 5. As in the literature, most of the respondents mentioned that the high cost of rooftop PV is the main barrier. Following this, the low cost of grid electricity was the second most often mentioned barrier since it would mean people are less likely to switch to an initially more expensive alternative. The lack of awareness of the benefits of rooftop solar PV from the public was the third most often mentioned barrier.

Regarding the opportunities to increase rooftop solar PV adoption in Sudan, most of the respondents recommended a financial incentive, such as a feed-in tariff or a net-metering policy (Fig. 6). The employee from the Ministry of Electricity and Mining recommended a net-metering scheme in which a discount is applied to the user's grid electricity bill, instead of direct cash, for any energy exported to the grid from the solar PV system. This was due to the lack of funding available to the ministry, making it unlikely for them to fulfil direct payments to end users.

3.2 Stage 2—Public instruments

Following a review of the risks associated with the adoption of rooftop solar PV in Sudan, the public instruments recommended to overcome these are listed below and summarized in Table 4. They have been grouped into two: one is financial de-risking instruments to help with the affordability of the rooftop solar PV system (financial energy policies) and the other is policy de-risking instruments to aid with effective implementation. The risks mitigated by each instrument are numbered according to Table 3.

3.2.1 *Financial de-risking instruments*

- Net metering

Risk mitigated: 1 and 2

Net metering allows excess electricity generated from the solar PV system to be sent to the grid and then deducted from the utility bill. From the interviews, such a system was advised would work better than one in which payments are sent directly to the customer, such as through feed-in tariff schemes. This is because the government has limited funds to make direct payments for electricity to end users.

- Tax incentive

Risk mitigated: 1 and 6

It is recommended that the government maintain the policy in which no tax is applied to imported solar PV products. This is done to ensure that costs are kept low for the systems and to encourage more people to purchase them. Fortunately, Sudan already has this policy in place. However, the policy should be better advertised so that more building users and solar PV contractors are aware of it. Additionally, local manufacturing of solar PV products should be encouraged to reduce the need for imports.

- Grants and international funding

Risk mitigated: 1, 4 and 7

To reduce the high upfront cost of solar PV systems, cash grants can be provided in certain cases. This can be paid directly to the supplier once a purchase is agreed upon with the building owner or refunded to the building owner afterward (rebate). However, the interview with the electricity employees of the ministry indicates that direct cash would be difficult for the ministry to fund due to a lack of capital. Therefore, the government can cooperate with international organizations for funding, such as through carbon-offset projects [42] or the Green Climate Fund.

3.2.2 *Policy de-risking instruments*

- Demand-side management

Risk mitigated: 10

Before connecting houses with rooftop solar PV, building residents or owners should be encouraged and supported to reduce energy demand. For example, replacing fluorescent bulbs with low-energy LED bulbs could create significant energy savings and reduce the overall PV system size and cost. Therefore, it is recommended that a household survey is conducted to identify high-consuming appliances (such as air conditioners and lighting) and encourage users to switch to more efficient versions before installing the rooftop solar PV system.

- Third-party organization for monitoring

Risk mitigated: 6 and 1

An independent (third-party) organization is recommended to be contracted by the government to monitor the implementation of the policy and provide feedback. This was strongly advised by the interviewee from the Ministry of Energy and Mining.

