

# Opportunities stemming from retrofitting low-resource East African dwellings by introducing passive cooling and daylighting measures

Nisrine Kebir<sup>a,\*</sup>, Nicole D. Miranda<sup>a,b</sup>, Laila Sedki<sup>c,d</sup>, Stephanie Hirmer<sup>a</sup>, Malcolm McCulloch<sup>a,b</sup>

<sup>a</sup> Energy and Power Group, University of Oxford, UK

<sup>b</sup> Future of Cooling Programme, Oxford Martin School, University of Oxford, UK

<sup>c</sup> Department of Electrical Engineering, Mohammadia School of Engineers, Mohammed V University in Rabat, Morocco

<sup>d</sup> M-Engineering Solardo, Morocco

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## ABSTRACT

This paper models the retrofitting of traditional rural dwellings in Uganda by introducing passive cooling and daylighting measures. With climate change, outdoor temperatures in parts of the Global South will become unbearable. Communities will be forced to spend more time indoors and thus require further cooling and daytime lighting for thermal and visual comfort. Passive measures can address this while also attenuating energy consumption and diversifying energy use. For the first time, these measures are combined and modelled for those purposes in a rural developing country context where there is limited access to electricity. Using SketchUp and EnergyPlus™, we simulate 15 scenarios of passive cooling and daylighting measures for two baseline scenarios: electrified mud hut and semi-permanent dwelling. Those are also feasible scenarios for similar greenfield unelectrified architectures. The results from the simulated scenarios on electrified dwellings include energy savings, and from these, payback periods are calculated. Two cost-effective scenarios are identified. For mud huts, combining shading (through vegetation) with a centralised fibre optic solar concentrator enables an annual reduction of 31 % of energy consumption. For semi-permanent dwellings, painting rooftops white combined with the integration of solar water light bulbs reduces energy consumption by 47 %. In terms of payback periods for the selected scenarios, the former is four years and nine months, while the latter is two months.

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## Introduction

This paper investigates the effectiveness of implementing passive cooling and daylighting measures in rural East African dwellings as means to ease the burden of electrification costs, improve overall energy efficiency of electrified households, and enhance indoor comfort. These measures align with the goals set out under Sustainable Development Goal 7 (SDG7). Such measures can help mitigate stresses on energy consumption, as the International Energy Agency (IEA) expects an unprecedented uptake of cooling devices in the continent – approaching 1.2 bn by 2040 compared with 0.6 bn registered in 2018 (IEA, 2019; International Energy Agency, 2018a). This is a result of population growth, temperature rise, and an increase in electrification access rates.

While the average temperature in Uganda varies throughout the year – ranging from 24 °C to 30 °C (Nsubuga et al., 2014) – in the summer months, temperatures can reach 36.1 °C in the north of the country (e.g., Kitgum) (Majaliwa et al., 2015). Besides, it has been predicted that

Uganda's temperatures will increase by 1.5 °C in the next 20 years and up to 4.3 °C by 2080 (Hashemi, 2017). To reduce discomfort from heat, traditional dwellings in rural areas in Uganda are commonly designed to maintain a cool indoor environment. However, it is unknown whether these tropical constructions (and the people living in them) are resilient to future escalating temperatures. Temperature rise may increase the time families are forced to spend indoors to avoid severe heat and sun exposure. This will subsequently increase their need for daytime lighting, as these dwellings are dark inside (Edwards & Torcellini, 2002; Sharp et al., 2014). For households that have access to electricity, they may prioritise the use of fans for cooling, and bulbs for lighting, over other essential appliances. This, in turn, may further increase energy demand and subsequent bills. As a result, there is an urgent need to explore ways to build climate resilience in rural Ugandan communities while keeping energy costs affordable (Andersson & Johansson, 2013).

In light of this, in this paper we examine retrofitting options for traditional North-Ugandan dwellings. The aim is not only to reduce the energy bill for electrified premises, but also improve living conditions by enhancing thermal and visual indoor comfort through passive solutions.

\* Corresponding author.

E-mail address: [nisrine.kebir@eng.ox.ac.uk](mailto:nisrine.kebir@eng.ox.ac.uk) (N. Kebir).

In the next section, further benefits from implementing passive cooling and daylighting measures on the dwellings and their occupants are discussed. A brief introductory state-of-the-art of those measures is also added to highlight the different technologies available and those that are more appropriate for low- and middle-income countries (LMICs), which naturally differ from those commonly found in high-income countries.

### *The benefits of passive cooling and lighting*

Passive measures for cooling and lighting can greatly improve rural life. This is important to minimise the migration from rural to urban areas in search of a better livelihood (Andersson & Johansson, 2013; Edwards & Torcellini, 2002; Sharp et al., 2014; United Nations & S. A. World Urbanization Prospects, 2018). Improved vision and heat comfort from better indoor daylighting and cooling can offer a more appropriate living environment (e.g., for educational and indoor working purposes) (Edwards & Torcellini, 2002), enhance occupants' productivity (e.g., from improved mood to lowering fatigue) (Edwards & Torcellini, 2002), and alleviate common subclinical problems in the population (e.g., oversleeping, overeating, energy loss) (Edwards & Torcellini, 2002).

For cooling, passive technologies offer the provision of thermal comfort as an alternative to wide-spread and energy-intensive air conditioners, which are already responsible for peak demand during hot days in large cities (Ortiz et al., 2018). In addition, the avoidance of air conditioners – which are predicted to triple by 2050 worldwide (International Energy Agency, 2018b) – can mitigate the use of high global warming potential refrigerants (e.g., f-gases such as hydrofluorocarbon and chlorofluorocarbon). Passive cooling technologies also produce less noise and have a longer life-span than their active counterparts, as they do not hold electro-mechanical parts. They are classified into three high-level groups (Bhamare et al., 2019): (i) technologies that protect buildings from thermal heat gains (i.e., solar radiation); (ii) those that use materials for time-attenuation of heat gains; and (iii) those that dissipate heat to water, air, the sky, and/or the ground. Previous work (Daioglou et al., 2012; Hashemi, 2016a, 2019; Kolokotroni et al., 2018; Opoku et al., 2020) has examined the use of these techniques in an East African rural context. For example, Hashemi (2016a, 2019) reported the effects of different materials for insulation, window and door sizes, shading, and white-painted roofs on indoor temperature, finding that measures applied to roofs (insulation and painting) were the most effective. Kolokotroni et al. (2018) also examined cool roofs in this context. However, the literature has thus far mainly looked at the effects of passive cooling measures on indoor temperatures and not on potential energy consumption. Further, it lacks a clear rationale for the selection and rejection of passive cooling measures applicable in these low-income dwellings. In this paper we hope to address this research gap.

