

Article

Environmental Hotspot Assessment for a PV Mini-Grid Design: A Case Study for Malawi

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Abstract: The United Nations Sustainable Goal 7, access to affordable and clean energy, is unlikely to be achieved, with an estimated 600 million people still without access to electricity by 2030. One potential route to support this goal is through the use of mini-grids to provide electricity in densely populated rural areas for which grid connection is not possible. This paper presents the results of a life cycle assessment of a mini-grid, designed for construction in Malawi. It analyses the cradle to end of use for this mini-grid configuration, for a grid sized for lighting, refrigeration and phone charging, and for a grid sized for electric cooking (e-cooking). The results suggest that for lighting configuration, the main contributors to environmental impact are the poles, the overhead cabling, and the PV panels. The use of a chromium-based preservative is the main issue for the poles, and a switch to concrete poles can deliver significant benefits. When the grid is sized for e-cooking, the PV panels become the greatest contributor. Adding a diesel generator to the mini-grid configuration can reduce number of panels required and hence the environmental impact, but only if the generator is used for no more than 2 h per day.

Keywords: PV mini-grid; PV hybrid mini-grid; life cycle assessment; e-cooking



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1. Introduction

The United Nations Sustainable Development Goal 7 [1] targets access to affordable, reliable, sustainable, and modern energy by 2030 and to date, good progress has been made in recent years towards achieving electrification across the globe. The number of people without access dropped from 1.2 billion in 2010 to 789 million in 2018, equating to an increase in access from 83% to 90% [2]. However, under current policies, and taking into account the effect of the Coronavirus pandemic, it is estimated that more than 600 million people will remain without access to electricity by 2030. The vast majority of these people will be in Sub-Saharan Africa.

The health benefits of electric cooking (e-cooking) over traditional fuels such as firewood and charcoal has been well established [2]; reduced exposure to household air pollution and reduced time and effort for cooking fuel collection, and recent work has also shown that the costs associated with e-cooking are now comparable to traditional fuels and Liquefied Petroleum Gas (LPG) in some cases. [3]. However, the environmental benefits of this transition are highly dependent on location, fuels used, and foods traditionally cooked. For urban locations, connection to existing grid systems is a sensible way forward, although again dependent on the capacity of the grid to provide the necessary higher loads to support e-cooking in a robust and consistent manner. In rural areas, grid electricity may not be an option, and thus local generation systems are of key interest. Community mini-grid or Solar Home System (SHS) offer the two routes to achieve this.

Mini-grids offer a potential solution to electrification for rural areas with reasonably high population density and demand. They are a cheaper option to expanding main grids because of the significant infrastructure requirements necessary for main grids, and capital costs for mini-grids have been and are expected to continue to decline [4]. Photovoltaic (PV) and PV hybrid mini-grids also have the potential to achieve positive environmental benefits, through avoided carbon dioxide (CO₂) emissions.

Estimation of the environmental benefits of mini-grid systems (PV, PV/hybrid, PV/Wind) has been a topic of interest in recent years, and attention has tended to focus on the power producing aspects of the systems and energy storage aspects, examples of which can be seen in references [5–11]. What is clear from these studies is that comparisons of the results generated are problematic, as the system boundaries (such as the inclusion or exclusion of the supporting equipment for a mini-grid system), choice of battery technology, efficiency of PV panels, etc., all vary. Additionally, data for batteries and PV panels vary in completeness and quality, as some of the technologies used are still developing, and in some cases, full data sets are not in the public domain [12]. Taken together, this suggests that the appropriateness of a mini-grid installation can only be assessed on a case-by-case basis.

This paper analyses the environmental impacts based on a mini-grid agreed for construction in Malawi. The mini-grid was originally designed to provide electricity for lighting and refrigeration for business applications, coupled with domestic connections for lighting and phone charging, and the initial assessment focused on the impacts associated with this configuration. To expand the analysis to understand the issues surrounding environmental impacts associated with mini-grid applications that include the capacity for e-cooking, greater PV and energy storage capacity was required, and further analysis has been undertaken with the battery and PV appropriately sized to accommodate this.

2. Materials and Methods

The study was conducted following the principles outlined in BS/EN ISO 14040 and 14044 [13,14]. The Simapro software (PRé Sustainability, Amersfoort, The Netherlands) and ecoinvent databases (ecoinvent, Zurich, Switzerland) were used to create the model of the mini-grid, and a bill of materials (BoM) for the mini-grid was provided by University of Strathclyde [15,16], see Table A1 for BoM. Component weights and component surface areas (for coatings) have been calculated from component dimensions, where direct weighing was not an option.

The study used a cradle to end of use approach, thus no end-stage impacts have been accounted for. Assumed lifetimes for the components of the mini-grid are provided in Table A2 in Appendix A. Details for the sub models built for the mini-grid assessment can be found in the Supplementary Materials. The functional unit for the study is one lifetime of the mini-grid, assumed to be 20 years.

The purpose of the assessment was to identify the key contributors, or hotspots, to the environmental impact for this mini-grid and to use these to draw some generalized conclusions with regard to the design of mini-grids. Scenario analysis was used to assess different options for those parts of the model that were associated with high impact.

Currently, there are no environmental assessment systems that focus specifically on the output to impact pathways for the African continent. For global impacts, such as climate change, this was not a concern. However, for local pathways and associated impacts, the different regions can affect the potential impacts created. The ReCiPe system [17], (which was built on CML 2002 and Eco indicator 99 systems) can be used for global contexts and was thus used to assess the midpoint and endpoint environmental categories. The Hierarchist perspective was taken, understood to be the consensus model, and is based on the most common policy principles with regards to the timeframe for impacts and other issues. It is the default model. [18] The endpoint results are normalized to the global per capita impact for each category; damage to human health, damage to ecosystems, and damage to resource availability. Figure 1 shows the relationship between the 18 midpoint and three endpoint categories.

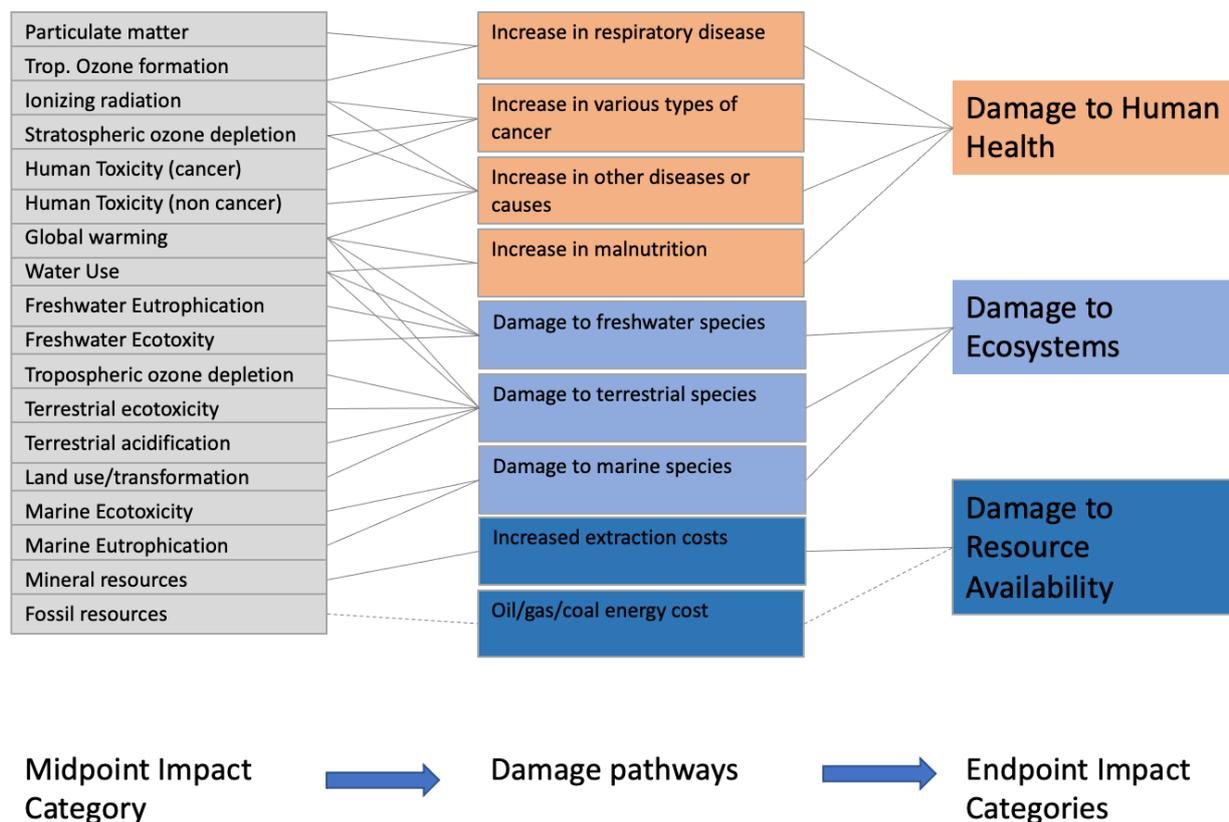


Figure 1. Representation of the relations between the impact categories midpoint and the areas of production (endpoint). Reproduced using information from [17].