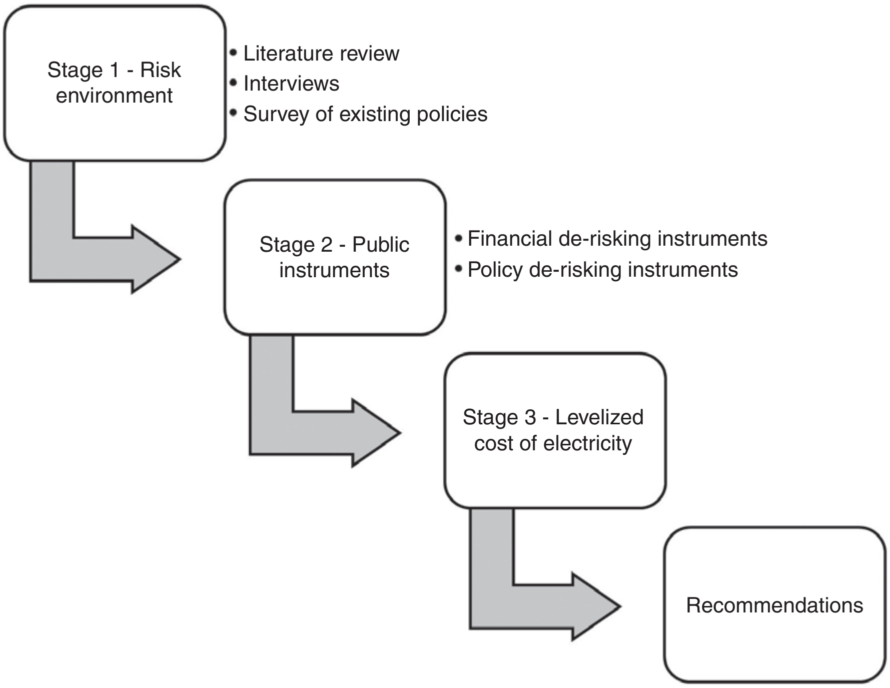

Fig. 3: Summary of methodology.

Furthermore, the literature [14] suggests that a reason for low solar power dissemination (particularly in Dongola, Northern Sudan) was the lack of monitoring and evaluation of previous solar PV projects. Furthermore, the third-party organization can be used to inspect and monitor imported solar PV products to ensure that they meet quality requirements. This is done to help reduce defective products and keep end-user trust.

- Education and awareness
Risk mitigated: 12

To strengthen the understanding of policy for government bodies and end users, workshops and seminars could be held to demonstrate solar PV technology and explain to potential users how the system and policy would work.

- Investment in grid infrastructure
Risk mitigated: 5, 9 and 11

Efforts should be made to study the current grid capacity to understand its ability to accept new solar PV connections. This should then be followed by targeted grid upgrades. This is to ensure that if a large number of solar rooftop PV systems are installed, the grid can handle the extra power loads (as advised by the government ministry employee). Without sufficient grid infrastructure, a new net-metering policy may fail to reach its intended goal. Standards and guidance should also be provided to contractors informing them of the rules to follow when connecting solar PV systems to the grid.

- Insurance policy
Risk mitigated: 3, 4 and 8

The high number of risks in Sudan makes an insurance policy attractive for end users. This can cover events such as political instability, which may disrupt the implementation of the net-metering scheme. It can also protect end users from losses of the solar PV system by theft. Such an insurance policy can be provided by an organization separate from the government so it is not impacted by political instability.

3.3 Stage 3—COE

The levelized COE for rooftop solar PV in Sudan was calculated, with three types considered:

COE 1—Baseline
COE 2—Rooftop PV (with no policy support)
COE 3—Rooftop PV (with net metering)

The system studied is a 2-kW solar PV connected to a building and grid. This is expected to produce an energy output of 3523 kWh per year or 294 kWh per month. Equation (1) was used to estimate the COE value and Equation (2) the expected energy output from the solar PV system. The main electrical power in the building is assumed to come from the grid, with the rooftop solar PV acting as a backup power source in case of grid outages and exporting generated power to the grid.

The COE was estimated to be 0.11 $/kWh (Appendix 1 in the online Supplementary Data). This is much higher than the subsidized grid electricity rate in Khartoum, which ranges from 0.01 to 0.07 $/kWh depending on the consumption levels. However, it is likely cheaper than the unsubsidized rate of electricity, as subsidies only cover ~10–20% of the total transmission and electricity cost in Sudan [6]. With net metering, the COE came to 0.069 $/kWh. This decrease in cost is due to the savings made by exporting the electricity produced by the solar PV system to the grid and this amount is deducted from the utility bill. The COE with net metering is much more aligned with the current

Table 3: Risks for rooftop solar PV adoption and implementation of energy policy in Sudan, as identified from literature review and interviews