In terms of lighting, daylighting measures can increase indoor visual comfort in a sustainable and cost-effective manner. The implementation of solar daylighting solutions can result in noteworthy energy savings (Sharp et al., 2014), safer indoor environments (Sanchez et al., 2013a) (i.e., replacing fuel-based harmful lighting sources (Bensch et al., 2017; Mills, 2016)), improvements to human health (Edwards & Torcellini, 2002), and improved wellbeing (e.g., enhanced morale and reduced eyestrain (Edwards & Torcellini, 2002)). Additionally, the majority of people prefer sunlit spaces because daylight consists of a balanced color spectrum (Edwards & Torcellini, 2002). Passive daylighting systems can be categorised into four groups (Kischkoweit-Lopin, 2002): (i) shading technologies that block direct sun and admit diffused light; (ii) light guiding systems that redirect the light from outside into the depth of the room; (iii) scattering systems used to realise an even lighting distribution; and (iv) light transport technologies that channel the light from outside by collating it and guiding it through a light guiding medium. However, most of these technologies are very

sophisticated and unaffordable to most rural villagers in LMICs, as their initial cost can range from US\$6500 (Mayhoub, 2014) to more than US\$230,000 (Mayhoub, 2014). To put this into context, the average monthly income of rural dwellers in Uganda does not exceed US\$36 (UBOS, n.d.). Thus, this renders the use of those technologies unsuitable. Previous work (Bensch et al., 2017; Kweka et al., 2011; Sanchez et al., 2013b) has examined the lighting transition in rural Africa but did not look at the integration of passive daylighting measures. For example, Gunther et al. (Bensch et al., 2017) assessed the transition from kerosene to LED lamps, Sanchez et al. (2013b) examined the lighting habits in Uganda, and Kweka et al. (2011) studied the feasibility of solar lighting bulbs in those rural communities. Yet, there is a gap in the literature regarding the assessment of suitable applicable passive daylighting systems to the rural vulnerable community context in East Africa. Likewise, the design and integration of those systems into traditional housing (e.g., mud huts) in those regions is missed, as well as their impact on the energy performance.

To select appropriate passive cooling and natural lighting systems for rural North Ugandan villages, this paper provides a structured justification that not only relies on technical performance (e.g., temperature and illumination levels) but also considers economic factors (e.g., affordability and cost) and the local context (e.g., architecture, availability and robustness of materials). The reminder of this paper focuses on rural dwellings potentially benefiting from electrification efforts to elaborate on the various choices (e.g., from low-cost microgrids).

### *The contribution of this study*

This study contributes to the emerging literature on the applications of passive cooling and daylighting measures for energy saving in buildings and will fill some of the gaps in the existing literature. For example, very few authors (Chi et al., 2020; Tsikra & Andreou, 2017) have assessed the impact of combining passive cooling and daylighting on energy saving, and only one study is found (Gago et al., 2015) to have evaluated the impact of passive daylighting on energy consumption relative to cooling. There also has been little focus on rural settings in LMICs, and the aforementioned studies focus on assessing the application of passive measures in high-income settings, a very different context than the African dwellings of this study. Hashemi (2018, 2019) have assessed the impact of passive cooling measures on low-income dwellings in East Africa; however, results focus on thermal impacts without assessing energy efficiency. Regarding the impact of passive daylighting measures on energy savings in low-income African dwellings, this has not been reported previously in the academic literature.

Therefore, this is the first work to assess the energy efficiency of passive cooling and daylighting measures simultaneously in a rural, low-income, East African context. It should be noted that this paper does not focus on the resulting thermal and visual indoor comfort assessment from those implemented measures, but on the energy assessment. To achieve this, a set of passive measures is selected and their impact on a dwelling's energy consumption is evaluated. We then examine the combined impact of passive cooling and daylighting measures. Finally, we provide a meticulous selection of the best scenarios to implement in the studied dwellings, based on energy savings, cost, and ease of deployment.

The rest of the paper is structured as follows: Section 2 presents the study context and the appliances that may be used by households to model the future energy demand patterns of the baseline scenarios. It also describes the methodology to select passive cooling and daylighting techniques and defines the 15 scenarios (each combining one form of passive cooling and one form of passive daylighting). Section 3 presents the tools to build models and scenarios and to evaluate their cost. The results are presented in Section 4 which first covers the energy use of the baseline scenarios (i.e., electrified dwellings without passive measures) and thereafter reports the energy savings of the 15 scenarios

with respect to baseline scenarios. Results also show the best scenario selected for each dwelling in terms of cost and energy savings. Finally, conclusive remarks are given in Section 5.

## Materials and methods

In this section, we first provide the context that underpins this paper. We define the energy use baseline scenario for the mud hut and semi-permanent dwellings. This is important as we do not have field data of similar communities connected to a microgrid to set baseline scenarios: we therefore construct a load profile. Based on literature and socio-economic surveys from Hirmer (2017) and Hirmer et al. (2022), we identify appliances likely to be used by the villagers, and we assess the impact on consumption of the community's activity indoors and occupancy patterns. We then provide the selection rationale for passive cooling and daylighting measures.

### Study context

We build on previous fieldwork (surveys) from Hirmer (2017), which studied rural villages in Uganda. Their study consisted of perception-based interviews (referred to as User-Perceived Value (UPV) Game) and socio-economic surveys. This study uses the data collected from the socio-economic survey in the three villages that are located in northern Uganda, located in Moyo and Arua districts. The data from the UPV Game is not considered. 36 dwellers were interviewed in the three villages. For more information on the surveys and the survey questions refer to the data article published by Hirmer et al. (2022).

The villages comprise a mixture of commercial and residential constructions. The authors found that, at the time of the surveys in 2016, 67 % of dwellings were mud hut exemplified in Fig. 1(a), 25 % semi-permanent as shown in Fig. 1(b), and 8 % permanent (see Fig. 1(c)) (Hirmer, 2017; Misinde, 2017). Considering the dominance of mud hut and semi-permanent structures, this paper focuses on these two dwelling types. Below we describe a number of key characteristics of these dwellings:

- **Construction.** Mud huts are characterised by thatched roofs, cylindrical-shaped mud walls, and open eaves (Rek et al., 2018). The walls of semi-permanent dwellings are like those of mud huts, but their roofing is composed of iron sheets, and they are usually rectangular in shape.
- **Homestead size.** The average household has six people. Households own between one and six dwellings (two or more dwellings are known as homestead (Hirmer, 2017)) with an average of three per household.
- **Function.** Each dwelling has a different function, such as bedroom, living room, dining room, and kitchen (Hirmer, 2017). A homestead consisting of mud huts typically comprises two large bedrooms and

one kitchen (Hirmer, 2017). Semi-permanent dwellings consist mostly of bedrooms with no kitchens included. Pit latrines are placed in common areas to be shared amongst multiple families (Hirmer, 2017).

- **Orientation.** The geographical orientation of the dwellings is assumed to be open towards the trading centre.
- **Energy access.** Fuel-based energy sources, in particular for lighting, are currently the norm in many rural and remote areas in Uganda (Hirmer & Guthrie, 2017), with some exception in the form of single PV array powered bulbs (shown in Fig. 2). Given current electrification plans in many SSA countries (including Uganda) to meet Sustainable Development Goal 7 (IEA et al., 2018), we consider a future increase of electrification effort into rural areas to be likely.

While we focus on the most impoverished communities in Northern Uganda (Hashemi, 2017), this work may also be applicable to other countries in Sub-Saharan Africa (SSA) and other contexts (such as peri-urban) where dwellings are characterised by similar construction materials and geometries (Bhikhoo et al., 2017; Tumwine et al., 2003).

### Appliances: energy consumption and schedules

Hirmer and Guthrie (2017) found that communities are likely to be interested in using electricity for lighting, phone charging, and radios. From that work, these are considered the representative loads. While fans are currently uncommon in rural East Africa, they are deemed to be necessary in the future (Kaygusuz, 2011) and a sharp uptake is assumed given increasing temperatures and population growth (IEA, 2019; International Energy Agency, 2018a). They are therefore included in the scenarios. The assumed power rate per appliance and per household is shown in Table S.1, and the daily routines for each household are given in Table S.2. The latter helps to estimate the energy consumption during appliance use. It should be noted that Tables S.1–S.2 provide citations where evidence can be found to support the assumed values.