3. Results

This section details the results from the life cycle assessment study. The contribution analysis identifies which of the items in the construction of the mini-grid have the highest environmental impacts. The scenario analysis shows how these impacts may be reduced by utilizing alternative materials or components.

3.1. Contribution Analysis

3.1.1. Mini-Grid Sized for Lighting, Phone Charging, and Refrigeration

Figure 2 shows which main component groups contributed the most to the environmental impact. The Energy_MGrid (green), (which covers all equipment other than the power generating system) and the PV life cycle (light blue), were seen to have the greatest contribution to the midpoint environmental impact categories. Of particular note was the very high contribution of the human carcinogenic impact from the Energy_MGrid. The lithium iron phosphate battery (yellow), inverter (dark orange), and converter (dark blue), were seen to contribute relatively little by comparison. This is somewhat surprising, and the result could be attributed to a number of factors. Each mini-grid will have a unique configuration of component sizing, depending on its designed use. The battery size specified for this grid was small. There are many chemistries for lithium-ion batteries (LIB), and each chemistry has different charge/discharge profiles that can affect the sizing needed. There is also considerable variation in the literature with respect to the life cycle environmental impacts from lithium batteries. Ellingsen [19] demonstrated considerable differences in calculated GHG emissions (from 38–336 kg CO₂ eq/kWh), and thus the choice of battery chemistry and assumptions made in evaluating the impacts could have a significant effect on these results.

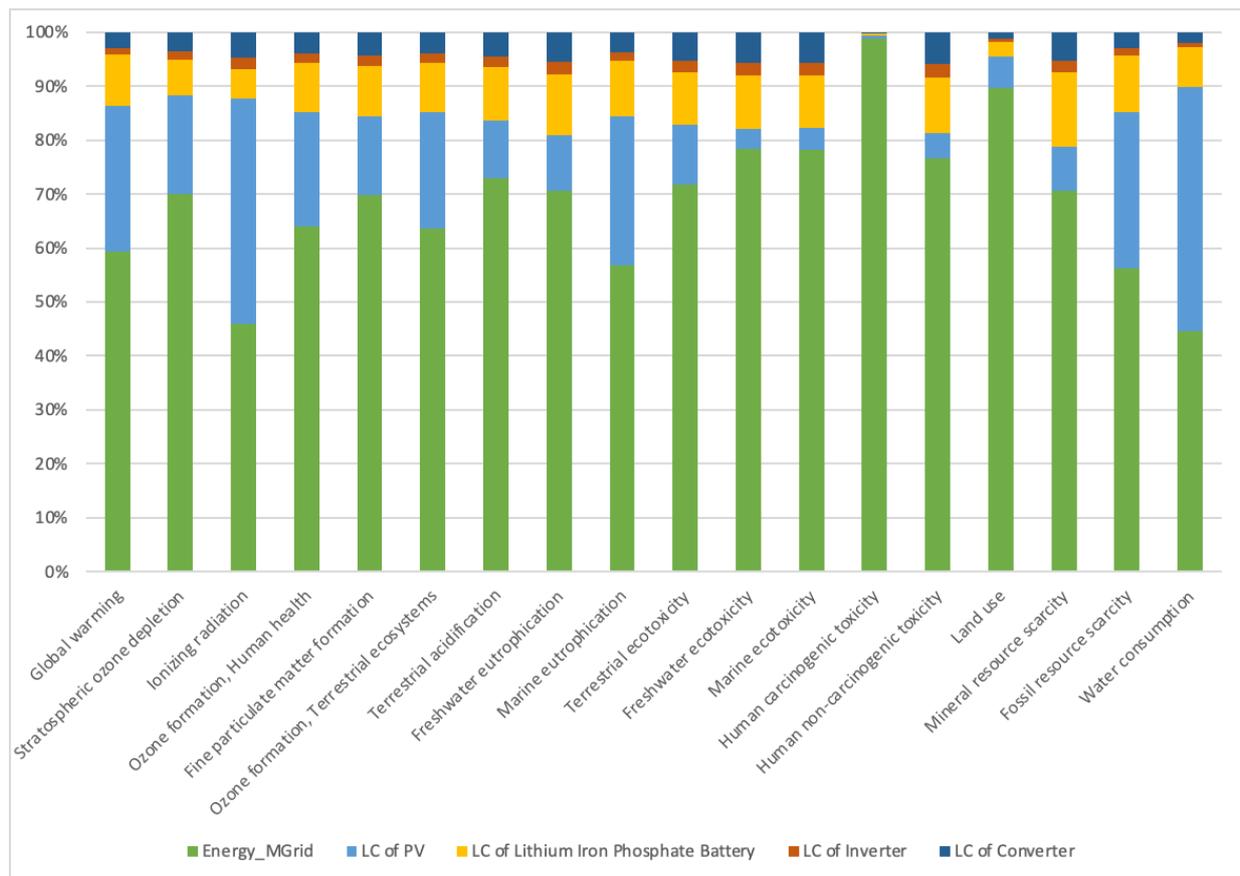


Figure 2. Contribution analysis to midpoint categories of main component groups to impacts from the mini-grid.

Analysing the Energy_MGrid system more closely, Figure 3 shows there were two sub groups of components of potential interest: the poles and stays and the cabling system. Between them, these two sub groups accounted for more than 70% of the impact across most of the midpoint categories. The overhead materials (not cables), PVC products, and earth rods contributed very little to the overall impact, and the shipping container (which houses the control equipment for the mini-grid) contributed more than 10% to only four midpoint categories. From Figure 3, it was seen that the high contribution to human carcinogenicity came from the poles and stays.

The poles and stays used essentially the same materials and processes and as such were considered a single component, but there are a range of cables used in the creation of a mini-grid, from heavy distribution cabling to domestic wiring. Based on this, further analysis of the cabling components was undertaken to identify which of the cabling used was of most concern. Figure 4 shows the contribution of the different cables used in the mini-grid. Two cables stand out as contributing the most; the AAC conductor (aluminium core), the main distribution cable from the PV power generating system (grey), and the twin figure 8 cable (copper core), used to connect to the buildings (green). The third cable of interest is the 1.5 mm² cable (copper core), used within the home to connect various appliances/lights, etc. (brown).

As a result of the contribution analysis, the following component groups were further investigated to identify the cause of the impacts, and whether changes to materials or processes could reduce the environmental impact (see Section 3.2):

