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Planning power systems in fragile and conflict-affected states

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Novel approaches are necessary to accelerate the provision of reliable electric power in fragile and conflict-affected countries. Existing approaches to planning power system investment tend to ignore conflict-related risk and its serious consequences. Here, we propose a framework for identifying power system investment strategies in fragile and conflict-affected countries, and apply it to South Sudan. Our results show that investment strategies that explicitly consider the challenges posed by potential conflict may improve the reliability of electricity service over the status-quo approach. Our analysis suggests investing in a diverse mix of supply types in the medium term, and building a power system with redundancies or a higher share of local resources in the long term, to reduce vulnerability to conflict and socio-political fragility.

Sub-Saharan Africa (SSA) has been identified as the epicentre of the energy poverty challenge[1], with 588 million people lacking access to electricity as of 2016[2]. Despite recent increases in the pace of electrification, the Sustainable Development Goal for universal energy access by 2030 (SDG7)[3] will not be met without intensified electrification efforts.

A challenge is that half of SSA countries have consistently ranked among the top 50 fragile countries globally in the past decade[4]. Conditions in fragile countries may condemn conventional development plans to failure[5]. Conventional power system planning methods are also susceptible to failure. However, only a slim minority of peer-reviewed quantitative planning studies about SSA consider political factors[6], and almost all widely used energy planning models overlook socio-political aspects, including political instability[7]. Therefore, enhanced planning approaches are needed to identify actionable plans.

A relatively small number of papers have considered political instability in the context of power system planning and operation. For example, Labordena et al.[8] vary the cost of capital for investment in concentrated solar power to reflect different political conditions. Zerriffi et al.[9] illustrate how reliability assessment that considers only normal operating conditions might undervalue system attributes that are useful under conflict, such as lower sensitivity of reliability to variations of repair time. Bazilian and Chattopadhyay[10] discuss how typical values for parameters such as capital cost may be unrealistic in a fragile country, making the resulting recommendations irrelevant. Instead, they introduced fragility into least-cost planning models through higher interest rates, lower available capital, prolonged construction time and damages over the entire planning horizon[10]. Patankar et al.[11] hypothesize that conflict could damage generating assets; they use stochastic programming to evaluate power system plans that hedge against that risk for South Sudan.

However, existing approaches[10,11] have at least two limitations as formal planning frameworks. First, they[10,11] fail to suggest adaptive strategies that acknowledge improvement or deterioration in conditions in the country, and adjust management decisions accordingly. Second, existing approaches[10,11] do not explicitly define a framework or sources to guide collection of data concerning conflict risks and their potential effects on power systems, rendering the approaches impractical for use by planners.

This Article proposes a practical framework that considers conflict-induced uncertainty and its evolution over a multidecadal time horizon, while taking the multiple effects of conflict on power system investment and operation into account. The framework is designed to be readily applied to diverse situations around the globe, relying on qualitative analysis or statistical models to characterize conflict uncertainty and documented quantitative evidence of conflict impacts. We present a case study on South Sudan to provide a concrete example of how different and time-varying conflict conditions influence the performance of alternative investment plans, and to demonstrate the applicability of the framework.

Conflict-aware models for power system planning

The proposed scenario-based modelling framework can be used to address many urgent questions that governments, donors, investors and utilities face. Should development of a centralized grid be an immediate priority for a fragile country? Should investments in large projects be postponed until conflict risk is lower? Which types of resources best serve domestic demand? The proposed framework consists of five analytical steps summarized in Fig. 1: data-driven characterization of power system vulnerability, development of conflict scenarios, scenario-based power system planning, uncertainty characterization and sensitivity analysis.

Under step 1, framework users qualitatively and comprehensively describe the ways in which conflict affects the power system and determine the quantitative impact on planning parameters. Figure 2 depicts the complex network of interactions that our review of past conflicts has revealed[12–18], and should be used as a starting point for step 1. We provide more details on how we quantify conflict impact in the Methods.

The very existence of the complex and multidimensional interactions depicted in Fig. 2 points to the intrinsic difficulty of modelling the effects of conflict. This difficulty arises for at least two reasons. First, limited or non-existent empirical research provides an inadequate basis for quantifying interactions. Second, omitting some interactions in the modelling framework will introduce biases favouring or disadvantaging certain investments. For example, past

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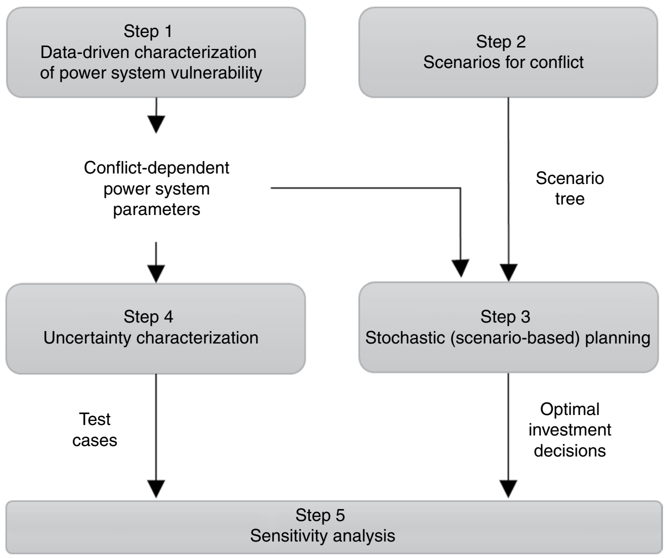

Fig. 1 | Schematic of the proposed scenario-based, conflict-aware planning framework. The framework incorporates five steps: (1) characterization of power system vulnerabilities based on past conflicts and selection of parameters with conflict-/trajectory-dependent values; (2) development of scenarios for evolution of conflict; (3) the scenario-based optimization model employs the scenarios of step 2 and distinguishes parameters across scenarios based on step 1, to identify the optimal plan; (4) development of test cases to describe the uncertainty surrounding the estimation of values for the state-/trajectory-dependent power system parameters; and (5) sensitivity analysis of the optimal plan under the test cases.

research[10] concluded that diesel generators can reduce outages in South Sudan during times of conflict, but this ignores the fact that diesel fuel shortages frequently occur in times of conflict. Similarly, past evidence might suggest that conflict leads to restricted access to capital, suggesting expansion of Fig. 2 to account for access to capital. Thus, planners should customize Fig. 2 to make it comprehensive and representative of local conditions.

In the second step, planners must decide the time horizon of the plan, the states (for example, peace or conflict) the country can be in during a given period, and the approach to define scenarios, which are sequences of states. The desired output of step 2 is a scenario tree, an example of which is shown in Fig. 3a. The time horizon is usually a couple of decades. The states reflect different degrees of political instability or conflict escalation. To develop scenarios and their associated probabilities (if necessary), planners may choose either a qualitative or quantitative approach[19]. Any approach providing the predictive skill of past states for future states is helpful for planning, because planners might examine conflict history to predict future conflict, and adjust their plans accordingly.