For the fans in particular, their use is conditioned by the weather and by the occupancy patterns of the household. The use of fans is therefore a function of temperature, rather than a fixed usage based on daily routines. We assume that the temperature levels condition the use as follows (Bhikhoo et al., 2017; Fikru & Gautier, 2015):

$$P_{ef,h} = \begin{cases} P_{ef,max} = 20W \text{ at } T_{amb} \geq 30.8^\circ C \text{ summer, } P_{ef,max} \text{ at } T_{amb} \geq 29^\circ C \text{ winter} \\ P_{ef,off} = 0W \text{ at } T_{amb} \leq 30.8^\circ C \text{ summer, } P_{ef,off} \text{ at } T_{amb} \leq 29^\circ C \text{ winter} \end{cases}$$

where  $P_{ef,h}$  is the power consumed by the electric fan following temperature levels and seasons (in this case summer and winter).  $P_{ef,max}$  is the nominal power of the fan at its maximum speed. If the ambient temperature is lower than the recommended comfort level temperature for summer or winter, the fan will be off ( $P_{ef,off} = 0$ ). The



Fig. 1. Examples of (a) mud hut (Hirmer, 2017), (b) semi-permanent (Misinde, 2017), and (c) permanent housing (Hirmer, 2017) in rural Northern Uganda.





**Fig. 2.** Examples of (a) PV panel on the thatched roof of a mud hut, (b) the LED light bulb powered by the panel in rural Northern Uganda (photographs by authors).

summer refers to the hottest months between December and February (McClellan et al., 2017). The rest of the year is considered winter.

It should be noted that the farming activity is only from May to December (Seymour et al., 2020). Hence, during the rest of the year, the dwellings are occupied more. This incurs further use of lights and also fans, especially in summer. Table S.3 presents the schedule of activities and indicates impact on appliance use (positive/negative).

#### Passive cooling and daylighting measures selection

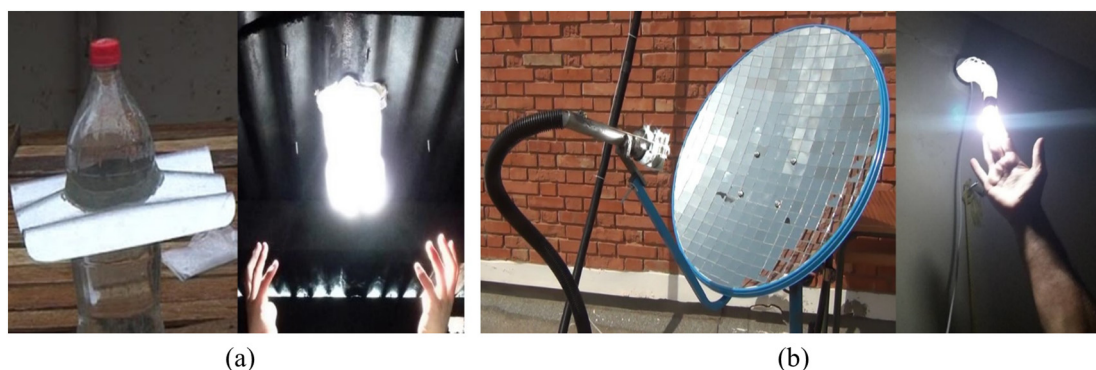
To model retrofitting scenarios, we select a set of passive measures' technologies and solutions. As a basis for the selection, a list of passive cooling and passive daylighting measures was compiled based on a review of the literature. More specifically we drew on the classification of Bhamare et al. (2019) for cooling, and a selection of literature from several authors for lighting (Azizkhani & Haberl, 2021; Kischkoweit-Lopin, 2002; Nair et al., 2014; Sedki & Maaroufi, 2017a). Regarding the selection of cooling solutions and daylighting systems we considered the following three factors: 1) the socio-economic context (affordability (i.e., price), mentality, and potential risks on the population), 2) the technical constraints (accessibility of materials for implementation, performance, and ease of use, repair, reproducibility and deployment), and 3) the constructions' architecture (material fragility and dwelling design). Taking these factors into consideration, passive cooling and daylighting systems were only selected if they use inexpensive resources (e.g., vegetation for shading or local clay bricks to thicken walls for cooling), can easily be incorporated into dwellings, and can be prefabricated or assembled locally (e.g., looking at the viability of bottles to create light bulbs, for lighting).

A more detailed rationale for the selection of passive measures is presented in Table 1, while the reasons for excluding other measures are given in Table S.4. For the mud huts, three passive cooling measures and one passive daylighting measure were selected. For the semi-permanent dwellings, four cooling measures and four lighting measure were selected. All of the selected options could promote the emergence of local micro-enterprises to build, assemble, or install daylighting systems or passive cooling measures, and therefore generate potential incomes.

The selected measures are combined into scenarios, where each scenario combines one passive cooling and one daylighting measure. Therefore, three scenarios are considered for the mud hut (not all options considered are suitable for this kind of dwelling: see Table 1 for details). For the semi-permanent dwelling, 12 scenarios are considered. Four additional scenarios were considered but not included as the different measures impacted each other's performance. For instance, tall vegetation can shade and affect all lighting measures except for the fibre optic solar concentrator (CSC). Discarded combinations include: 1) skylight (SLT) and shading with trees (SWT), 2) double glazing window (DGW) and SWT, 3) DGW and shading with vegetation (SWV), and 4) solar water bulb (SWB) and SWT (see Table 1 for measures description). As a result, the remainder of the paper considers the evaluation of the energy performance of homesteads through 15 scenarios (3 for the mud hut and 12 for the semi-permanent dwelling) as detailed in Section 4.2.

#### Calculations

This section details the simulations' inputs to evaluate the energy performance of both the baseline and the 15 passive measure



**Fig. 3.** Illustration of (a) Solar water light bulb technology (Pabari, 2017) and its indoor illumination, and (b) centralised Solar Concentrator technology (Sedki & Maaroufi, 2017a,b), and its indoor illumination.