- Poles and stays
- Cabling components
- PV panels

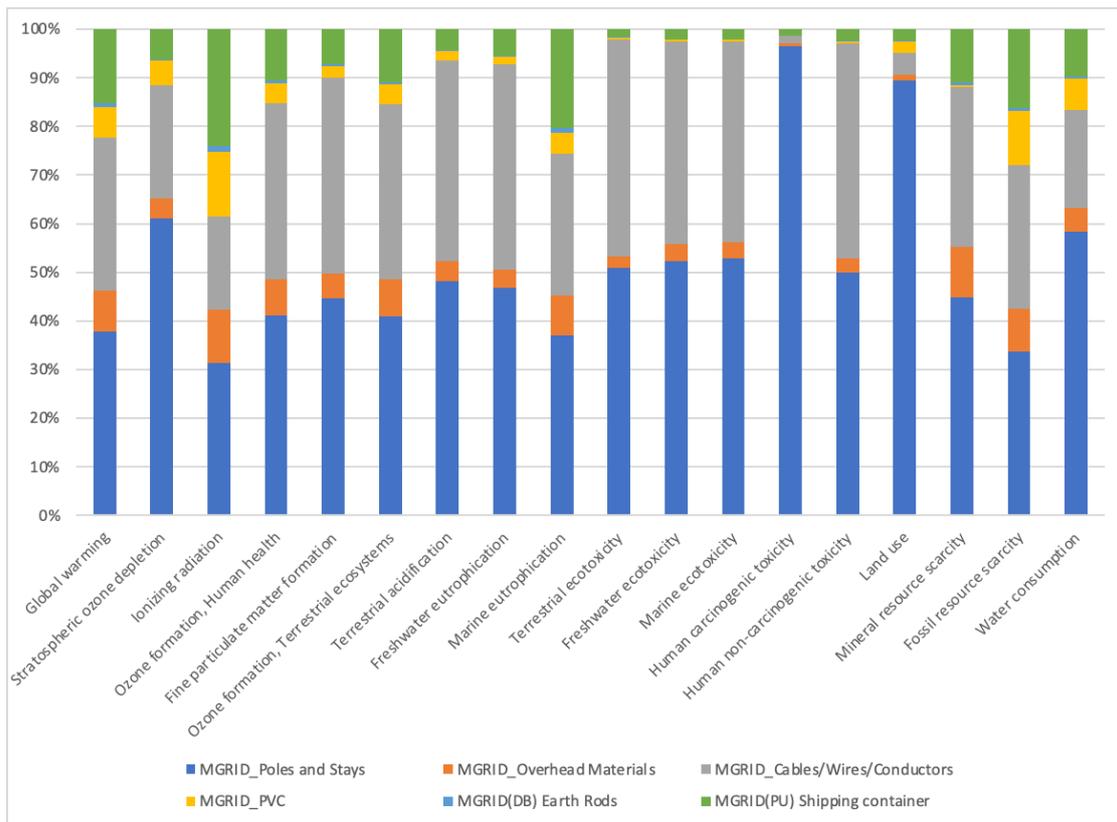


Figure 3. Contribution analysis to midpoint categories of component groups in Energy_MGrid.

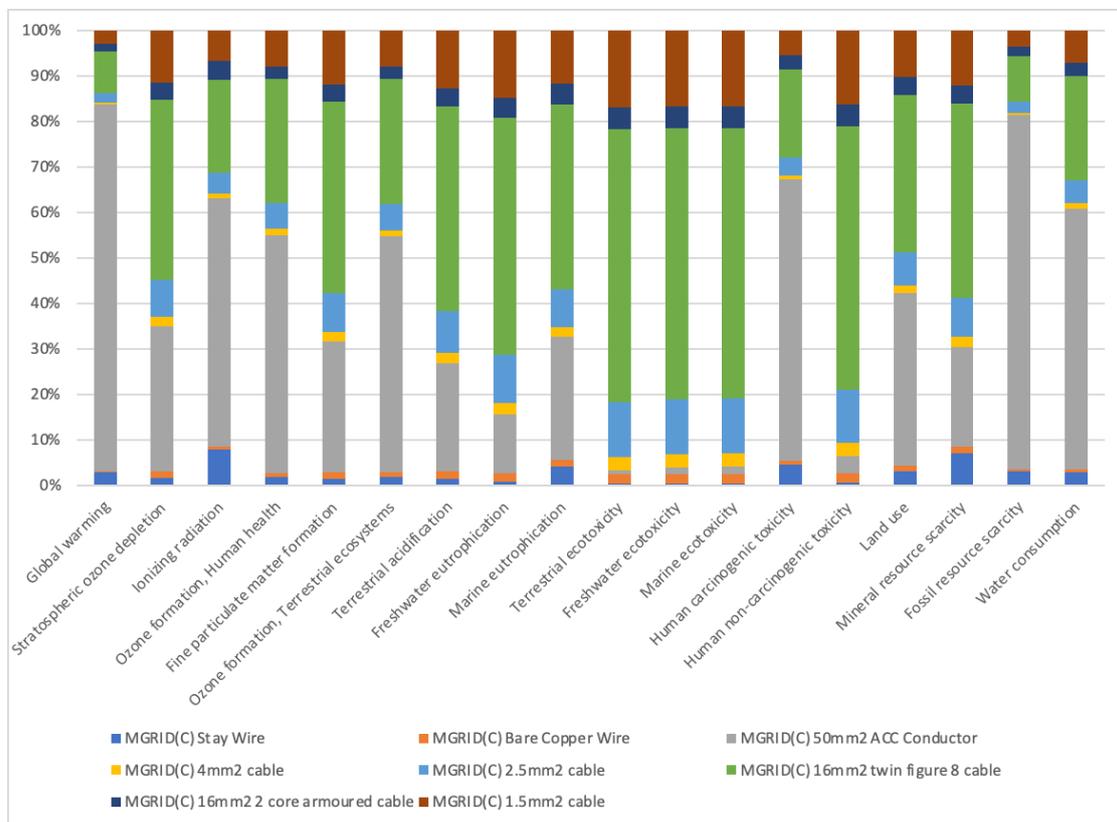


Figure 4. Contribution analysis to midpoint categories of component groups in cables to impacts from the mini-grid.

3.1.2. Mini-Grid Sized for e-Cooking

The results above relate to a mini-grid that was sized for lighting and relatively low electricity consumption. However, transitioning to e-cooking has significant benefits, and mini-grids have the potential to contribute to this transition. Taking data from Keddar [20], a contribution analysis was undertaken for this mini-grid, but sized to support 100% e-cooking needs. Table 1 provides details on the size of PV, battery, inverter, etc., required. All other components to the mini-grid remained constant (cables, poles etc.).

Table 1. Sizing of power components for a mini-grid used to support e-cooking.

	Base Load with No e-Cooking	Base Load Plus 100% e-Cooking
PV panel size, kWp m ² (assume 16% efficiency)	14.1 76.6	190 1032
Battery kWh	41.1	124
Inverter kW	5	20
Converter kW	11.6	24

Figure 5 shows the results from this analysis, and it can be seen that increasing the PV size (from 76.6 m² for lighting to 1032 m² to include e-cooking) increases their contribution to the total impact, whereas for the mini-grid sized for lighting, (see Figure 2), the supporting components (Energy_MGrid) were seen to contribute most to the environmental impact: for the e-cooking sized grid, the PV panels were seen to be the greatest contributor. This would suggest that for mini-grids, which utilise a relatively low PV area, the efficiency of the PV panels was less critical, and attention to reducing the impacts of the supporting system would be more effective in reducing the overall impact of the mini-grid. However, for those systems that required a large area of PV, the PV panel efficiency was considerably more important, and significant benefits would be found through the use of latest technology and high panel efficiency (although this would probably increase the economic cost of the system). It was also interesting to note that despite the battery requirements significantly increasing, they still did not contribute overly to the total environmental impact from cradle to end of use for this particular mini-grid design.

3.2. Scenario Analysis

This section reports the results of the in-depth analysis of the main contributing factors identified in the contribution analysis.

3.2.1. Poles and Stays

Looking at the poles and stays in more detail, Figure 6 shows just how much the environmental impact was overwhelmingly dominated by the wood preservative and process, rather than the production of the wood itself. The only category where this was not the case was land use. It was thus useful to compare alternative systems to try to reduce the impact from the choice of wood and preservative.

The original choice of preservative and preserving process was based on East African Standard 324: Copper/chromium/arsenic compositions for the preservation of timber [21]. Two alternatives were identified and modelled, one changing the process and one changing the base material. The first alternative maintained the use of wood but used a non-chromium-based liquid preservative applied using the same, vacuum pressure, application method. The second utilised concrete poles and concrete stays.