In the third step, the framework employs a model that uses the scenario tree of step 2 and scenario-dependent values for the conflict-affected parameters of step 1. The model is formulated as a multistage mathematical program[20] with decision variables for investment and operations (see Fig. 3b). Planners choose a model type (stochastic[20] or robust[21]) and an objective function that reflects investors' attitudes towards risk and considers available data. For example, a stochastic programming model that minimizes the probability-weighted present worth of costs can represent a competitive, risk-neutral investment environment in which investment decisions are conditioned on the country's conflict history and are made knowing only the probabilities of the following states. In contrast, alternative objective functions, such as conditional value at risk[20] or a risk-averse utility function, might be more appropriate in the case of risk-averse investors within a stochastic framework.

For any of these choices, the mathematical program should model the dynamics of the conflict and acknowledge that the planner can adapt investments based on conflict history. The time between planning studies affects how flexible the plan can be in response to changing states. A stochastic model, such as the one applied in the case study, endogenously assesses the conflict risks and suggests the most efficient strategy—in terms of the objective function—to meet the projected demand. Moreover, the temporal, technological and geographical resolution of the model allows planners to assess the relative vulnerability to conflict effects of investments pursued in different years, technologies and locations. In particular, the model evaluates three generic courses of action: (1) planners can wait for some of the conflict uncertainty to be resolved, deferring certain investments; (2) planners can diversify or change the technological/geographical composition of the investment plan; and (3) planners can adjust capacity levels (for example, install redundant capacity as back-ups). In general, a strategy (that is, the set of scenario-dependent investment plans comprising the solution of our model) can include a single action or combinations. Later in this paper, we show how recommended strategies often include instances of all three.

Step 4 requires planners to consider how uncertain the values used for conflict-dependent parameters in step 1 are. In our example, we focus on extreme values for each conflict-affected parameter. The best possible value for each parameter is the value considered in the conflict-naive model (which disregards the possibility of conflict), and the worst possible value is based on past data or experience elsewhere.

Sensitivity analysis (step 5) is needed because crucial information on conflict impacts is missing. The purpose of step 5 is to indicate the importance of each uncertain parameter, informing discussions on actions that might limit the impact of the uncertainty. An example of such an action is to adopt emergency response practices to reduce vulnerability or repair times.

Four effects of conflict on the power system

The model of the case study considers effects of conflict on the power system through four planning parameters. However, the framework allows planners to model more conflict effects and a greater number of levels of intensity of conflict by expanding the set of conflict-affected parameters and conflict states, respectively.

Forced outages increase during times of conflict for multiple reasons. Power system assets, especially transmission lines, are frequent targets of attacks[16,22]. Repair times tend to increase because of labour shortages, site access problems and unavailability of imported spare parts[23]. Inadequate maintenance of equipment during conflict could also lead to higher malfunction rates[12].

Fuel shortages are common in conflict zones[24]. Factors that contribute to fuel shortages include deliberate attacks on fuel supply lines[15,17,25], disruption of imports[24] and transportation infrastructure, and shortages of labour.

Cost changes during conflict for a variety of reasons: currency exchange rates improve or deteriorate[26], unforeseen repair and replacement costs[13], extra security measures[27] and so on. In this case study, we focus on exchange rates for the local currency.

Construction time is frequently prolonged in times of conflict due to problems with importing equipment[18] or recruiting workers, site access, sabotage[14] and temporary suspension of funding[28].

In the Methods, we explain how we chose the values of these parameters. In our example, values for some parameters (exchange rate and forced outage) depend only on the present status of conflict, while others (fuel supply and construction time) also depend on the conflict status in previous years due to time lags.

The intensity and mix of conflict effects determines the recommended strategy because the impact of a conflict effect depends on

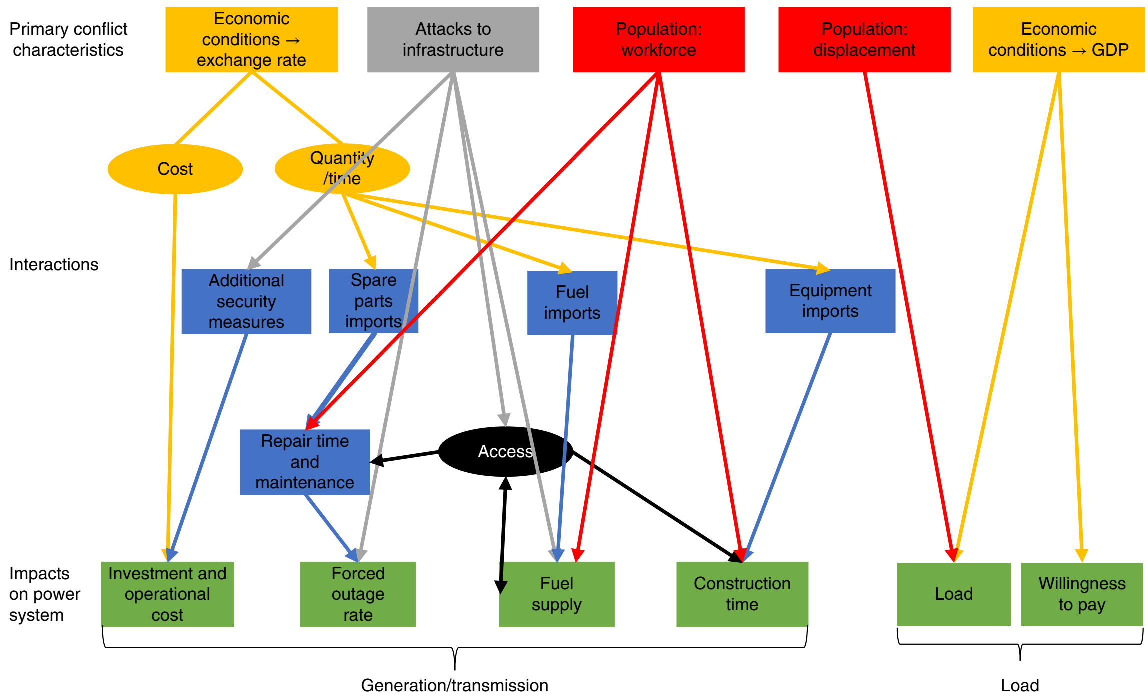

Fig. 2 | Schematic describing the effects of conflict on power systems. We adopt a hierarchical structure to model the impacts of conflict. At the top level, we identify several conflict characteristics, such as the deterioration of economic conditions affecting exchange rates and gross domestic product (GDP) (yellow boxes), population displacement and involvement in war (red boxes), and deliberate attacks on infrastructure (grey box). At the intermediate level, we include conflict-affected power system processes (blue boxes). Ovals describe conflict-affected aspects of processes, such as cost, time to deliver and access to sites. For example, imports of spare parts might be suspended if the exchange rate is high. Therefore, limited availability of spare parts might explain increased repair times. In parallel, other reasons, such as difficulty accessing the damaged asset or limited availability of technicians, might also contribute to prolonged repair times. Processes included in the intermediate level affect values of power system planning parameters at the lower level (green boxes); for example, prolonged repair times along with frequent attacks to the network might justify the use of higher outage rates for transmission lines under conflict.

a resource's attributes (see Table 1). Moreover, the impact of conflict effects can also change depending on other attributes—besides those listed in Table 1—such as location, size or ownership of resources. For example, if lines connected to larger power plants attract more attacks, a second attribute listed under attacks on transmission should be the size of a resource.