**Table 1**  
Selected passive cooling and daylighting techniques for mud huts and semi-permanent dwellings.

Technology/technique		Description	Rationale for selection and study assumptions	
			Mud hut	Semi-permanent dwelling
Passive cooling	Shading with trees (SWT)	Using large vegetation for shading. For this to be effective, orientation of a construction with respect to the sun must be considered, together with the type of vegetation.	This measure is selected considering the extensive vegetation available in the region and to the local communities (e.g., bamboo and banana). Given water access limitations, vegetation from this area is preferable with resilience to the local conditions. <i>Assumptions:</i> <ul style="list-style-type: none"> <li>• Trees are in East and West orientation following other work results to best mitigate solar gains (Hashemi, 2018; Hashemi, 2019).</li> <li>• Tree height is assumed to be 4 m based on banana trees reported in the area (Ploetz et al., 2007);</li> <li>• Three trees are planted per side;</li> <li>• Tree transmittance is set at 15% (Montgomery &amp; Chazdon, 2001) (considered an optimistic vertical coverage).</li> </ul>	
	Shading with wall vegetation (SWV)	Addition of low plants directly surrounding all exterior walls (i.e., green walls), except doors and windows, to benefit from shading and the plant process of evapotranspiration <sup>a</sup> .	This was selected considering that families could grow crops surrounding their dwelling, and thus giving a coupled benefit. As for SWT, given water access limitations, local and resilient plants are preferred. <i>Assumptions:</i> <ul style="list-style-type: none"> <li>• Vegetation height is around 2 m (wall height);</li> <li>• Vegetation transmittance set at 15% (Montgomery &amp; Chazdon, 2001);</li> <li>• Width per plant assumed to be 1.1 m.</li> </ul>	
	Increasing thermal mass (ITM) in walls White-painted roof (WPR)	Increasing thickness of walls to time-attenuate the transfer of heat from outside to the inside. It is a form of heat modulation. It is a form of radiative cooling, where solar radiation is repelled into the sky.	This is selected because the villagers have the skills and experience in building walls already, and the resource material (bricks of clay) is locally available.  Not applicable, as roofs are made of straw.  It is assumed that the villagers with sufficient income to buy metal ceilings, could also afford white paint.	
Passive daylighting	Double-glazing window with air gap (DGW)	Double insulated glass unit of 3 mm thickness each, with 3 mm air gap. The Solar Heat Gain Coefficient of this solution is SHCG = 0.775 (Hee et al., 2015).	Not applicable to the mud huts, as there are no windows in our case study, but we recommend considering them in case of mud huts including windows.  Using DGW instead of existing iron windows, could ensure optimal balance between daylighting factors, thermal characteristic, and price. Using Perspex Acrylic unit in this case is locally affordable, cost-effective, and practical.	
	Skylight (SLT)	A window built into the roof to allow light in. In our case we consider Perspex Acrylic double-glazed window with 3 mm thickness per sheet and 3 mm of air gap.	Not applicable due to the conical mud hut thatched roof.  SLT installations can typically be made locally with simple prefabricated Perspex Acrylic double-glazing units. The choice of Acrylic over polycarbonate plastic glazing is because the former can better balance between a good level of light and minimal heat gain (Al-Obaidi et al., 2014a) while being less expensive than the latter. The skylight will be 5 % of the floor area. To maximise daylighting and/or passive solar heating potential, we consider roof double-glazing skylights that face north to provide constant but cool illumination (Chel et al., 2010; Wang et al., 2015; Wong, 2017; Zheng et al., 2020). <i>Assumptions:</i> <ul style="list-style-type: none"> <li>• The opening is 2 m in length and 1 m in width.</li> </ul>	
	Solar water light bulb (SWB)	Plastic bottles filled with water and chlorine bleach fitted into the roof to refract incoming sunlight into the house and provide indoor light.	SWBs need a large opening in the fragile thatched roof which is not technically possible.  The bottle is fixed to the corrugated metal roof with a third of the bottle outside (see Fig. 3(a)). This technique uses mostly inexpensive and locally available recycled resources (Bansod & Wandile, 2015; Pabari, 2017; Wang et al., 2015). <i>Assumptions:</i> <ul style="list-style-type: none"> <li>• The bottle's bottom diameter is 11 cm, and its height is 23cm (Degife &amp; Bogale, 2019; Pabari, 2017);</li> <li>• The roof's opening to hold the bottle is considered a circle of 11 cm in diameter.</li> <li>• Heat losses are deemed to be zero (Wang et al., 2015);</li> <li>• Three SWB per dwelling are considered for minimum suitable interior lighting.</li> </ul>	
	Centralised fibre optic solar concentrator (CSC)	The fibre optic solar system is composed of a mirrored parabolic solar concentrator, Polymethyl Methacrylate (PMMA), fibre optic wires, and a triple heat filtration device based on a previous validated field work from Sedki and Maaroufi (2017a,b,c) (Fig. 3(b)). This system concentrates and channels solar light using fibre optic transmission.	This measure is selected considering the architecture of a mud hut's roof and walls that limits the implementation of various daylighting measures. In addition, the combination of some proposed passive cooling solutions (e.g., shading with trees and vegetation) is counterproductive for most passive lighting systems which require direct exposure to the sun for dwellings. Therefore, in this case the only possible method is using fibre optic solar concentrator for mud hut dwelling. For both mud hut and semi-permanent premises, this system needs only a small opening in the dwelling envelope and is an effective way to avoid heat gains. It is also the most flexible	

(continued on next page)

Table 1 (continued)

Technology/technique	Description	Rationale for selection and study assumptions	
		Mud hut	Semi-permanent dwelling
		<p>for channelling light inside dwellings (i.e., PMMA fibres are malleable) and able to bring illumination (see Fig. 3(b)) deep into the building at a low cost (Sedki &amp; Maaroufi, 2016, 2017a,b). The mirrored parabolic solar concentrator can be made locally and to further increase the system cost effectiveness, we introduce for the first time in this paper the proposition of a CSC for lighting 3 mud huts/or semi-permanent dwellings at the same time using one passive solar concentrator oriented towards the East for the highest annual radiation (Mukisa et al., 2019; Ramirez et al., 2018).</p> <p><i>Assumptions:</i></p> <ul style="list-style-type: none"> <li>• A bundle of 48 PMMA, fibre optic wires of 2 mm diameter</li> <li>• The parabolic collecting diameter is 1 m.</li> <li>• The parabolic area is formed of 345 pieces of mirror tiles with specular reflectivity index: <math>\rho_m = 0.94</math>. The depth of the parabola is 0.09m (Sedki &amp; Maaroufi, 2016; Sedki &amp; Maaroufi, 2017b);</li> <li>• The opening used to insert the (PMMA) fibre optic inside the dwelling is equal to the diameter of 16 wires of 2 mm diameter each. The length is 15 m per bundle.</li> <li>• Heat gain is considered to be zero (Sedki &amp; Maaroufi, 2017a) for this technology.</li> </ul>	

<sup>a</sup> Evapotranspiration of plants is not modelled in this work, but the shading of these plants surrounding the dwellings is.

representative scenarios embedded into the architecture baseline (i.e., the mud hut and semi-permanent dwellings). First, we describe the material and geometrical inputs of the dwellings and those necessary for the passive measures to build the SketchUp models. Second, to evaluate the dwellings' thermal performance, this section presents the inputs used by EnergyPlus™ and integrated through OpenStudio® interface. These include the SketchUp models, the detailed thermal characteristics of the materials, transmittance levels for shading, and energy appliance use (type and schedule). Finally, we calculate the cost of integrating each measure to calculate payback.

#### Geometrical modelling

To model the baseline and representative scenarios using SketchUp (Zhang et al., 2020), we make a number of assumptions for the material and geometrical properties of the architecture baseline. These include, for example, the description of surfaces, orientation, and doors and windows (Bhikhoo et al., 2017; Cullen & Dezulueta, 1964; Hirmer, 2017; Kakudidi, 2007; Kolokotroni et al., 2018; MacMillan et al., 2011; Nsubuga & Rautenbach, 2018). For a full list of assumptions refer to Table S.5. Building on the baseline scenarios, we then model the passive cooling and daylighting measures, considering the assumptions illustrated in Table 1.

#### Thermal modelling

To evaluate the dwellings' energy performance, we used EnergyPlus™ (Fumo et al., 2010). We consider thermal mass properties, shading (modelled in SketchUp), lighting characteristics, the geometry of construction (loaded from SketchUp), and weather data. For the latter, we adopted the Energy Plus™ default weather data relative to Lodwar in North Kenya as it is at the same northings in latitude as Arua in Uganda. The simulations were ran for an annual time-span, which was built based on monthly and hourly inputs of energy usage and weather conditions.

For the baseline architecture, the material thermal properties (Hashemi, 2016b) used as input for EnergyPlus™ are defined in Table S.6.

For the scenarios which include passive measures, each measure requires the integration of new materials into the dwellings, which will impact the premises' energy performance. Table S.7 presents the thermal properties of materials used for passive measures that were integrated into EnergyPlus™. The geometrical inputs are added as stated in Table 1. OpenStudio® does not yet support tubular daylighting

devices and light transportation technologies (SWB and CSC in the case of our study). Therefore, we model the heat transfer from the light as zero, and we only consider their ability to replace artificial lighting whatever the level of illumination generated by each measure. We ignore the variations in illumination.

#### Costing assumptions for measures and scenarios

Given the low income in rural communities in Uganda, cost assessment complements the analysis of energy performance. To assess the costs of retrofitting the dwellings with passive cooling and daylighting measures, material costs in the region are based on prices given by a couple of local project developers for cooling, and manufacturers' quotations for lighting. The costs of passive cooling measures are calculated based on material costs, and the quantities required. For the passive daylighting they are set per system, as reported in Table 2.