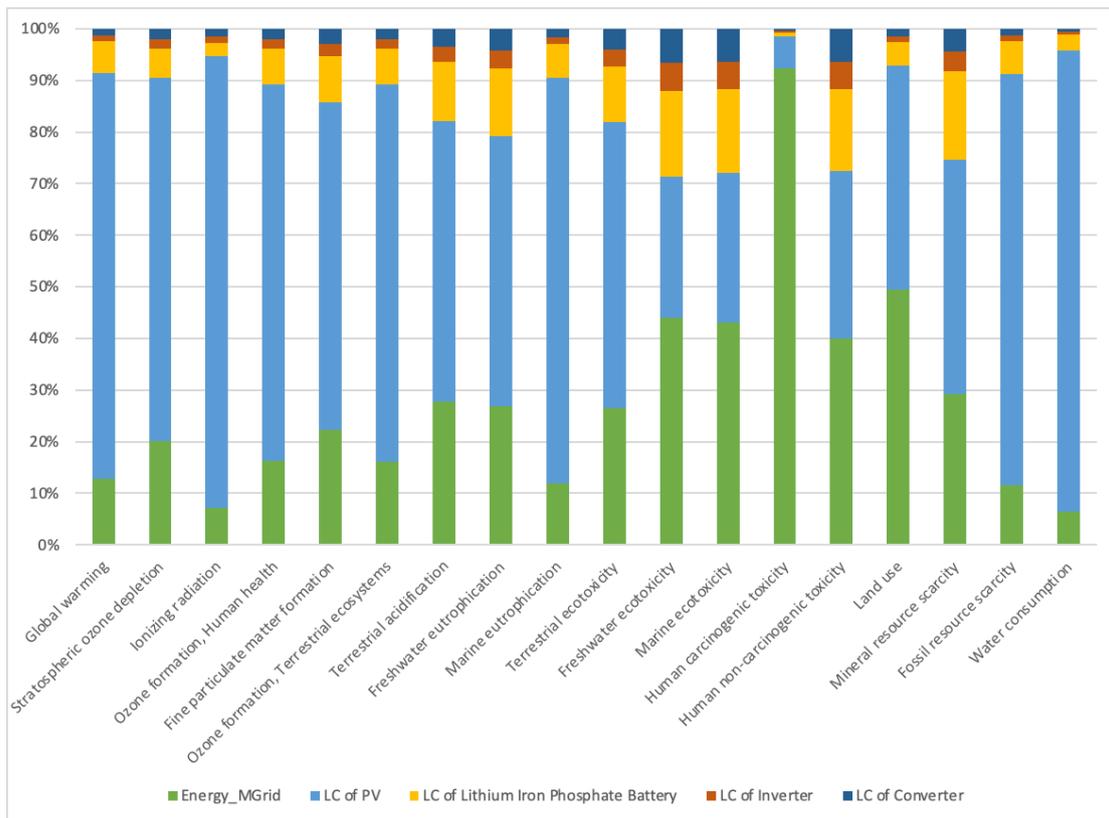


Figure 5. Contribution analysis to midpoint categories of main component groups to impacts from a mini-grid sized for e-cooking.

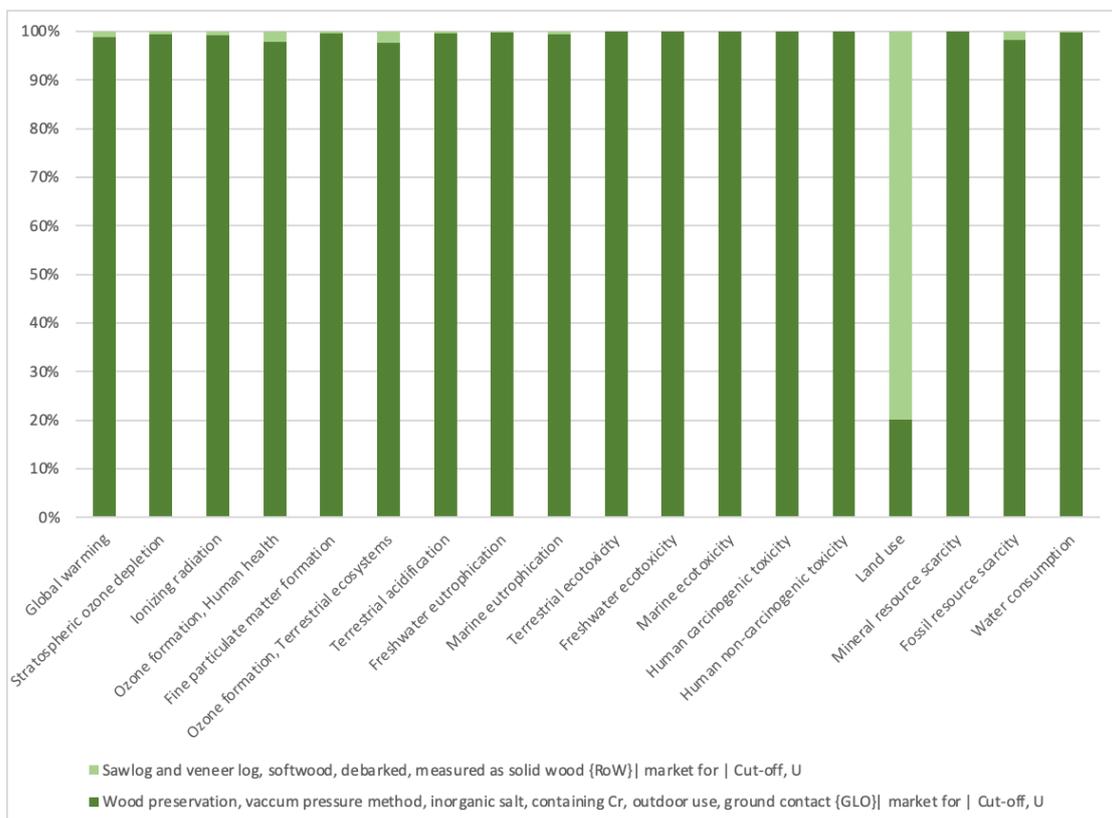


Figure 6. Contribution analysis to midpoint categories for the poles and stays.

Figure 7 shows the results of this comparison for environmental impacts. It is interesting to see that for all impact categories, apart from human carcinogens, the non-chromium wood preservative had a higher impact, suggesting that the chromium-based preservative would be better than a non-chromium-based preservative. Concrete had a lower contribution across all impact categories. The high values for global warming potential for the chromium-based and alternative preservative were found to originate in the manufacturing of the preservative itself. These are seen to be higher than those for the concrete, which is a known contributor to global warming through the CO₂ emissions in concrete production.