Conflict effects and alternative investment plans

The framework can be applied to any country. Here, we present a case study, to offer a concrete example of ways the framework could be applied and illustrate what sort of insights can be derived. We choose South Sudan as our case country for three reasons. First, two years after its independence in 2011, the country fell into a five-year civil conflict. Divisions within the government that caused the civil conflict[29] were at least temporarily resolved in August 2018[30,31]. Second, the country has the third lowest electrification rate in the world (9% in 2016)[32]. Electricity is almost entirely produced by local diesel generators (99% of electricity came from oil sources in 2015[33]). Thus, power grid development in South Sudan is a green-field application, with no existing infrastructure constraining the design of future power systems. Third, the country has considerable hydropower potential along the river Nile[34] and has previously encouraged investment in large-scale hydropower projects that did not materialize (see past preliminary agreements with investors for a 540-MW dam[35] and presentations by government officials[36]). We conjecture that one reason for this failure is the risk of conflict, which was not considered when planning those projects.

We consider the demand for 13 major cities at target levels set in a past study[37]. We assess the economics of possible investment in batteries and three types of power generation: oil, hydropower and photovoltaics (PV). For oil, PV and batteries, the technology characterization is general because it does not specify exactly how those resources are deployed—as centralized grid installations, or distributed among customers or microgrids. The key assumption is that resources can always provide energy to any load located at the same node as the resource, even when the centralized network has been compromised. Meanwhile for hydropower, we consider five specific projects ranging from small- to large-scale plants (see Supplementary Note 5).

Moreover, we do not simulate system operations in detail (for example, with hourly resolution or trade with neighbours) because our primary purpose is to introduce the framework and the insights it can provide. The example of South Sudan is provided as a proof of concept for our approach and is not as detailed and thorough as a comprehensive planning exercise for the country would be. In future applications of the proposed framework, the planning model could be expanded to consider more resources such as solar-home systems, estimate system reliability, simulate systems operations with finer temporal resolutions including operational constraints[38], consider costs of expanding the distribution network and expand the scope to the entire East Africa region.

We identify nine strategies (see Table 2) using the model of step 3 (see Methods). Strategy 1 does not consider conflict effects at all. Strategy 2 considers the effect of increased transmission outages, then 3 adds fuel shortages, 4 adds exchange rate deterioration and 5 adds increases in construction time, at which point all four effects are modelled. Strategies 6 and 7 are part of the sensitivity analysis (step 5) to account for different intensities of conflict effects. Lastly,

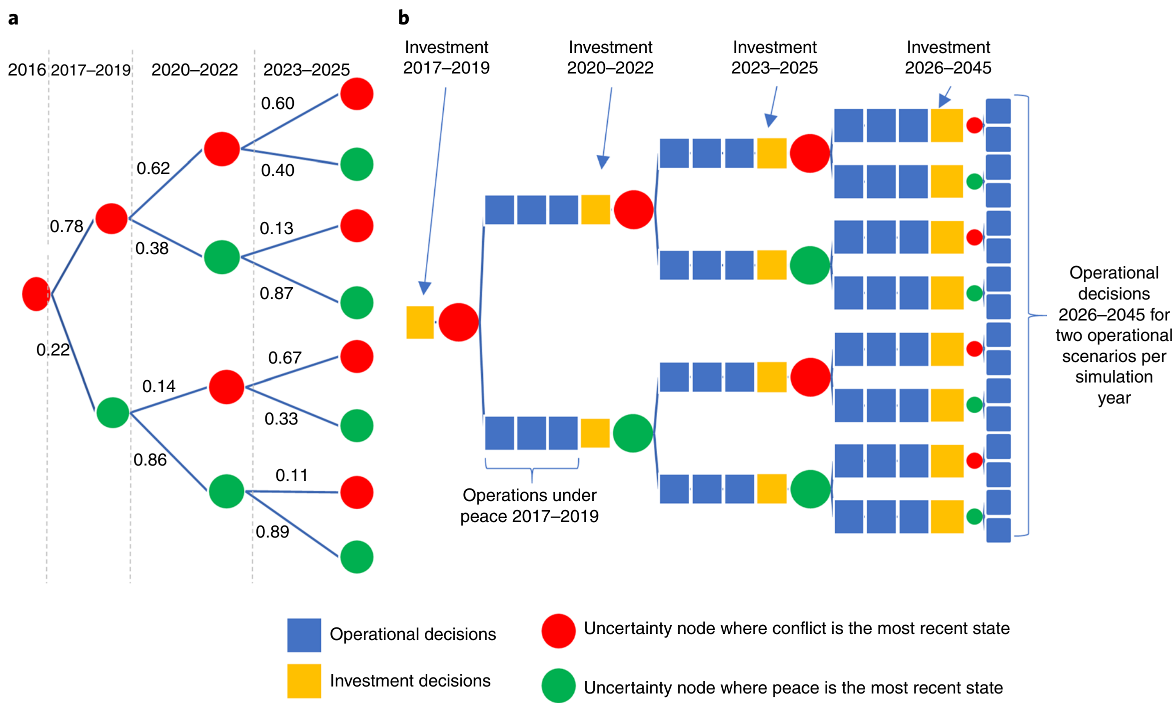

Fig. 3 | Scenario and decision tree considered for the South Sudan case study. Here, we model decisions taking place at 17 different times, of which the first 13 (2017–2029) are consecutive years and the last 4 represent 5 year periods. We group the first nine years into three stages, assuming that the investment plan can be changed only every three years and the state of the country is approximately the same until the next investment decision node. We simulate 2^{11} operational scenarios, allowing for two states (peace or conflict) during the first three stages, years 2026–2029, and the last four half-decades. **a**, We consider 2^3 scenarios of conflict history to 2025. The investment plans are conditioned on the conflict history to 2025. **b**, The planner commits to investments for the next period knowing the conflict states of the preceding periods but being uncertain about the following states. However, operational decisions are made after the state of the conflict is known. We calculated probabilities for the scenarios using the model by Hegre et al.[53] (see Methods).