#### Results and discussion

In this section, we first present the energy performance of the baseline scenarios. We then assess the energy saving from the 15 scenarios to retrofit into the dwellings and discuss the payback period according to cost. The time-span used for the various Energy Plus™ simulations is yearly, using monthly and hourly inputs for weather data (to differentiate seasons and set the time of use of fans) and appliances energy usage patterns.

#### Energy performance baseline scenario

The modelled baseline scenarios (from SketchUp) for mud huts and semi-permanent dwellings can be seen in Fig. 4(a) and (b), respectively. The energy performance evaluation (from EnergyPlus™) for these scenarios is summarised in Table 3.

In terms of homestead<sup>1</sup> type, the baseline mud hut homestead consumes 33 % less electric power than the semi-permanent considering all four appliances (i.e., LED light bulb, fan, phone charger, and radio). This is mainly due to the differences in the composition of dwelling room types in the homestead types (see Section 2.1). When comparing the same room, in this case bedroom, for both mud huts and semi-permanent constructions, the results indicate that the bedroom in the semi-permanent consumes 3 % more than that in the mud hut. This is

<sup>1</sup> A homestead consists of 2 bedrooms and a kitchen for a mud hut and 3 bedrooms for a semi-permanent dwelling.



**Table 2**

Estimated cost (in USD) of materials proposed for passive cooling measures (based on input from local project developers) and daylighting systems (based on manufacturers' quotations) for both mud huts (MH) and semi-permanent (SP) dwellings.

Passive measures	Material(s)	Cost per unit	Units required per dwelling	Cost <sup>b</sup>	
				Dwelling	Homestead
SWT	Large trees (>4 m height)	\$3.00 per tree	6	\$18	MH: \$36 SP: \$54
SWV	Vegetation or crops (2 m height)	\$1.50 per plant	MH: 18 SP: 24	MH: \$27 SP: \$36	MH: \$54 SP: \$108
WPR	White painting	\$0.70 per liter	7	SP: \$5	SP: \$15
ITM	Clay bricks	\$0.10 per brick	MH: 2950 SP: 4030	MH: \$295 SP: \$403	MH: \$590 SP: \$1209
DGW	Measure per lighting system			\$75	\$225
SLT				\$140	\$420
SWB				\$6	\$18
CSC				\$214 <sup>a</sup>	\$642

<sup>a</sup> This is the proportion estimated by dwelling, as CSC systems are shared by homestead.

<sup>b</sup> The costs do not include the cost of labour.

despite the fact that the family schedules and the installed power of the mud hut and semi-permanent bedrooms is the same (44 W). Nonetheless, this is expected as mud huts have more natural ventilation due to their open eaves compared to the semi-permanent dwellings which are assumed to have one closed iron window. Further, due to the lack of ventilation, semi-permanent dwellings require more cooling due to the higher thermal conductivity of iron sheet roofs compared to thatched roofs (mud hut).

In terms of comparing energy consumption of the four appliances, the model shows that for both mud huts and semi-permanent dwellings LED lights are the predominant energy consumer (i.e., 44 % and 42 % respectively). This is explained by the fact that both dwelling types are dark inside throughout the day and therefore lighting is required continuously. Similar results have been shown in other studies of East African communities (Bensch et al., 2017; Williams et al., 2017). They found that lighting represents approximately 50 % of the total energy consumption.

In our study we find that electric fans account for 27 % of electricity use for mud huts and 30 % for the semi-permanent dwellings. This is aligned with field data from the literature (Adeoye & Spataru, 2019) which reports that, in West Africa, the use of electric fans in similar residential rural housing represents between 10 % and 30 % of the total energy consumption.

#### Energy performance of scenarios with passive measures

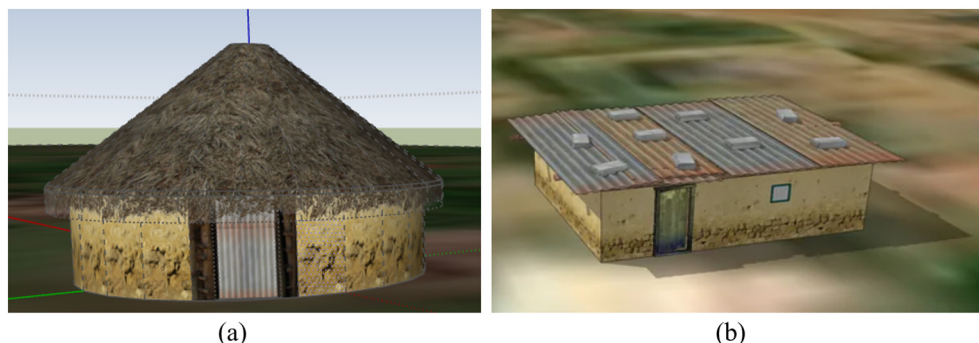
In this subsection, we reassess the energy performance of dwellings and homesteads under the 15 scenarios presented in Table 4. Each of the different scenarios will have an impact on energy consumption for lighting and cooling. The energy use for phone charging and radios will remain constant.

#### Mud hut dwellings

The results in Fig. 5 correspond to the three scenarios which model the retrofitting of mud huts with passive measures. These scenarios (MH-1 to MH-3) enable inspection and comparison of passive cooling measures as there is only one passive daylighting measure (CSC) compatible with mud huts (see Table 4). From Fig. 5, the most effective passive cooling measure in terms of energy savings (with respect to baseline scenario) is the thickening of walls (ITM in scenario MH-3). This is a robust measure compared to the SWT and SWV measures applied in MH-1 and MH-2, given that these considers optimistic shading (high transmittance or thick covering) of either tall trees or vertical vegetation on walls. Scenario MH-3 saves 33 % of the annual power consumption in the bedroom with respect to the baseline scenario (4 % more than MH-1 and 2 % more than MH-2). The scenario MH-2 (including shading with vegetation alongside outer walls) is shown to reduce the energy consumption by 31 % compared to 29 % for the shading with trees scenario (MH-1). The difference in the performance of greenery measures can be explained by the fact that the thatched roofs already provide insulation, thus the shading of large trees (which is mainly over roofs) is less effective than avoiding heat gains through the walls. A further advantage from shading with greenery is its potential multi-purpose use, as it could also provide food crops.

For the daylighting techniques, the architecture of a mud hut's roof and walls limits the implementation of various measures (as explained in Section 2.3). Therefore, only the fibre optic solar concentrator (CSC) was considered (see Fig. 6 for an illustration of CSC). It is suggested that there is one such system per homestead.

The simulations show that the integration of this daylighting measure on its own has the ability to reduce the energy consumption with respect to the baseline scenario by 29 % annually for a typical bedroom. This is in line with the findings from Sedki and Maaroufi (2016, 2017b). The authors found that the installation of the low-cost solar



**Fig. 4.** SketchUp models of: (a) mud hut (MH) baseline scenario and (b) semi-permanent (SP) baseline scenario.

**Table 3**  
Electricity consumption of baseline scenario.

Dwelling type	Dwelling room	Room annual electricity consumption [kWh]	Percentage of electricity consumption per appliance <sup>a</sup>	Homestead <sup>b</sup> annual electricity consumption [kWh]
Mud hut	Bedroom	152.8	44 % LED light bulb 27 % fan 26 % phone charger 3 % radio	319.5
	Kitchen	13.9	100 % LED light bulb	
Semi-permanent	Bedroom	158.3	42 % LED light bulb 30 % fan 25 % phone charger 3 % radio	474.9

<sup>a</sup> To better understand the relative energy consumption of lighting and cooling appliances, we consider all appliances that are commonly used by households in rural Uganda (Hirmer & Guthrie, 2017) in our baseline scenario, taking into account the schedules outlined in Section 2.2.