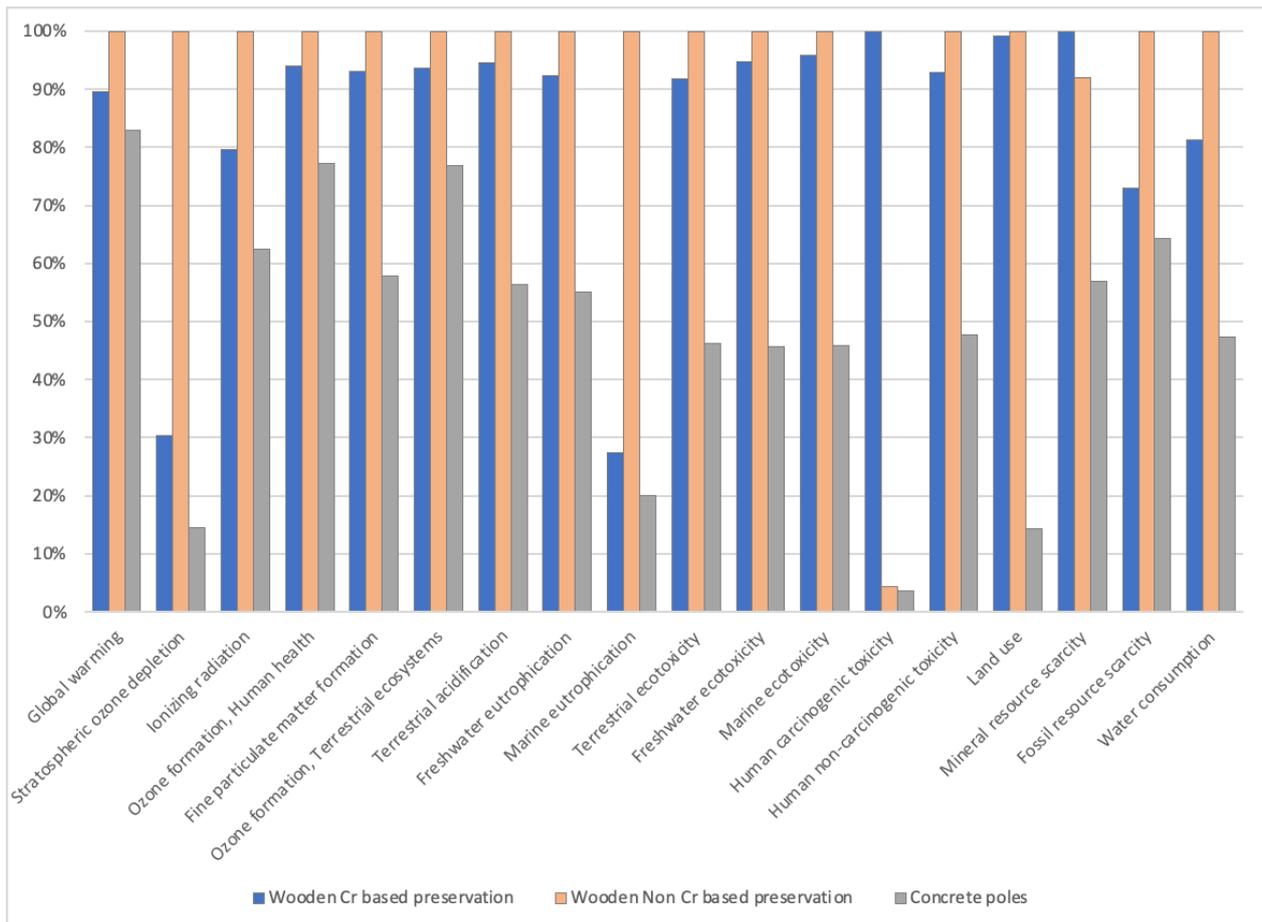


Figure 7. Midpoint category results for different pole and stay systems: wood with a chromium-based preservative, wood with a non-chromium-based preservative, and concrete.

When examining the endpoint impacts, Figure 8 shows the damage assessment for the three alternative systems. It shows that it was only for the human health endpoint that the chromium-based preservative contributed more; for both ecotoxicity and resource use, the non-chromium version contributed more. This again suggested that the non-chromium preservative would deliver a worse environmental outcome. When human health, ecosystem, and resource damages were normalized, however, a different picture emerged.

Figure 9 shows the normalized endpoint results and emphasizes that, despite the non-chromium wood preservative having a higher environmental impact in all impact categories except human carcinogens, overall it had a significantly lower impact for all endpoint categories. This result confirmed the overwhelming dominance of the human carcinogen impact category for human health, and it was this issue with the chromium-based preservative that was of concern.

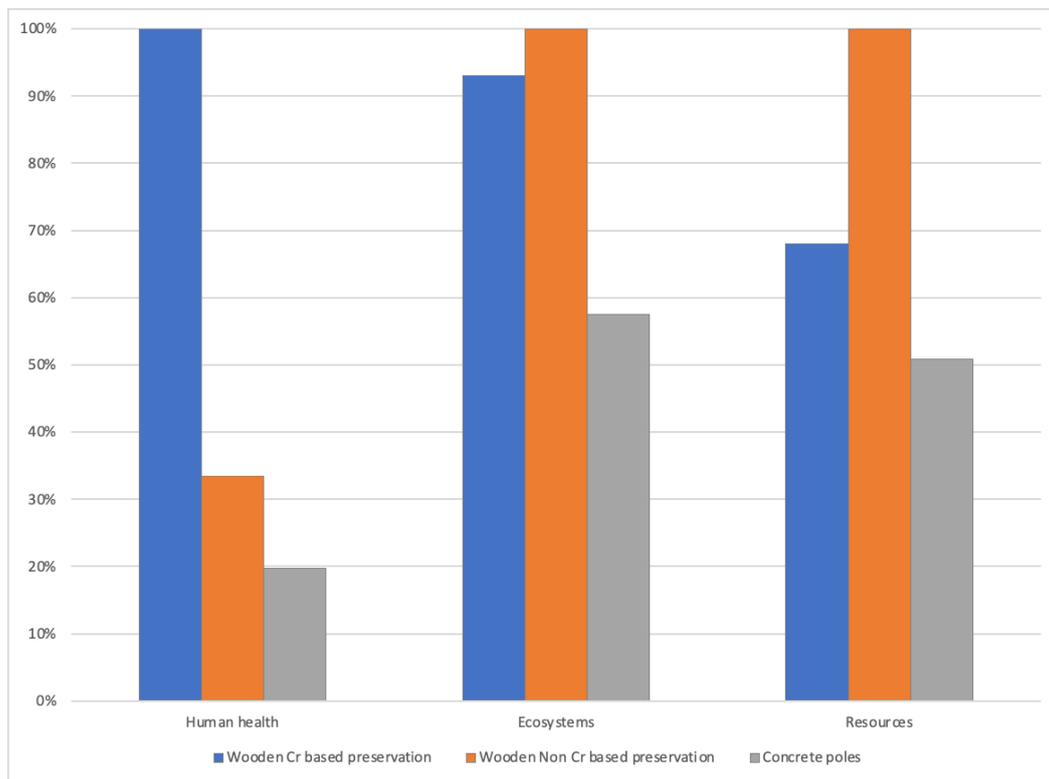


Figure 8. Endpoint damage assessment for three alternative systems for poles and stays.

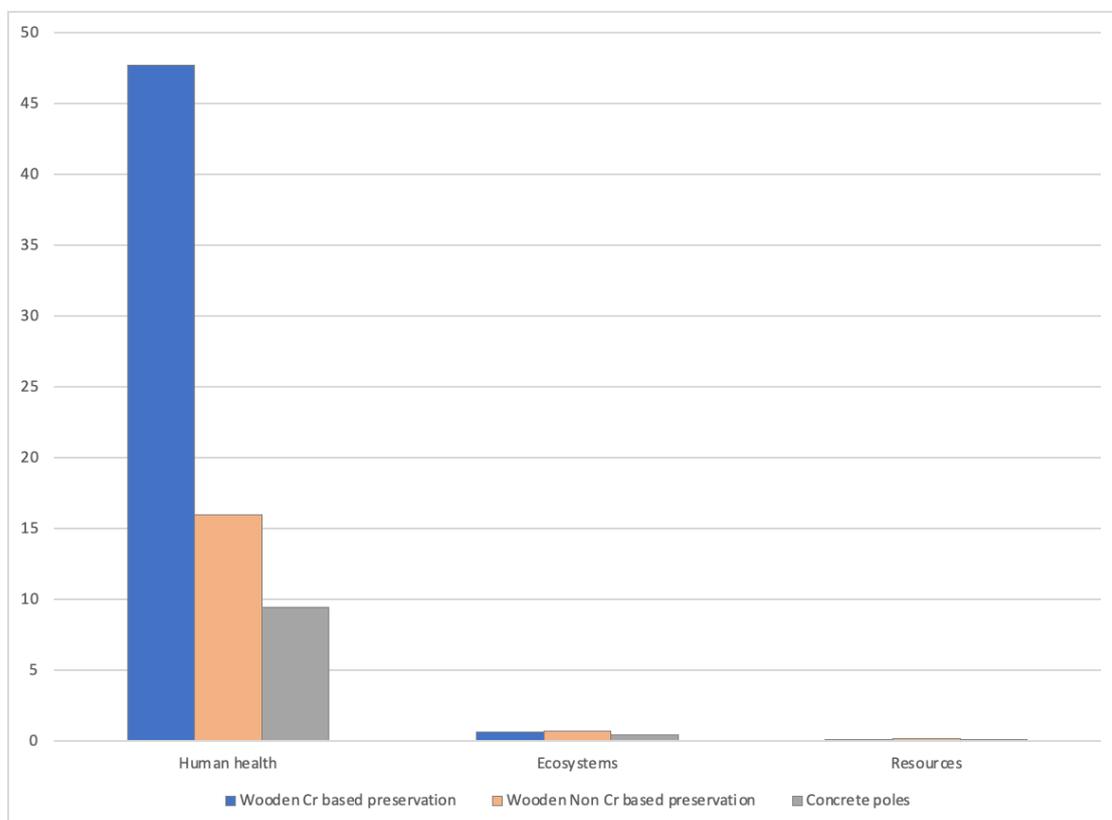


Figure 9. Normalised endpoint impact categories for the mini-grid (excluding power components) for three alternative poles and stays systems.

The results for the concrete poles and stays are shown in Figures 6–9, which have a lower environmental impact and contribute less to the endpoint impacts than either of the wooden pole options.

The results from this suggest that if possible, using locally made concrete poles and stays would deliver the greatest environmental benefit, but failing that, moving to a non-chromium-based preserving solution would deliver nearly as good a level of environmental improvement.