Risk title	Description	Reference
1. Affordability	The upfront cost to purchase a solar PV system for a building is high for an average citizen in Sudan **Impact:** This would be a large barrier to adoption, as confirmed in previous studies (Section 1.2) **Causes:** - Most solar PV products are imported, which has increased costs from shipping fees compared with local manufacturing - Low purchasing power of citizens	**Literature:** [6, 8, 12, 13, 45, 46] **Interviews:** Interviewees A, B, D, E, F, G, H and I
2. Low cost of grid electricity	Sudan has the lowest grid electricity rates in sub-Saharan Africa at ~$0.015 per kWh [6], although it is currently increasing **Impact:** It would discourage people from spending money on alternative electricity sources. It also encourages high electricity consumption habits, which would lead to higher requirements for the size of the solar PV system **Causes:** - High government subsidies - Fear of civil upheaval if prices are raised too much - Some citizens may struggle to afford higher electricity costs	**Literature:** [6, 17] **Interviews:** Interviewees A, B, D, G and F
3. Political stability	Sudan recently witnessed much political upheaval. It is still in the process of transitioning to democracy, although there is a risk of sudden changes in government **Impact:** This risk could delay the implementation of the policy leading to ineffectiveness and a possible reduction in rooftop PV adoption. Also, if the policy is adopted and there is a sudden change in government, then there is a risk that the new government will significantly amend or cancel it **Causes:** - Weak rule of law and institutions - Regular civil disturbance	**Literature:** [6] **Interviewee:** Interviewee C
4. Currency inflation risks	Inflation in Sudan is one of the highest in the world [47], although the currency has been more stable towards the end of 2021 **Impact:** More inflation means higher prices for solar PV systems, making the systems even more unaffordable to local citizens than before **Causes:** - Weak national economy and institutions	**Literature:** [6]
5. Grid infrastructure risk	The current grid infrastructure may require further upgrades to allow solar PV to connect to it and to ensure grid reliability is maintained **Impact:** This may reduce the number of rooftop PV systems allowed to connect to the grid. This could delay the implementation of the energy policy **Causes:** - Low level of investment in grid infrastructure over the years	**Literature:** [10, 11, 48] **Interview:** Interviewee D
6. Lack of energy policy implementation	Risk arising from the government's inability to efficiently administer an energy policy design to increase rooftop solar PV adoption **Impact:** Low uptake of rooftop solar PV by homeowners **Causes:** - Not enough resources within the ministry - Lack of staff training/experience in the proper administration of such policies - Too much bureaucracy, corruption or lack of clear processes to follow	**Literature:** [8, 9, 12, 14, 17, 46] **Interviews:** Interviewees A, C, E and F
7. Low government funds	Not enough money to invest sufficiently in new energy policies **Impact:** Delays in the implementation of the policy or poor uptake from weak implementation **Causes:** - Not enough budget allocated to the programme - Low government revenue	**Literature:** [14] **Interviews:** Interviewees A, B and F
8. Risk of Theft	Risk of theft of solar PV systems from homes. **Impact**: Reduced number of installed systems. Increased thefts may cause others to reject installing it. **Causes**: - Poor security measures in place. - Increased poverty causing more people to steal. - Weak rule of law.	**Literature:** [49]
9. Lack of codes and standards	Lack of standards for integrating solar PV into buildings and the grid not defined **Impact**: Potential technical faults when connecting rooftop PV to the grid. Inconsistent connections. Poor quality installations. **Causes:** - No specific national standards to guide installations. - Poor awareness or implementation of standards if they do exist	**Interviews:** Interviewees A, C, E and F

Table 3. Continued

Risk title	Description	Reference
10. High energy consumption	Sudan has high average energy consumption, particularly in urban centres **Impact:** This would lead to a large rooftop solar PV size, which adds to costs **Causes:** - High energy consumption from inefficient equipment or air conditioning - Low grid prices encourage high energy consumption	**Literature:** [6]
11. Grid-connected inverter	All grid-connected solar PV systems will require a grid inverter. The cost of this item needs to be covered by someone, either the homeowner, the government or installation contractor **Impact:** This device will increase the overall cost of the system. If added to the homeowner's scope, it could discourage them from ever getting a rooftop PV system **Causes:** - Lack of clear guidance on who is responsible for the grid-connected inverter	**Interview:** Interviewee B
12. Low public awareness	Poor marketing and advertising of the rooftop solar PV system and its policy **Impact:** Low uptake of solar PV panels and poor policy implementation **Causes:** - Lack of strong marketing and education campaigns	**Literature:** [8, 12, 14] **Interviews:** Interviewees C, D, H and I
13. Quality of solar PV products	Some solar PV products imported from abroad may be of poor quality and do not perform as required **Impact:** The solar PV system may not work as intended and it can cause bad publicity for the system **Causes:** - Lack of quality checks on imported solar PV products - Difficulty in exercising warranty due to manufacturer being overseas	**Literature:** [50]