<sup>b</sup> A homestead consists of 2 bedrooms and a kitchen for mud hut and 3 bedrooms for the semi-permanent.

fibre optic daylighting system generates annual savings ranging from 30 % to 40 % and can provide uniform illumination deep into the building. The specific savings will depend on the characteristics of the system's fibre optic wires and weather conditions. This means that the CSC has an important potential to improve the overall energy efficiency of the mud hut dwelling.

An additional benefit of CSC is that it could also be used for cooking (Biermann et al., 1999; Patel et al., 2018). The parabolic solar concentrators, the main part of the proposed CSC, can be designed to be adjustable for both lighting and cooking purposes. The parabolic solar cooker is an environmentally friendly food cooking system that can improve the quality of life and reduce consumption of conventional energy (Arenas, 2007; Biermann et al., 1999; Patel et al., 2018). It should be noted that the nature of the technology means that its usage for cooking is limited to hours of daylight, which may reduce the benefit of its potential for multifunctionality.

#### Semi-permanent dwellings

The results for energy performance of semi-permanent scenarios are presented in Fig. 7. It is observed that the scenarios which save most energy with respect to the baseline scenario are SP-8 and SP-11. They both include radiative cooling through painting the roof (WPR) as a passive cooling measure combined with either solar concentrator (CSC) or water bulb (SWB) for lighting. It should be noted that these lighting

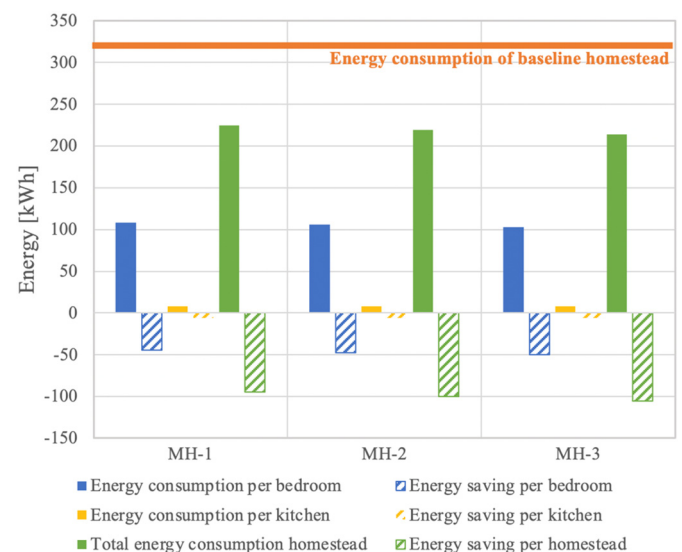
measures both contribute negligible heat gains (Sedki & Maaroufi, 2017a; Wang et al., 2015). These two best scenarios generate 47 % of energy savings, from which 30 % are due to the implementation of SWB or CSC, and 18 % associated to WPR.

For cooling measures, the painting of roofs (WPR) in scenarios SP-2, SP-4, SP-8 and SP-11 show the best results as they produce up to 19 % energy savings. This is an expected result, as implementing this radiative measure has also been found to be the most effective by other authors (Al-Obaidi et al., 2014b) in the urban tropical context. Further, it has been identified as contributing to the reduction of internal heat gains indoors (Al-Obaidi et al., 2014b) and the risk of overheating (Hashemi, 2019). The thickening of walls to improve thermal mass (ITM) and hence attenuate the heat gains in scenarios SP-3, SP-5, and SP-9 follows in terms of energy performance improvement. Specifically, it shows a reduction in energy use for cooling with respect to the baseline scenario of 2 % in scenarios SP-3, SP-5, SP-9, and SP-12. The shading with different greenery (SWT in scenario SP-6 and the SWV in scenarios SP-1, SP-7 and SP-10) results in fewer effective measures, with an average of 1.6 % of energy savings. It should be noted that these results are despite the assumption of high transmittance (thick cover). Other authors (Hashemi, 2019) similarly have reported that shading strategies would need to be combined with other passive cooling measures to show better efficiency. Lastly, when comparing the results of scenarios with the same cooling measures in different dwellings, MH-3 and SP-9

**Table 4**  
Scenarios with passive measures for mud hut and semi-permanent dwellings.

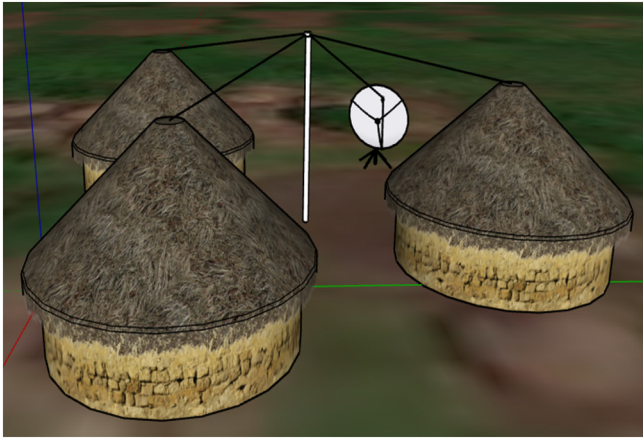
Scenario	Dwelling type	Passive cooling measures				Passive daylighting measures			
		SWT	SWV	WPR	ITM	CSC	SLT	DGW	SWB
MH-1	Mud hut	✓				✓			
MH-2			✓			✓			
MH-3					✓	✓			
SP-1	Semi-permanent		✓				✓		
SP-2				✓			✓		
SP-3					✓		✓		
SP-4				✓				✓	
SP-5					✓			✓	
SP-6		✓				✓			
SP-7			✓			✓			
SP-8				✓		✓			
SP-9					✓	✓			
SP-10			✓						✓
SP-11				✓					✓
SP-12					✓				✓

MH: Mud hut, SP: Semi-permanent, SWT: Shading with trees, SWV: Shading with surrounding vegetation, WPR: White-painted roof, ITM: Increased thermal mass, CSC: Centralised low-cost solar concentrator, SLT: Skylight, DGW: Double-glazed window, SWB: Solar water light bulb.



**Fig. 5.** Energy performance results for scenarios retrofitting mud hut (MH) dwellings with passive cooling and lighting measures per annum.





**Fig. 6.** Solar concentrator (CSC) daylighting distribution system in mud hut homestead illustrated using SketchUp.

(both embedding ITM and CSC measures), it is apparent that the savings in mud huts are 3 % (equivalent to 2.2 kWh) more than in the semi-permanent dwelling. This is due to the difference in roofing with thatched roof allowing a better thermal performance inside the dwelling than iron sheets. Other authors (Bhikhoo et al., 2017) have also found similar results.

All daylighting systems simulated (SLT, DGW, SWB, and CSC) will substitute the artificial light used during the daytime. This is 12 h in North Uganda throughout the year (from 6 am to 6 pm). These systems can generate a 44.5kWh energy saving annually for both bedroom types, but they provide different levels of indoor light. For the skylight (SLT), it has been identified that a higher level of useful daylight illuminance could be achieved with roof light (e.g., a roof light area of about 20 % of the total building floor area could contribute >1000 lx of illuminance in horizontal plane (Ploetz et al., 2007)). According to literature, the double-glazed unit (DGW) could offer a good balance between visual comfort and thermal energy performance (Seymour et al., 2020). The SWB illumination was reported by others (Hee et al., 2015), who confirmed that the SWB could provide a minimum illumination for reading over an extensive period of the day (illuminance > 10 lx) (Wang et al., 2015). Concerning the CSC system, the test field done by Sedki et al.