3.2.2. Cable Options

From Figure 4 it could be seen that within the cable sub system, the 16 mm² twin figure 8 cable with a copper core and the 50 mm AAC cable, with an aluminium core, stood out as having the greatest contribution to environmental impacts. In the majority of cases, the cables used have sheaths, made from flexible PVC. Analysis showed that it was the metals within the cables that contributed most to the environmental impact, and that the sheathing material(s) contributed a significantly smaller amount.

To reduce the impact from these cables, two opportunities exist. The first is to ensure that routing of the cable from the point of power delivery to each building is as efficient as possible, and the PV plant should be located as centrally as possible. The second opportunity is to investigate other cabling systems that could be used in place of the AAC and twin core cables. Developments in electricity distribution have created ABC cables (aluminium bundled cables), which deliver similar levels of performance as AAC and twin core cabling. Figure 10 shows the midpoint environmental indicators for the two alternative cabling systems. Since there was not much differentiation between the impacts for each system, it can be inferred that there were no major environmental gains to be made in changing the cabling system.

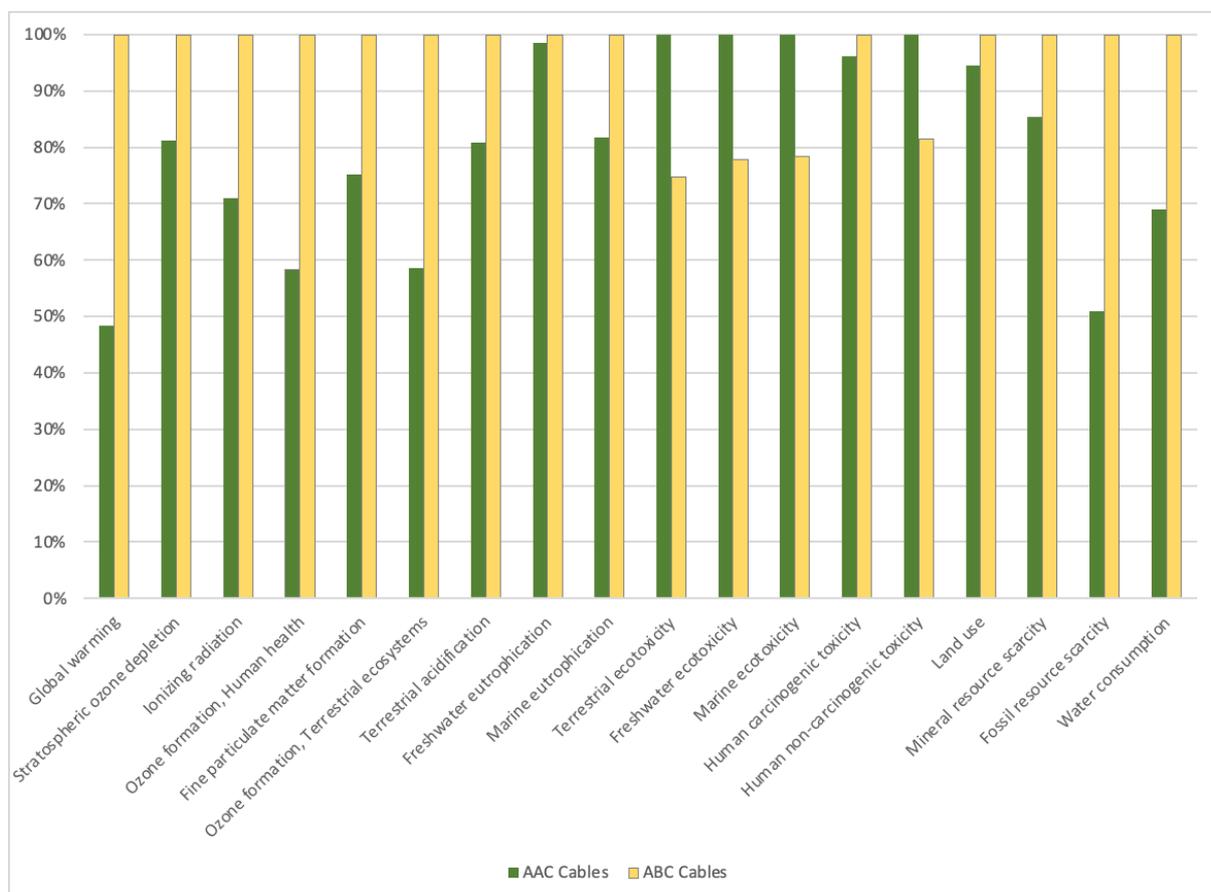


Figure 10. Midpoint category results for AAC and twin figure 8 cable with the ABC cabling option.

Figure 11 shows the normalised endpoint results for each system, where ABC cables were seen to have a marginally higher impact than the AAC cable system. The results from this analysis suggest that careful planning of the grid delivery system to minimise cable distance would deliver a much greater benefit than utilising a specific cable system, as each system contributes approximately the same impact.

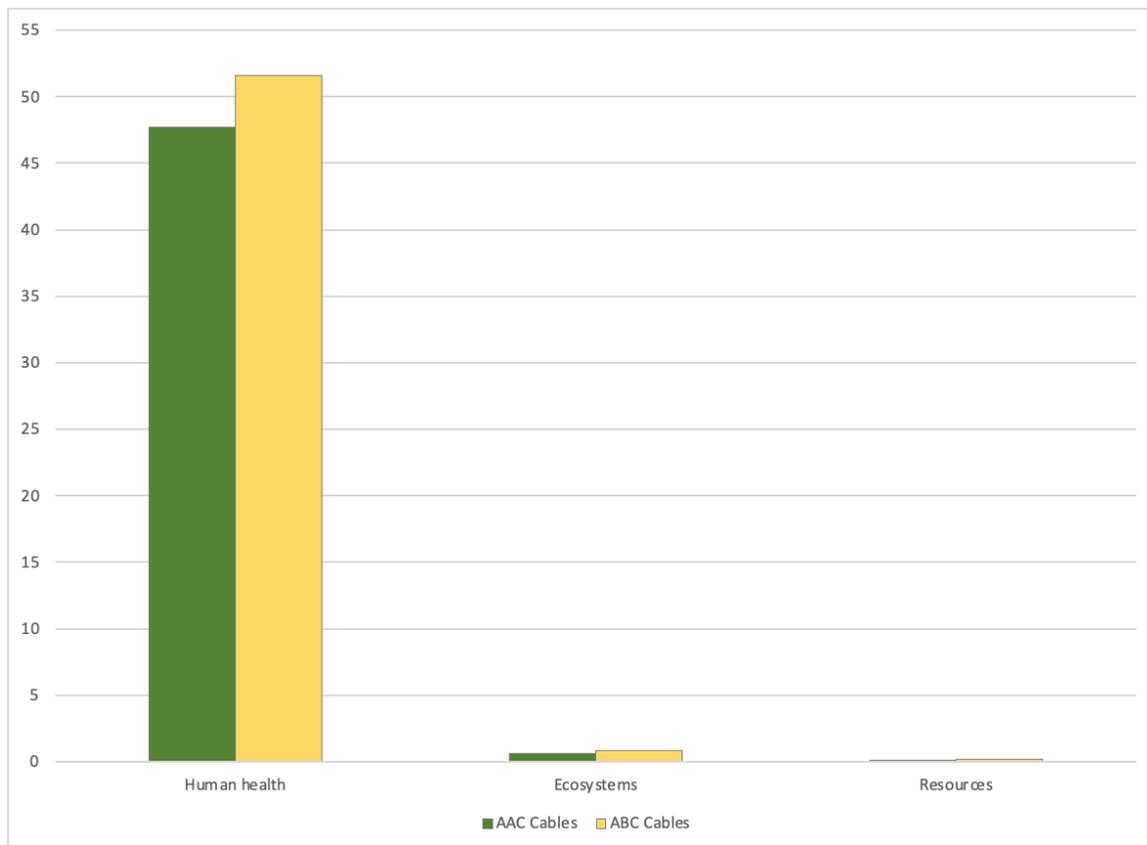


Figure 11. Normalised endpoint impact categories for the AAC cable system and ABC cable system.