Table 1 | Attributes that determine how vulnerable resources are to conflict

Resource attribute	Attribute value	Conflict effects							
		Attacks on transmission		Fuel shortages		Exchange rate fluctuations		Construction time	
		Relatively immune	Vulnerable	Relatively immune	Vulnerable	Relatively immune	Vulnerable	Relatively immune	Vulnerable
Type of connection to load	Via distribution or transmission	(Local) PV, oil, batteries	(Remote) hydropower						
Primary energy source	Primary energy source relies or not on a supply chain			Hydropower, PV, batteries	Oil				
Origin of fuel	Domestic or imported					Hydropower, PV, batteries	Oil		
Valuation of loan	Domestic or international (hard) currency						Hydropower, PV, batteries, oil		
Length of construction	Short or long							PV, batteries, oil	Hydropower

Here, we summarize which specific resource attributes are impacted by each category of conflict effects. We qualitatively assign the candidate resources of the case study to two groups: resources that are relatively immune or vulnerable to the conflict effect considered.

strategies 8 and 9 provide insights on how policy targets and financing constraints could alter the results.

Applying a standard least-cost planning model (see Methods) that disregards disruptions due to conflict, we identify a strategy (hereafter, the conflict-naive strategy). In the short term (up to 2024), while hydropower capacity is under construction, the conflict-naive strategy relies mainly on oil (>75% of generation) to meet demand. In the medium term (up to 2035), large-scale hydropower becomes the major source (>80% of generation during 2024–2035). Finally, in the long term (2040–2045), hydropower serves ~70% of

Table 2 | Model assumptions employed in the model of step 3 to identify investment strategies

	Conflict effects				Policy objectives		Financing constraints	
	Forced outages	Fuel shortages	Exchange rate changes	Construction time	Unserved demand allowed throughout the horizon	Unserved demand fixed to zero after a certain year per scenario	With unlimited access to capital	Requiring annual break—even for investors
(1) Conflict-naive strategy					+		+	
(2) Transmission outage-aware strategy	+				+		+	
(3) Outage/shortage-aware strategy	+	+			+		+	
(4) Outage/shortage/exchange rate-aware strategy	+	+	+		+		+	
(5) Conflict-aware strategy	+	+	+	+	+		+	
(6) Maximum-forced outage rate conflict-aware strategy	+	+	+	+	+		+	
(7) Maximum-exchange rate conflict-aware strategy	+	+	+	+	+		+	
(8) Zero-USE strategy	+	+	+	+		+	+	
(9) Conflict-aware strategy with financing constraint	+	+	+	+	+			+

We use a plus symbol to indicate which conflict effects and assumptions are imposed on the model to identify strategies (1)–(9) discussed in the text.

the demand, while PV and oil provide the rest. From a least-cost perspective, the conflict-naive strategy seems reasonable: hydropower is a promising option with satisfactory capacity factors; the other options are less attractive because of high oil prices (due to the absence of local refineries) and incompatibility of night peaking demand with PV generation.

The standard (conflict-naive) model assumes uninterrupted peace, and estimates that the conflict-naive strategy has a levelized cost of electricity (LCOE) of 942 South Sudanese pounds (SSP) per MWh and an unserved energy (USE) rate of 0.14%. However, both LCOE and USE of the resulting conflict-naive strategy deteriorate across all scenarios when the effects of conflict are considered. When all four effects are present, the LCOE of the conflict-naive strategy actually worsens to between SSP1,161 and 2,213 per MWh, depending on the scenario, and USE levels rise to 5% at best and 47% at worst (Table 3). So, by disregarding conflict conditions, the conflict-naive framework underestimates both cost (SSP942 per MWh) and USE (0.14%). As the number of conflict effects considered increases, following the conflict-naive strategy leads to increasingly worse USE rates (Fig. 4). The LCOE also deteriorates because of unforeseen cost increases in fuel prices and loan paybacks.

Table 3 | Performance of the conflict-naive and conflict-aware strategies considering four conflict effects

State			LCOE for strategy 1/ strategy 5 (2014 SSP per MWh)	USE for strategy 1/ strategy 5 (%)
2017–2019	2020–2022	2023–2025		
Conflict	Conflict	Peace	1,504/1,349	27/25
Conflict	Conflict	Conflict	2,213/1,853	47/42
Conflict	Peace	Peace	1,395/1,258	16/14
Conflict	Peace	Conflict	1,981/1,833	31/25
Peace	Conflict	Peace	1,407/1,407	12/10
Peace	Conflict	Conflict	2,015/2,006	27/22
Peace	Peace	Peace	1,161/1,198	5/4
Peace	Peace	Conflict	1,768/1,687	20/12

Performance metrics are provided for each of the eight scenarios constructed under step 2. Calculations were made using the conflict-aware model. The state of the country in any of the first three periods is determined by the scenario; however, both states are simulated in each scenario after 2025. For example, under the peace–peace–peace scenario, the first three periods are peaceful, but during the years 2026–2045, both states are possible. As expected, USE has the best performance when the first three periods are peaceful and the worst when they experience conflict.

Discussion

We study the impact of conflict on the conflict-naive strategy along with alternative strategies suggested by the proposed framework (strategies 2–5). By construction, the alternative strategies perform better in the conflict-aware model than the conflict-naive strategy in expectation (that is, in terms of the probability-weighted objective function), as they consider the interplay of conflict effects on power system investment and operation. We briefly describe each strategy in Table 4, and provide detailed information in Supplementary Notes 7–13.

A key feature of the proposed framework that helps in the interpretation of results is that it simulates the evolution of the conflict, which allows for dynamic adjustment of investment decisions based on conflict history. In particular, the probability of being in one state in a given stage depends on the state in the previous stage, with, for instance, peace following peace being more likely than peace following conflict. Investment commitments are therefore made knowing the past state, but not the following states. Thus, considering the likelihood of conflict, the extent of conflict impacts and customers' willingness to pay (WTP), the model might shift the recommended strategy away from investments vulnerable to conflict effects, especially if conflict has already occurred, which increases the posterior probability of conflict in the future.

In summary, alternative strategies 2–5 differ from the conflict-naive strategy in three ways. First, they invest in a more geographically diverse resource mix, integrating higher share of local resources (PV and oil) in the medium term. The share of PV depends on the combination of conflict effects considered, being highest when only outages and fuel shortages are considered. However, the share of