(McClellan et al., 2017; Wang et al., 2015), using 98 wires of PMMA fibre optic and the same solar concentrator, confirmed that the system gives a very high level of illumination (from 1412 lx to 2824 lx). Regarding trade-offs between daylighting systems and heat gains, results suggest that the measures that use Perspex Acrylic material (SLT and DGW) impact the thermal properties of the dwelling, as opposed to CSC and SWB that have a heat transfer close to zero (McClellan et al., 2017; Nair et al., 2014). Furthermore, if we compare between SLT and DGW, we find that the former promotes more heat transfer because of its size and location (i.e., SLT on roof and DGW on wall), as illustrated in Fig. 8(a) and (b).

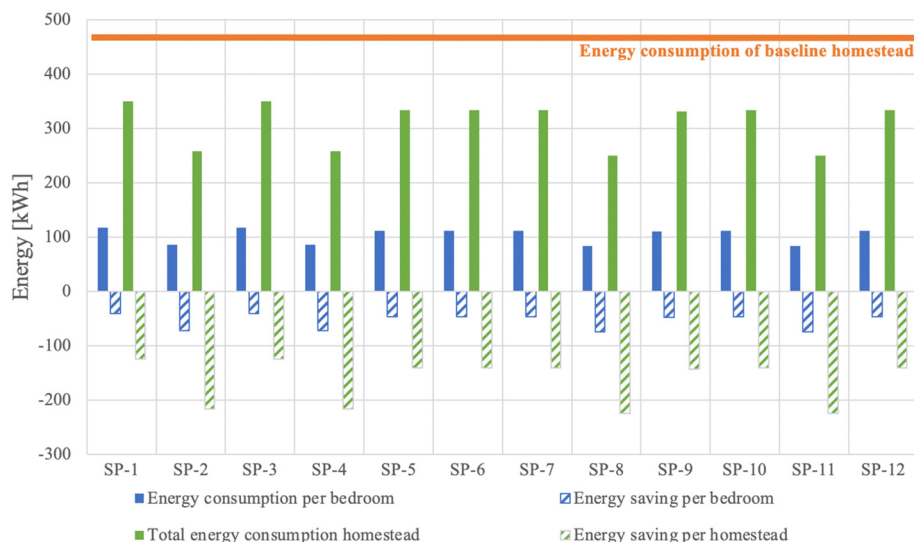
In summary, for the mud hut dwelling we find that combining CSC with SWV (MH-2) or ITM (MH-3) are the most energy efficient solutions to propose for this baseline architecture. For the semi-permanent dwelling, combining WPR with either SWB (SP-8) or CSC (SP-11) is the most energy efficient solution.

In the next section we will focus on calculating the payback periods relative to the application of the different measures for both mud hut and semi-permanent dwellings.

### Comparing costs of passive measures

From the costs of materials for passive measures (see Section 3.3), we calculate the cost per scenario and present results in Fig. 9. The cost of labour has been excluded as the proposed solutions are easy to implement: they commonly align with existing skills (e.g., in the case of planting vegetation) or can be easily learnt by villagers. This reduces the overall cost of the solutions.

This is important as cost is a significant decision-making factor for the selection of solutions as most rural villagers in Northern Uganda are poor (Hirmer et al., 2021). Looking at the passive daylighting techniques, we can clearly notice a noteworthy difference in cost per system. This is because the level of illumination of the different technologies considered was not assessed as part of this study – a core limitation of this study – but has a direct impact on cost variation. For cooling, increasing the thermal mass of walls is very expensive compared to the other solutions suggested in this study. Therefore, for mud huts, the results indicate solution MH-3 is the costliest to install, while the most cost-effective is MH-2 (CSC and SWV). For semi-permanent dwellings, the most expensive solution is SP-9, while the most cost-effective is SP-11 (SWB and WPR).



**Fig. 7.** Energy performance results for scenarios retrofitting semi-permanent (SP) dwellings with passive cooling and lighting measures.

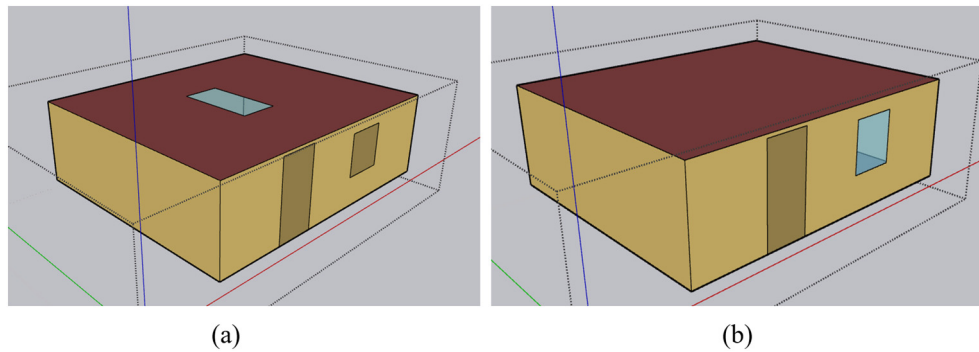


Fig. 8. SketchUp modelling of: (a) Skylight (SLT) measure in Semi-Permanent dwelling and (b) Double-glazed window (DGW) measure in Semi-Permanent dwelling.

Regarding the payback period of each of those measures, the calculation is based on two components: (1) the energy savings from each applied scenario compared to the baseline and (2) the cost of electricity purchased. In other words, we calculate the payback time of passive alternatives as a measure of the cost saved from shifting away from daytime electric light and fan use. This is because in this paper we assess the impact of those passive measures on the community once connected to electricity, as our baseline, as explained in Section 4.1. The cost of purchased energy is estimated to be 1.47 \$/kWh, representing an average of energy cost in microgrids in rural subsidies (Neal, 2020). The next part of the discussion focuses on payback times and maintenance.

In terms of analysing the savings in energy and payback time, the results are presented for mud hut scenarios in Fig. 10. We can observe that the most economical scenario in terms of payback to implement for mud huts is MH-2. This solution combines SWV and CSC. This scenario results in four years and nine months of payback time. It allows an annual energy reduction of 31 %. From this, 29 % reduction is achieved by installing the CSC for lighting and 2 % from the application of the SWV measure for cooling.

From Fig. 11, we notice that the best scenario for the semi-permanent homesteads is scenario SP-11, which combines painting the roof (WPR) and solar water bulb (SWB) and has a two months payback period. It generates an annual energy reduction of 47 %. From this, 28 % reduction is achieved by installing the SWB for lighting and 19 % from WPR as a measure for cooling. The illustration of the packages applied to mud hut and semi-permanent homesteads are shown in Fig. 12 (a) and (b).

Although all passive measures were selected based on price and ease of deployment, here we briefly consider the maintenance for

the selected scenarios: MH-2 and SP-11. We find that vegetation (SWV) and white roofs (WPR) are fairly easy to maintain. SWV requires watering of plants, and to cope with the limited access to water, it is preferable then to use local vegetation or crops. WPR requires cleaning of the roof when dust has accumulated as dust can make the roof darker and hence lower the performance of this measure. A life-cycle assessment in the recent literature (Shittu et al., 2020) has reported that for cool roofs water is commonly used for cleaning (1.4 kg/m<sup>2</sup>) and their lifespan is five years. Similarly, for the daylighting measures centralised solar concentrator (CSC) and solar water bulb (SWB), the maintenance consists of regular cleaning (likely to be done by the occupants). In term of lifespan, for SWB it is five years and up to 20 years for the CSC (Mayhoub, 2017). Therefore, maintenance does not have a significant impact on cost increase during the lifecycle of the proposed scenarios. Yet, there are other factors that may need to be considered in the selection of technologies, such as risk of theft.