3.2.3. PV Efficiency

From Figure 2 it was seen that, within the power delivery components, the PV panels were the greatest contributors to environmental impact by a considerable margin. The data used for the production of a single crystal PV panel were obtained from generic averaged industry data (single crystal PV panel, (GLO) from ecoinvent) and do not necessarily accurately reflect the specific processes used by the manufacturer listed in the bill of materials for the mini-grid. As a result, an assessment of the efficiency of the panels was carried out to evaluate how much the efficiency of the panels affected the overall environmental impact of the mini-grid system. The analysis evaluated the change in environmental impact that results from the efficiency of the panel increasing from 8% (the efficiency of the panels described in the ecoinvent Database for single crystal panel), to 16% (a current assessment of efficiency) to 25%, the optimum efficiency that has been suggested that could be obtained for this technology [22]. The increasing panel efficiency essentially equated to a reduction in the panel size required, with a corresponding reduction in materials needed and thus environmental impact. The chemistry and manufacture of the panel have been kept constant (as data on new materials and processing systems are not available), and it is recognised that this introduced some inaccuracies into the results.

From Section 3.1.2, it was shown that the function of the mini-grid, (lighting, phone charging, or lighting plus e-cooking,) will change the quantity of PV panels and storage required, shifting the greatest contribution from the non-power related components to the

PV panels. For these larger sized mini-grids, the sensitivity of the overall impact of the PV panels was more important, and there is considerable research ongoing to develop more efficient panels, with different (and perhaps more complex) chemistry. If improved PV panel efficiency does not significantly improve the overall impact of the mini-grid, the environmental benefits of its use may be negative or marginal for this application.

Table 2 shows the normalized endpoint impact on the mini grid for each of the three efficiencies. It can be seen that whilst there was a mild overall improvement as the efficiency increased, it was not significant, suggesting that the use of highly efficient PV panels may not improve the overall impact of the mini-grid very much. Thus, for this system, there was thus limited benefit in focusing effort and resources on developing higher efficiency panels, as the overall impact will not be reduced significantly.

Table 2. Normalised endpoint categories for different PV panel efficiencies.

	PV Efficiency 8%	PV Efficiency 16%	PV Efficiency 25%
Human Health	52.04	49.96	49.21
Ecosystems	0.88	0.76	0.72
Resources	0.19	0.15	0.13

Given that the PV panels were one of the main contributors to the environmental impact of the mini-grid, and that panel efficiency does not seem to significantly reduce overall impact, it was sensible to consider what other options could be employed to reduce the impact driven by PV panel use. One option would be to consider the use of an additional power generation system to minimise the number of panels required. Keddar [20] suggested that complementing a PV system with a diesel generator can reduce the number of panels needed (especially since electricity requirement fluctuates throughout the day, peaking at mealtime and in the evening) [23]. Table 3 below (taken from Keddar) [24] provides the sizing for the PV, battery, inverter, and converter needed to cover 100% of the electricity requirements from a mini-grid using only PV panels and using a PV/diesel generator combination.

Table 3. Sizing of power components for a PV mini-grid and PV/diesel generator combination min-grid.

	PV Only	PV and Diesel Generator
PV panel size, kWp m ² (assume 16% efficiency)	190 1032	81.1 440
Battery kWh	124	110.4
Inverter kW	20	20
Converter kW	24	21.6
Diesel Generator kW	n/a	28
Hours of Operation over 20 years	n/a	4300

Figure 12 shows the environmental midpoint impact categories for the mini-grid, comparing a system without a diesel generator and one with. It was seen that out of the 18 categories listed, the combined PV/Diesel mini-grid system contributed less to the impact categories in 16 categories.

Figure 13 shows the normalized endpoint impact results and demonstrates that the effect of adding a diesel generator was to deliver a reduced impact. Clearly, this reduced impact is dependent on how long the diesel generator needs to operate. Thus, a sensitivity analysis was undertaken to assess the implication of the generator operating for 4300 h in 20 years (approx. 30 min per day), 14,600 h (approx. 2 h per day), and 43,800 (approx. 6 h per day).

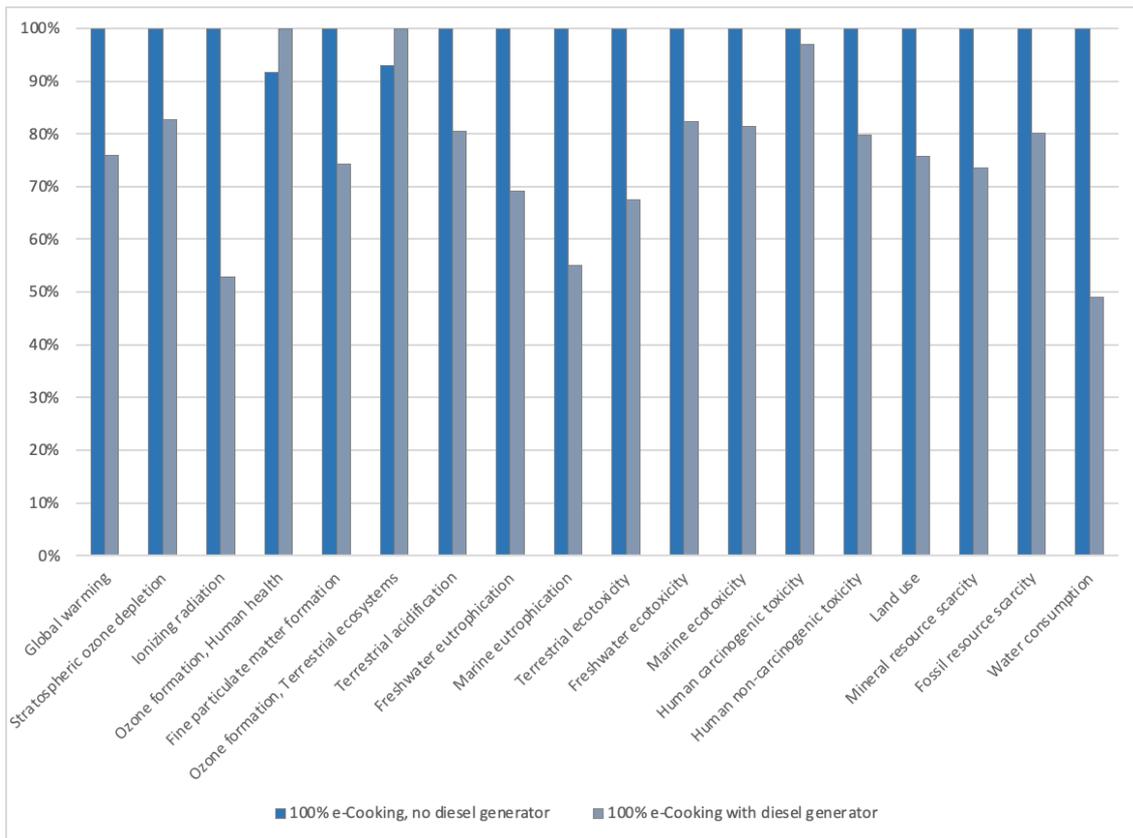


Figure 12. Midpoint category results for the PV mini-grid and PV/diesel generator mini-grid.