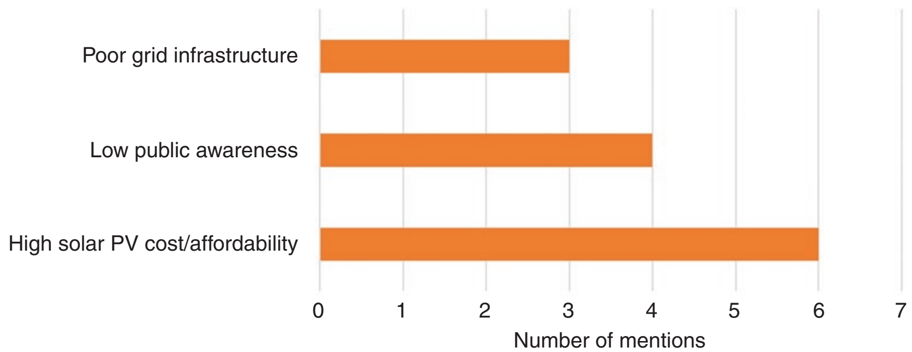

Fig. 4: Literature review: main barriers to uptake of rooftop solar PV in Sudan.

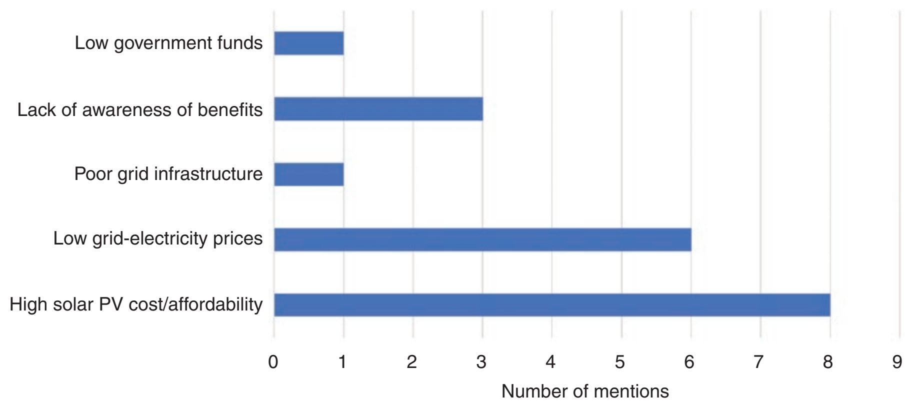

Fig. 5: Stakeholder interviews responses: main barriers to uptake of grid-connected rooftop solar PV in Sudan.

grid rates and therefore makes the system more affordable in the long run. The added benefit of this system is that during grid power outages, the building can still benefit from backup power from solar PV, as batteries are considered in the system cost. All three COEs are summarized in Table 5.

4 Conclusion and policy implications

In this study, methods to increase rooftop solar PV adoption in Sudan were investigated based on the first three stages of a simplified UNDP framework for DREI. First, risks and barriers

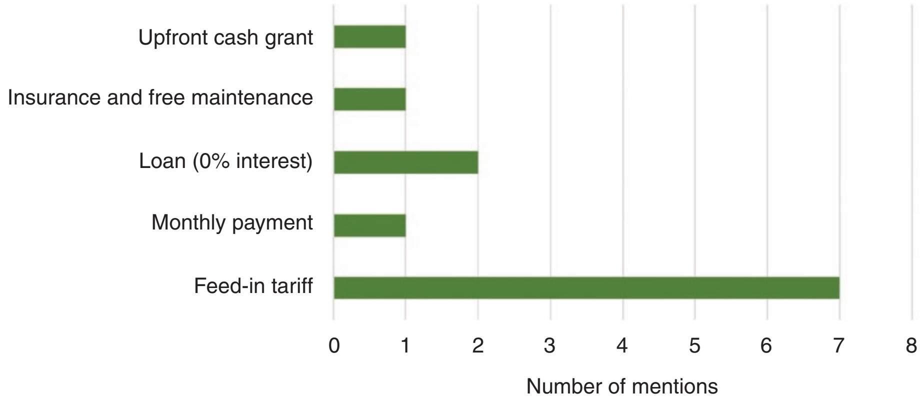

Fig. 6: Stakeholders interview responses: opportunities to increase rooftop solar PV uptake in Sudan.