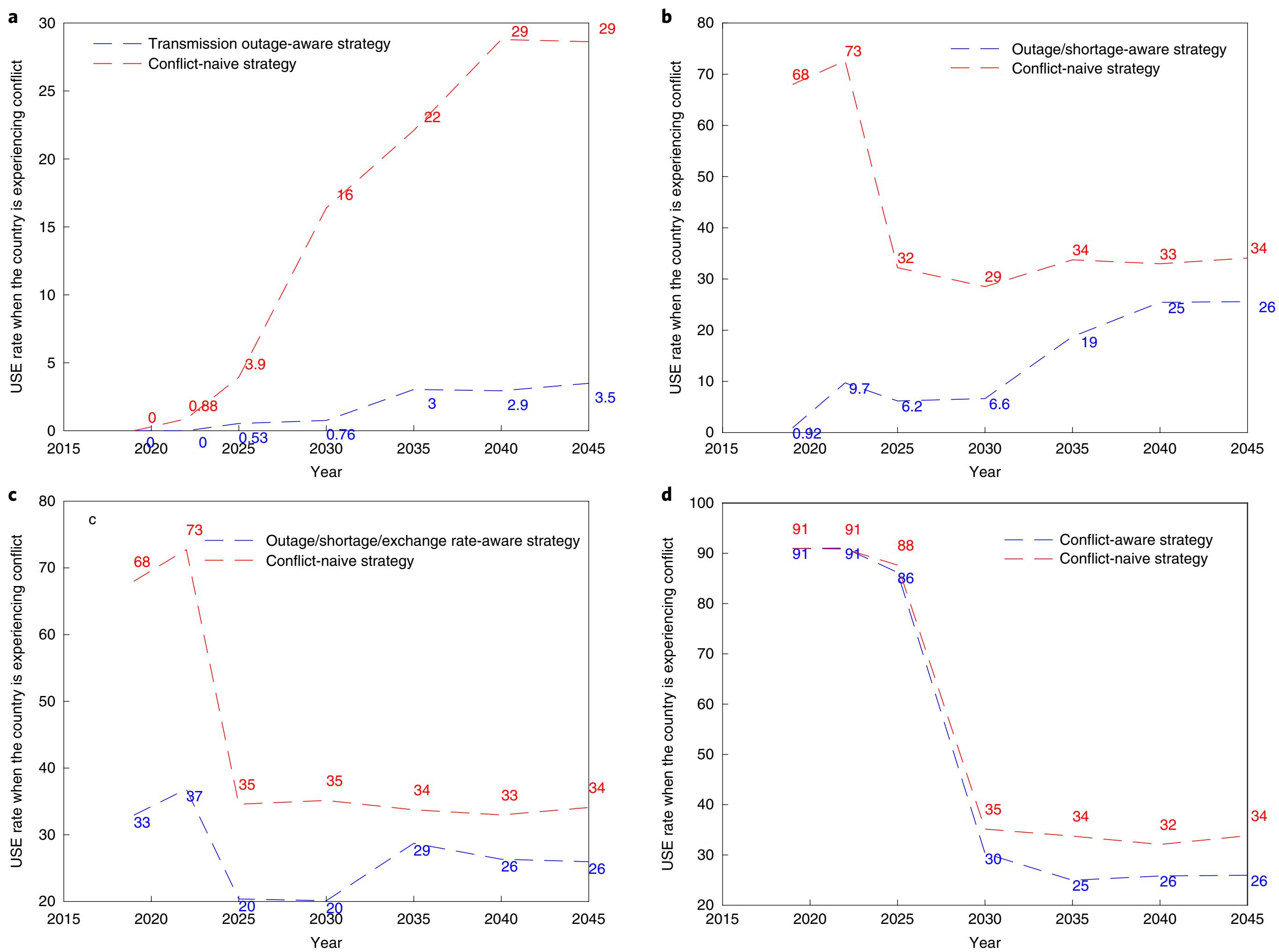

Fig. 4 | USE rate when the status is 'conflict'. a–d, Levels of USE as estimated by the conflict-aware model (see formula for USE rate in the Methods) when one (**a**), two (**b**), three (**c**) and four (**d**) conflict effects are considered simultaneously for two strategies: strategy 1 (the conflict-naive strategy) and the alternative strategy recommended by the proposed framework considering the conflict effects in question. In particular, **a** considers transmission outages (so the alternative strategy is strategy 2), **b** accounts for fuel shortages on top of outages (so the alternative is strategy 3), **c** includes exchange rate deterioration on top of the aforementioned two effects (so the alternative is strategy 4) and **d** considers all four conflict effects discussed in this Article (so the alternative is strategy 5).

oil resources is highest when only outages are considered, and is significantly reduced when fuel shortages are taken into account.

The second difference is that planners sometimes decide to postpone or reprioritize large hydropower investments. For example, strategies 2 and 3 choose a 300-MW hydropower plant as the first hydropower investment over the 1,100-MW hydropower plant recommended by the conflict-naive strategy. Meanwhile, strategy 4 chooses the 300- or 1,100-MW hydropower plant as the first hydropower investment in case the first period experiences conflict or peace, respectively. Anticipating the possibility of delays, strategy 5 chooses to wait until the probability of conflict has approached its long-term value before a decision is made on high financial commitments such as those associated with the largest hydropower plant (1,100 MW). Moreover, in contrast with the conflict-naive strategy, strategies 3–5 choose not to integrate a 522-MW hydropower plant in the long term if the third period experiences conflict.

The third way that alternative strategies differ from the conflict-naive strategy is that they sometimes include investments just as a back-up. For example, strategy 2 includes back-up oil because fuel shortages are not accounted for and the redundant capacity helps the system cope with unavailability of the centralized system.

Despite the improvements in USE during conflict that the conflict-aware strategy achieves compared with the conflict-naive strategy, the rate for strategy 5 for 2030 can still approach ~30% (see Fig. 4). Therefore, we also investigate how the optimum mix would change in case the planner aims to have zero USE as soon as possible (see Supplementary Table 45). In that case (strategy 8), expected costs are 56% higher than under the conflict-aware strategy. This increase in supply costs greatly exceeds the assumed WTP for power. PV and storage are central in the power development strategy in that case, as we have assumed that PV and storage operations are invulnerable to conflict, and that they only experience financial impacts.

We also observe that strategy 5 decreases the amount of USE in later years, but not in the short term (up to 2025). So, if revenues depend on the served energy, they may be inadequate to pay back loans. Therefore, we identified one additional strategy (strategy 9) based on an assumption that annual capital and operational spending is limited to the product of the demand fulfilled and the WTP. In that case, short-term investments in oil significantly drop because its ability to serve the load is affected by fuel shortages. In contrast, short-term installation of PV increases compared with a

Table 4 | Conflict effects on the conflict-naive strategy and key features of alternative conflict-aware strategies