In summary, the selection of cheap, straightforwardly deployable, and easy to maintain measures for both mud hut and semi-permanent architectures has led to implementable scenarios combining passive cooling and daylighting measures which are adequate for rural vulnerable communities in East-Africa.

## Conclusion

This paper investigated the role of passive cooling and daylighting measures in enhancing the dwelling's overall energy performance while enabling a better indoor comfort. To assess this, we applied technically applicable and financially affordable passive cooling and

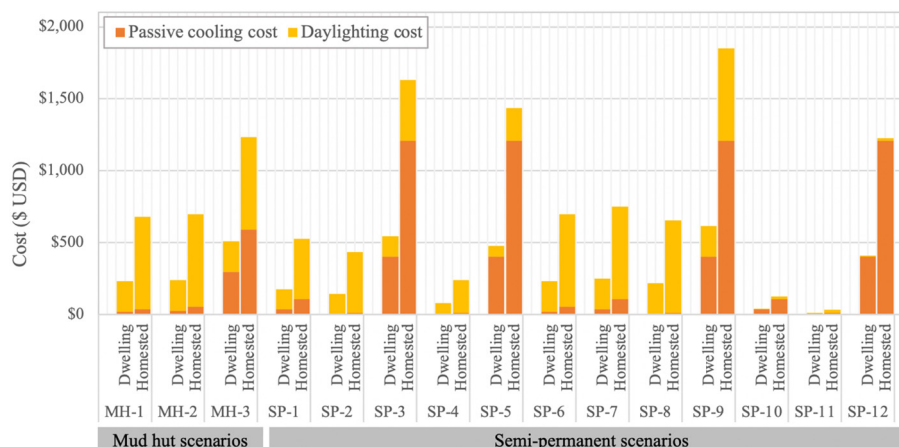


Fig. 9. Estimated costs of implementing passive measures in scenarios.

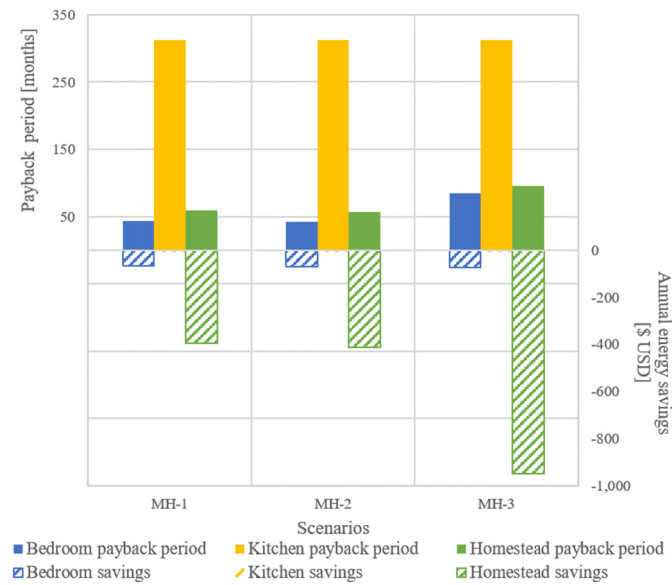


Fig. 10. Payback period and energy saving in USD per implemented scenario for MH dwellings.

daylighting measures adequate to rural North Ugandan premises. Those measures have been combined into 15 scenarios and applied to carefully chosen baseline architectures (mud hut and semi-permanent dwelling types) with representative electrical appliances. The most cost-effective scenario (best scenario) per architecture type has been selected based on payback periods calculation and microgrids estimated electrification cost.

The results showed that combining wall vegetation for shading with a centralised fibre optic solar concentrator for daytime indoor lighting is the best scenario for mud hut dwellings. For the semi-permanent ones, painting roofs white for cooling and using solar water light bulbs for daylighting are the best options. The application of these measures in low-income residential dwellings can allow communities to reduce energy consumption, avoid more expensive use of fans and light bulbs, and shift to more sustainable rural housing with improved overall

indoor comfort. With climate change, this will be further beneficial, as existing fans, for example, will not be sufficient to cover the populating needs in terms of cooling, which may require them to purchase more. Likewise, decreasing the heat coming from conventional lighting and replacing it with zero-heat daylighting systems will also become a priority.

While the study focused on rural Northern Uganda, the findings may also be applicable to other countries in SSA and contexts (such as peri-urban) where dwellings are characterised by similar construction materials and geometries.

The limitations of this study that could be addressed in future research are twofold. First, the level of illumination of the different daylighting technologies considered was not assessed. Future work may evaluate the daylight factor, the uniform daylight index, and indoor illuminance corresponding to each applied passive daylighting measure using DIALux. This will allow accurate assessment of the visual comfort resulting from the proposed scenarios. Second, the eight possible orientations for the two baseline architectures have not been fully explored. Future work may consider meticulous analysis regarding the impact of each orientation on the energy performance of each dwelling type as this study only focused on comparing scenarios for a single orientation per dwelling type. The thermal comfort resulting from the scenarios applied to each orientation per dwelling could be part of the same research. However, that may eventually require real-world fieldwork testing.

Further research topics that we identified as thought-provoking based on this research paper are as follows: 1) assessment of the benefits of integrating passive measures on off-grid low-cost microgrids planning and operation in the rural East-African regions, 2) investigation into the financial implications of using fuel-based cooking and lighting and comparison with the cost of centralised fibre optic solar concentrators, and 3) consideration of the application of the outcomes of this work in urban East African settings. Regarding this latter topic, by applying the scenarios used in this paper to permanent dwellings from urban settings, more benefits for larger populations could be uncovered.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

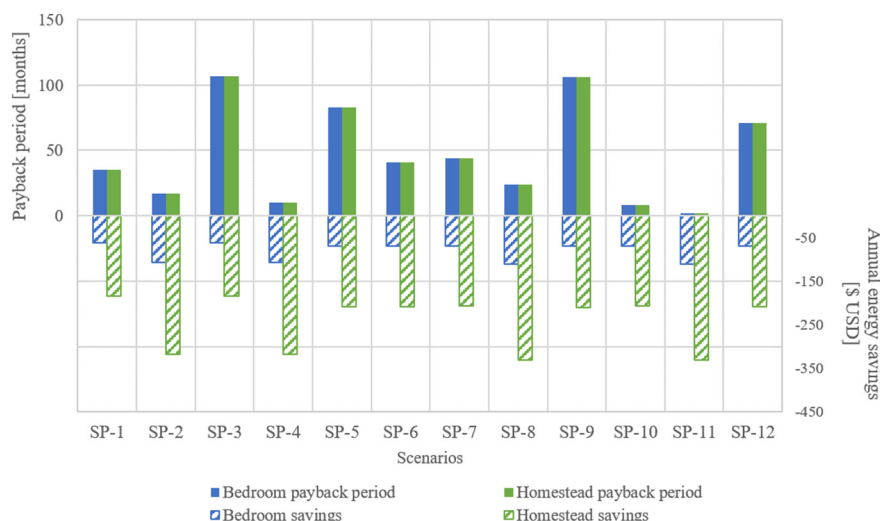


Fig. 11. Payback period and energy saving in USD per implemented scenario for SP dwellings.





**Fig. 12.** SketchUp modelling of: (a) vegetation (SWV) and centralised solar concentrator (CSC) passive measures in a mud hut (MH) homestead (MH-2 scenario); and (b) white roofs (WPR) and solar water bulb (SWB) passive measures in a semi-permanent (SP) homestead (SP-11 scenario).

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esd.2022.06.007>.

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