Table 4: De-risking instruments for rooftop solar PV in Sudan

Risk	Policy de-risking instrument	Financial de-risking instrument
1. Affordability	–	Net metering, tax incentives, grants and international funding
2. Low cost of grid electricity	–	Net metering
3. Political stability	Insurance policy	–
4. Currency inflation risks	–	Grants and international funding
5. Grid infrastructure risk	Investment in grid infrastructure	–
6. Lack of energy policy implementation	Third-party organization for monitoring	–
7. Low government funds	–	Grants and international funding
8. Risk of theft	–	–
9. Lack of codes and standards	Investment in grid infrastructure	–
10. High energy consumption	Demand-side management	–
11. Grid-connected inverter	Investment in grid infrastructure	–
12. Low public awareness	Education and awareness	–
13. Quality of solar PV products	Third-party organization for monitoring	–

Table 5: Summary of cost of electricity findings

Description	Cost of electricity (COE)
Current cost of electricity (subsidized)—grid	0.01–0.07 \$/kWh (depending on usage)
COE for rooftop solar PV—no policy	0.11 \$/kWh
COE for rooftop solar PV—with net metering	0.069 \$/kWh

were identified (Stage 1), then public instruments to overcome these were suggested (Stage 2) and then the levelized COE (Stage 3) was estimated to compare the \$/kWh before and after the implementation of the policy.

The literature survey highlighted the great potential of grid-connected solar rooftop PV systems in Sudan, almost all mentioning the high levels of solar radiation in the country. Such systems also bring energy security to buildings in case of grid power outages. In addition, the amount of electricity available to the grid is increased from the excess electricity sent to the grid by the rooftop PV systems.

However, the risk analysis identified the main barriers to rooftop PV uptake in Sudan, as highlighted by the nine stakeholders interviewed and the literature. These were: the high cost of the solar PV system/affordability, low grid electricity rates and poor grid infrastructure. Eight out of the nine interviewees mentioned high cost and affordability as major risks to rooftop solar PV adoption in Sudan. Following analysis of these barriers, de-risking public instruments were considered from both a financial and a policy implementation perspective. These public instruments are recommended for the government to form the basis of an energy policy and actions to help increase rooftop solar PV in Sudan. In summary, these are as follows:

(i) Introduce a net-metering scheme so that grid-connected rooftop solar PV users benefit from reduced utility bills.
(ii) Improve the infrastructure of the grid in readiness for the scheme and ensure grid stability when rooftop solar PV connections increase.
(iii) Form a dedicated government department to administer the scheme and allow a third-party agency to monitor the progress and quality of the solar PV systems.
(iv) Establish a demand-side management scheme focused on energy efficiency to help reduce electricity consumption

and promote energy-efficient appliances. This can help reduce the overall size of the solar PV system and initial costs for users.

(v) Start an awareness campaign, through advertisements and educational courses, to increase interest in rooftop solar PV.

Net metering was considered more suitable than giving direct cash grants to end users who install rooftop PV. This was recommended by the government employee with the main reason being the unlikely ability of the ministry to provide direct cash to users due to funding shortages. With net metering, discounts can be deducted from the utility bill at the end of each month depending on how much electricity was exported to the grid from the rooftop PV system.

The levelized COE with net metering was estimated to be 0.069 $/kWh for a 2-kW system installed in Khartoum, Sudan. This was much lower compared with the rate of 0.11 $/kWh without net metering. However, this is still higher than the grid utility prices, which range from 0.01 to 0.07 $/kWh (depending on usage). This suggests that other benefits should be considered to encourage people to switch to rooftop solar PV. One of the interviewees commented that the advantage of having power during grid outages is a key reason for people to switch to rooftop PV.

Sudan is in a fortunate position in that energy policy schemes such as net metering or energy efficiency programmes have already been drafted into law and planned. So, all that remains is implementation. Furthermore, previously drafted and implemented policies such as zero tax on solar PV products need to be better advertised to raise awareness and monitored to ensure that they are being implemented effectively.

Supplementary data

Supplementary data is available at *Clean Energy* online.

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Conflict of interest statement

None declared.

Author contributions

Tarig Z Ahmed (Introduction, Conclusion, Results and Discussion, Editing), Ayah Mohamed (Literature Review), Mawahib Eltayeb Ahmed (Results and Discussion review), Ahmed Osman Elamin Abdalgader (Literature Review), Mohamed G Hassan-Sayed (Conclusion and Writing Review)

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