Stresses on the power system assets	How stresses deteriorate the performance of the conflict-naive strategy	How the conflict-aware strategy better manages stresses (changes relative to the conflict-naive strategy, unless otherwise noted)
Conflict-induced transmission outages	During transmission outages, electricity from remote generation (especially hydropower) and excess generation from different nodes does not reach load. Local generators (mostly oil) increase output to the extent possible to accommodate the loss of hydropower.	Strategy 2 Higher short-term installations of local capacity (oil, PV, storage). Adjustment of hydropower capacity: earlier investments are in smaller units; large hydropower plant (1.1 GW) not constructed until 2035. In the long term, oil capacity is at least four times as high as for the conflict-naive strategy. The additional oil capacity, which is redundant under peaceful conditions, allows the system to cope with the transmission outages during conflict.
Conflict-induced transmission outages and fuel shortages	Transmission outages do not allow remote generation to reach load and, at the same time, fuel shortages significantly undermine the generation capability of oil (local resource) during conflict.	Strategy 3 More geographically diverse investment, including more PV and storage. Differentiated investments according to the conflict trajectory realized; for example, in case the first stage is peaceful, there is a short-term shift from PV and storage towards oil capacity compared with scenarios under which conflict occurs in the first period. Adjustment of hydropower capacity: waits until 2035 before including the largest hydropower plant (1.1 GW) in the mix. In scenarios with conflict occurring in the third period, the long-term probability of conflict is relatively high (see Supplementary Table 3), which discourages investments in remote large-scale hydropower, leaving some potential untapped. Under scenarios with untapped hydropower, more PV is integrated, leading to lower USE rates than under the conflict-naive strategy.
Conflict-induced transmission outages, fuel shortages and deteriorating exchange rates	Here, we assume that exchange rates deteriorate under conflict because the local currency depreciated during the most recent conflict in South Sudan[45]. Thus, we increase all cost components in line with the exchange rate, except one: the WTP for electricity. One consequence is that oil generation in all states except Central Equatoria becomes unaffordable during conflict, leaving PV as the sole source of power at times when the transmission grid is not operational.	Strategy 4 Adjustment of the hydropower investment to the trajectory; for example, if the first period is peaceful or violent, a larger or smaller hydropower plant investment is pursued, respectively. In the long term, the capacity mix is similar to the outage/shortage-aware strategy, with some of the hydropower potential remaining untapped in case the third period experiences conflict. The PV and storage capacity of the outage/shortage/exchange rate-aware strategy in 2025 is at least three times as high as under the conflict-naive strategy but lower than the amount installed in strategy 3.
Conflict-induced transmission outages, fuel shortages, deteriorating exchange rates and prolonged construction time	Prolonged construction times during a conflict might delay the commission of new generators, increasing the levels of USE before commission of the new units. If conflict continues through several stages, fulfilment of electricity demand seems impossible given disruption of PV supply chains, suspension of hydropower investment and fuel shortages.	Strategy 5 The full conflict-aware strategy cannot significantly reduce USE in case there are consecutive years of conflict following the first conflict period, but it can lessen the financial burden. Anticipating the possibility of delays, the strategy chooses to wait until the probability of conflict has approached its long-term value before a decision is made on high financial commitments such as those associated with large hydropower development. For example, if the first period is peaceful, construction of 0.3 GW hydropower starts in 2020. In contrast, if the first three periods are violent or the second period is a brief truce period, hydropower does not become part of the energy mix until 2035. While postponing the investment in large-scale hydropower, the plan recommends higher investment in local generation in the horizon.
Conflict-induced extreme transmission outages, fuel shortages, deteriorating exchange rates and prolonged construction time	The network is completely unavailable during times of conflict to represent extreme disruption of centralized system operations. The USE rates significantly increase because the system can only rely on PV and limited oil generation (mainly in Juba) during times of conflict.	Strategy 6 Adjustment of hydropower investments: invest in small hydropower (300 MW) in case the first period is peaceful; otherwise, wait to see if the third period is peaceful. Hydropower potential in not exploited at the levels of the conflict-naive strategy in any of the scenarios considered. PV supported by storage meets a higher share of the electricity demand.
Conflict-induced transmission outages, fuel shortages, extreme deteriorating exchange rates and prolonged construction time	High exchange rates experienced in times of conflict; the payments for loans valued at international currency become unaffordable, exceeding customers' WTP. At the same time, the high exchange rate renders oil unaffordable for electricity generation in the entire country.	Strategy 7 Investment up to 2035 predominantly on oil capacity given its low capital cost (despite risk of oil supply disruption) and decreased PV capacity to avoid risk of high interest rates. Adjustment of hydropower investment to the trajectory of conflict, including ≤1 hydropower plant in the long term. Significant share of the hydropower potential remains untapped. PV investment is significantly lower because of the risk of high loan repayments in times of conflict.

Continued

Table 4 | Conflict effects on the conflict-naive strategy and key features of alternative conflict-aware strategies (Continued)

Stresses on the power system assets	How stresses deteriorate the performance of the conflict-naive strategy	How the conflict-aware strategy better manages stresses (changes relative to the conflict-naive strategy, unless otherwise noted)
Conflict-induced transmission outages, fuel shortages, deteriorating exchange rates and prolonged construction time, along with policy target for zero unserved rate as soon as possible	The earliest year that zero USE can be achieved varies among scenarios: from 2017 to 2027 (see Supplementary Table 45). The conflict-naive strategy experiences USE in times of conflict across scenarios and years because of its reliance on central grid and oil resources.	Strategy 8 Focus of power development shifts to a mix heavily dominated by PV resources, supported by storage. Plans are very similar across scenarios with respect to the timing of construction, but the performance is different because of different timelines for construction across scenarios and exchange rates. Strategy recommends immediate commitment to low oil capacity (2017) and encouragement of large PV investments (2019), to meet the target demand as early as possible.
Conflict-induced transmission outages, fuel shortages, deteriorating exchange rates, prolonged construction time and annual financing limitation	Financing limitations are a practical constraint in most markets, but are omitted by most planning models, which usually assume unlimited access to capital markets. The conflict-aware strategy does not allow utilities to pay back their loans in case conflict resumes immediately after its resolution.	Strategy 9 The conflict-aware strategy with the financing constraint differs from the conflict-aware strategy only in the short term (up to 2025). The short-term mix integrates less oil-fired capacity under scenarios where conflict precedes the investment accounting for the possibility of oil shortages and acute prices that might prevent operation of oil capacity. Instead, investments in PV are made earlier. The precise timing depends on the conflict history.

The first column lists the stresses considered in different simulations. The second column describes how the performance of the conflict-naive strategy is affected by the stresses listed in column 1. The third column highlights key features of the alternative strategies, for which detailed information is provided in Supplementary Notes 7–13.

solution without this financing constraint, and PV delivers energy as expected as soon as it is online, not being disrupted by transmission outages and fuel shortages.

Lastly, each effect that we examine penalizes some technologies more than others, as Table 1 indicates. As a result, the conflict-aware model recommends a strategy that almost completely eliminates the most impacted technology from the short-term mix and suggests a relatively low amount of investment in it in the later stages. Thus, severe shortages penalize oil investments (see strategy 3); long transmission outages restrict hydropower investment (see strategy 6); and acute exchange rates discourage capital-intensive investments such as storage, hydropower and PV (see strategy 7).

Conclusions

To build a power system that better serves the population in a fragile and conflict-affected environment, there are at least three alternatives for power sector investment strategies. First, planners can wait to see how the conflict evolves before investing. Second, planners can pursue a more balanced and diverse portfolio of investments, integrating higher shares of technologies that are less vulnerable to conflict. Third, planners can strengthen the least-cost capacity mix with additional back-up resources.

The trade-off between power outages and cost determines which of the three options to pursue. For example, application of the conflict-aware model to South Sudan considers the capital cost of hydropower and the effects of conflict-induced transmission outages on delivery of its generation, and suggests a wait-and-see strategy for large hydropower investments. It also recommends diversifying generation mix in the medium term, with the optimum extent of geographical and technological diversity varying based on the mix of conflict effects considered and conflict history, which affects the anticipated probability of future conflict. Finally, redundant oil-fired capacity is attractive if fuel supply is unlikely to be severely disrupted by conflict; otherwise, fuel shortages would render redundant capacity useless.

The current outlook for electrification of major cities in South Sudan seems pessimistic since all available electrification options are financially or operationally vulnerable. The plan recommended by our framework has higher net benefits than the conflict-naive strategy because the latter is biased towards certain technologies for which conflict-induced costs and deterioration of performance are high, but disregarded in the conflict-naive model. A centralized, predominantly hydropower system seems to be the most economical option for South Sudan under the assumption of continued peace; however, our results instead suggest postponing large-scale hydropower projects until political conditions have stabilized.

Lastly, it is worth emphasizing that the value of recommendations provided by frameworks such as the one proposed here depends on the credibility of conflict simulations and the quality of input data. Potential advancements in conflict prediction and quantification of power system effects of conflict would improve the usefulness of the results. Collection of reliable data is often a challenge in developing countries, and characterizing societal risks is difficult everywhere. However, investments—and financial analyses of those investments—are necessary to achieve electrification. Despite data difficulties, investors and planners presently evaluate investments using models that ignore context-specific risks, either because such models are unavailable or because planners prefer to avoid assumptions concerning the risks. However, planners already implicitly make such assumptions. When they ignore the risks, they essentially assume a risk-free environment and obtain overly optimistic plans. Our framework corrects this by considering the possibility of conflict, even if precise estimates of conflict risks cannot be justified. In contrast, when planners exclude certain technologies and candidate sites, they implicitly assume, without analysis, that the excluded options are less beneficial to the system than the included options. In this situation, planners can use the framework to explore how alternative risk assumptions affect the net benefits of a wide range of alternatives without a priori excluding any options.

To conclude, the proposed framework can assist power system planners to adopt strategies that will be less vulnerable to the effects of conflict. Still, adoption of a particular planning approach cannot be a panacea. The technical contribution will probably not translate into benefits for service delivery unless many other steps are taken, including actively engaging with local agencies and researchers to improve the quality of data, and continuing to refine the prediction models and estimation of power system vulnerability to conflict. Finally, future research might support several framework extensions. For example, previous studies have investigated the impact of aid[39,40] on conflict risk and discussed the necessity of public services for economic development and state building in a post-conflict environment[41], but the impact of power sector development on conflict risk remains unexamined. Thus, the proposed framework could be expanded to account for the impact of power sector development on conflict risk and thus its potential benefits to peace building.

Methods

Conflict impact on power system investment and operation. A literature review helped us to select the four conflict effects discussed in the main body of the article. However, the literature was less helpful in the quantification of those effects. We explain here the approach that we followed to develop our assumptions on the level of consequences.

First, data from the Energy Infrastructure Attack Database[22] were used to quantify the impact of conflict on the availability of the transmission grid. The Energy Infrastructure Attack Database has particularly good coverage of attacks to the Colombian power system for the years 1995–2011. In the future, if more data become available, assumptions could rely on a broader analysis at a global level or within a set of countries with conflict dynamics similar to the country of interest. Here, we calculate an average outage rate of ~41% for lines that connected more than 1,000 MW of generation to the network over 1998–2002 (when the homicide rate was consistently increasing[42]). Therefore, we adopt a uniform assumption concerning the unavailability of the transmission network. All lines are assumed to be unavailable for half a year when the country is in conflict. Our approach could be interpreted as a rebel group taking over the control room and the warehouse with spare parts for transmission lines for six months, not allowing energy to flow over the transmission system. However, we have to note that the estimated outage rate varied a lot within our sample (see Supplementary Note 1), with some lines being almost completely down during the full five-year period and others experiencing only short outages. Multiple reasons might explain the observed differences, but a model predicting the outage of a transmission line given its attributes (for example, length, region, MW and so on) is out of the scope of this study. We consider alternative values for the outage rate in step 4 and discuss strategy 6.

Second, we developed assumptions on fuel availability in South Sudan based on a recent report by the Sudd Institute[24]. The report provides information on the historical availability of oil in South Sudan and outlines some of the options to increase availability in the future. In particular, the supply of oil for power generation during conflict occurring in the first stage is assumed to be equal to the supply of diesel in December 2015 (2.3 million litres). If the country experiences three years of peace between conflict years, we assume that the depots with total capacity of 100 million litres described in the report will be available and refilled once per year during times of conflict. Under peaceful conditions, we assume four levels for the supply of oil for power generation. When peace is restored in the country, the quantity of level 1 is supplied and then it takes three years of peace to move to a higher level. For level 1, we assume that the Juba storage facility can be refilled once per month and the whole quantity can be used for power generation. On top of that, imports of 40 million litres per month resume. For level 2, in addition to the previous options, depots with a total capacity of 100 million litres are available and refilled once per quarter, increasing the annual quantity available by 400 million litres. At level 3, the production of a refinery at 3,000 barrels d^{-1} (ref. [43]) is added to the supply options of level 2. Lastly, level 4 includes the production of a refinery that provides 50,000 barrels d^{-1} (ref. [43]), along with the supply options of level 3.

In situations of fuel supply shortages, prices are higher than usual. To properly account for the price increase, we would need a supply–demand model for the oil market in South Sudan. However, given the unavailability of such a model, we resort to a simple multiplier (2.0) that we apply every time the country is in conflict. Our assumption seems to be in line with observed prices in Juba[44] (see Supplementary Note 2).

Third, projecting the exchange rate in such an environment is highly challenging. Since the abandonment of the constant rate of SSP2.96/US^{-1} on 15 December 2015[45], the exchange rate has risen to SSP133/US^{-1} in December 2017[44]. Note that we refer to the official/commercial exchange rate, but there is a parallel exchange rate at much higher values. So, for the purposes of this model, we adopt a simple assumption with two distinct levels for the real exchange rate based on the International Monetary Fund's World Economic Outlook projections[46]: SSP13.6/US^{-1} when the country is in conflict and SSP6/US^{-1} when peaceful conditions prevail.

Fourth, we assume that the construction time in South Sudan is identical to the construction time in the United States when the country is experiencing peace. Because this assumption may be optimistic for developing countries[47,48], the initial construction time for hydropower plants is the one we consider when the country is in conflict. The assumed time falls to the United States value post-2020 in case of continued peace. We apply the following logic to predict the construction time under conflict. Units for which construction started in times of conflict under any of the first three stages will generate after double the construction time of peace has passed and consecutive years of peace equal to the construction time during peace have been experienced.

Fifth, in the application presented here, we do not consider certain other conflict effects. For instance, we do not account for damages for power infrastructure. This simplification is not expected to significantly affect the results for two reasons. First, damage on generation assets is minor as long as power plants are well guarded. Second, repair costs for transmission lines might further discourage remote generation, but our application shows that operational disruptions caused by outages will already significantly shift the plan away from remote generation.

Moreover, we do not analyse any effects of conflict on load. Population displacement is frequently observed in a conflict[49]. For example, the second-biggest city in South Sudan (Malakal) has been evacuated multiple times during the past couple of years[50,51]. Existing literature on the return of the forcibly displaced population is scarce and focuses on factors that influence the desire and/or decision to return[52]. Hence, the population distribution post-conflict is highly uncertain. Here, given the focus of the study on urban centres, we assume that reintegration programmes by the United Nations or similar agencies will be successful and the population distribution will be the same as pre-conflict. In addition, we do not consider any link between national gross domestic product and load projections, assuming that the demand projection just covers basic population needs.

Lastly, we do not allow for differentiated status of the conflict among regions within the country. This assumption might seem limiting since it is common for conflicts to be more intense in specific states or areas. In contrast, even when one region of the country is in conflict, there might be power disruptions in other parts of the country.

Scenarios for conflict trajectories. We make three important sets of assumptions in generating the scenarios for our example. First, we use four stages. Each of the first three stages lasts three years and the fourth approximates 24 years. We choose three years as the duration of the first three stages to keep it short enough to benefit from recent history (if a stage is long, its very first years are probably of low predictive value for the status of the next period), but long enough to align with typical power sector planning cycles. That way, for instance, we let the planner choose between investments in the fourth year based on the conflict record of the first three years (stage 1). Then, in the seventh year, the planner can choose a strategy based on the conflict record of the first two stages, and finally in the ninth year, the planner can choose a strategy based on the conflict record of the first three stages. Note that after year 9 we do not allow for further differentiation in strategies because the complexity of the model would not be justified by the limited value the additional options would provide to the immediate plan. However, we simulate the operational impact of conflict and allow differentiation of operational decisions in the fourth stage.

Second, given computational limitations and our limited data on how the extent of conflict effects might differentiate under different severities of conflict, we choose to model just one conflict state.

Third, we choose to use the model developed by Hegre et al.[53] to estimate the probability of each scenario (that is, sequence of states for the first three stages). In general, there are at least two classes of methods the planner could use to predict conflict[19]: qualitative, where regional experts prepare plausible scenarios based on deep understanding of a region and its conflict dynamics; and quantitative[54], where a model quantifies the relationship between structural causes of conflict such as infant mortality and the probability of onset of conflict, transition to conflict and so on. The first class of methods has been traditionally employed by intelligence agencies, but it requires a substantial amount of time and expertise[19]. The second has been a popular topic of recent research[54] as more data become available.

Here, we choose the model by Hegre et al.[53] because it provides the probability of transition from conflict to peace and vice versa, allowing us to generate long-term conflict projections. Its predictive skill, as judged by the Akaike information criterion and Brier score, is acceptable, and it can conveniently produce predictions for any country around the world. Future users of the framework should compare the relative advantages of Hegre et al.'s model with alternatives.

We formulate the chosen model in MATLAB using input data described in Supplementary Note 4. That way, we generate 9,000 sequences of states for South Sudan spanning 2017–2045. Each year, the country can be in any of the following three states: minor conflict, major conflict or peace.

For each sequence, we determine the status of the country during the first three stages. If the country is under minor or major conflict for two or three years belonging to a stage (2017–2019, 2020–2022 or 2023–2025), the status of the relevant stage is conflict. We assign each of the 9,000 sequences to 1 of the 8 scenarios of Table 3 based on the conflict status during the first 3 stages. On assignment of each of the 9,000 sequences to a scenario, we calculate the probability of the scenario as the number of sequences assigned to the scenario divided by the total number of sequences (that is, 9,000). For years belonging to the fourth stage (that is, 2026–2030, 2035, 2040 and 2045), we calculate the probability of conflict for each year under each scenario as follows. First, we count the number of sequences that are assigned to the scenario and have minor/major conflict that year. Last, we divide this number by the total number of sequences that are assigned to the scenario.

Stochastic programming model. The third step of the proposed framework is the power sector modelling component, which replaces the traditional deterministic least-cost planning models. It is an optimization model that minimizes investment and operational cost along with penalties for USE. The problem is formulated as a mixed-integer linear program to account for the lumpy nature of large-scale hydropower projects and transmission lines. We formulate this model in GAMS[55], where we also solve our model using standard mixed-integer programming solvers provided by CPLEX 12.6 (ref. [56]). We present the model formulation in Supplementary Note 2.

Value of lost load (VOLL). We use a VOLL of US\$800 MWh^{-1}, in line with the estimated average WTP by consumers in Juba[57]. Multiple levels of VOLL could be considered to reflect different types of load and the impact that disruption of their provision could have on the community. For example, hospitals have loads with high VOLL, which are usually secured through on-site back-up generators. The model could readily be formulated to recognize this value and capability and curtail such loads only if all other loads are curtailed first.

Representative hours. Modellers can choose from several alternative temporal resolutions for operations within the planning model[58]. Recently proposed methods, such as the one by Tejada-Arango et al.[59], attempt to preserve chronological information to better simulate short-term constraints on operations; however, none of these recent methods is widely used yet. Generally, chronological representations require more variables and thus larger and less wieldy models. Therefore, for this paper, we follow a simple clustering technique to choose a smaller sample of representative hours to keep a reasonable model size. In the future, however, planners could adopt a more sophisticated method and benefit from improved approximations of short-term operations. Here, we use *k*-means clustering to group the 8,760 h into 12 representative hours per year. We cluster them based on transmission line unavailability, load and solar PV output. Clustering splits the 12 representative hours into 2 groups: 6 h when the network is on and 6 h when the network is off in times of conflict. Note that the network is always on when peace prevails in the country. More information can be found in Supplementary Note 3.

Oil price regional factors. Fuel prices vary across the country. We adopt a typical approach[60] that assumes that oil is sold at the international price in the capital but a mark-up applies to other regions. The mark-up is assumed to be equal to the transportation cost from the capital. We estimate it assuming a truck travelling at 40 km h^{-1}, carrying 300 l per trip and consuming 12 l h^{-1}. We slightly adjust some of the mark-ups based on historical data from the country.

LCOE and USE calculations. To compare results from different investment plans, we calculate two metrics: (1) LCOE and (2) USE rate. Their definitions are provided in Supplementary Note 6.

Data availability

The code and data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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E.S. reviewed the literature, conducted the analysis and wrote the main manuscript text. All authors helped plan the analysis and reviewed the manuscript.

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