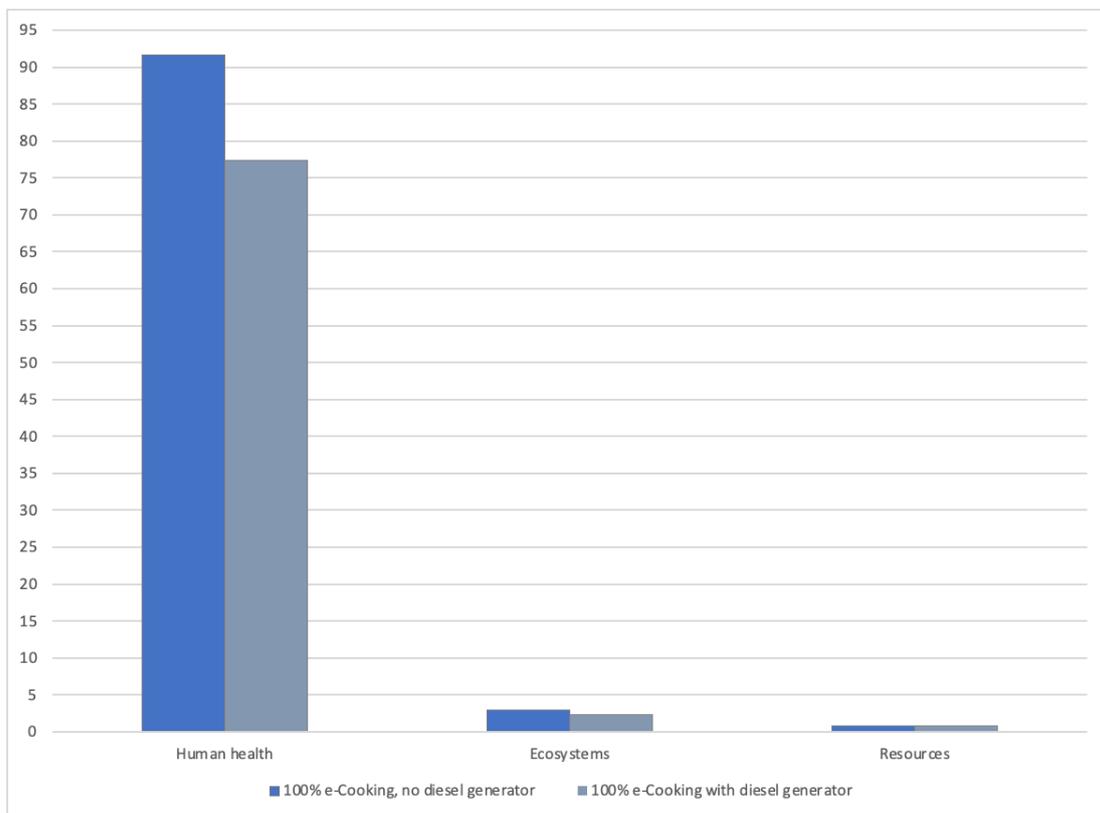


Figure 13. Normalised endpoint impact categories for a PV mini-grid and PV/diesel mini-grid.

Figure 14 shows the normalised endpoint impact category results. It can clearly be seen that, for this particular system, the benefits from using a diesel generator to supplement PV panels were only achievable when the diesel generator did not operate for more than about 2 h per day. This fits with the work by Keddar in that the diesel generator is used only when the system is at peak load, i.e., when many users require power at the same time, such as for cooking an evening meal. Above 2 h, the standalone PV system provided a more environmentally beneficial system.

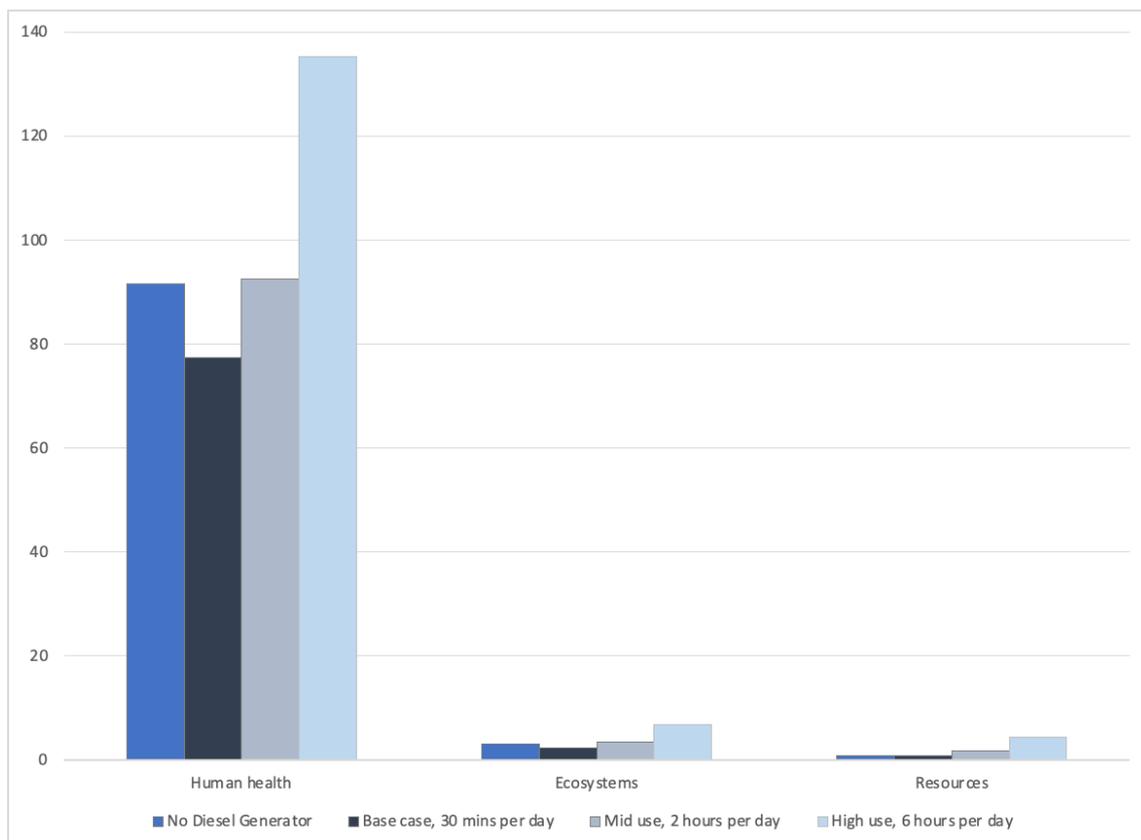


Figure 14. Normalised endpoint impact categories for the mini-grid with PV alone and mini-grid with PV/diesel generator operating for 30 min per day, 2 h per day, and 6 h per day.

4. Discussion

The environmental impact analysis for the mini-grid configuration and sizing for lighting, refrigeration, and phone charging suggests that the three areas of the mini-grid that show the highest impact scores were the PV panels, the wooden poles and stays, and cabling (specifically the AAC cable and the 16 mm² twin figure 8 cable).

The most effective action to reduce the environmental impact of a mini-grid was to consider the material used for the poles and stays. It has been shown that concrete may be a suitable alternative material, but analysis would be needed to determine if the transport of concrete poles (if not produced locally) would outweigh the benefits over locally sourced and preserved wooden poles. The assumption that a chromium-based preservative was used on the wooden poles and stays was as a result of research into the production of telegraph poles and the standards used in Africa [21]. This assumption dominated the impact results for the non-power based mini-grid components and drove the scenario assessment for alternatives. If local wooden poles were chosen, then a non-chromium-based wood preservation process would significantly reduce the impact on human health.

For cables, the analysis suggests there was little benefit in substituting the AAC cables for the alternative, so the most beneficial option was to reduce the quantity required. This is highly dependent on the local landscape and available space to install the mini-grid power components. Security concerns also need to be considered, to stop trespassing near the equipment that could cause injury or death.

The overall impacts of the mini-grid were not unduly sensitive to the efficiency of the PV panel. The specification of highly efficient panels may (depending on complexity and chemistry) actually increase the overall impact of the mini-grid. For the mini-grid sized for lighting, more efficient PV panels would reduce the overall environmental impact of the system less than changing the poles and stays. For the mini-grid sized for e-cooking, the opposite is true: improving the panel efficiency would lead to greater environmental benefits overall. In general, however, as improvements to the manufacturing technology for PV panels increase, it is appropriate to assume that the PV panel contribution will reduce over time.

When the power components are modified to accommodate increased expected loadings, it can be seen that the main contribution to the environmental impact switches to the PV system, away from such items as poles/stays and cables. For mini-grids with this level of power requirements, it would be useful to consider combining PV panels with a diesel generator. The diesel generator is manufactured mainly from steel, a relatively low environmental impact material. The production of diesel itself produces more emissions, but it is the use of the diesel generator and associated emissions of combustion products that are the drivers of the impacts from the use of the diesel generator in supporting a PV mini-grid. Whilst it may seem counterintuitive that the combination of a diesel generator can reduce the environmental impact of a PV-powered mini-grid, this analysis suggests that the reduction in panels required (and the environmental impact associated with those) outweighs the environmental impact associated with the manufacture of a diesel generator and combustion of fossil fuel. Sizing the PV panels to meet the peak power demands of the mini-grid may not be sensible as it would require more than 13 times the PV panel area (see Table 1), and the inclusion of a diesel generator to provide the extra power at peak times is a simple solution. The diesel generator also removes the redundancy of panels not needed outside of peak loading. Essentially, the PV provides the base load for the mini-grid, and the diesel generator is used for peak load only. However, this only holds true when the generator is operated for less than 2 h per day. Should peak loading require the generator to operate for more than 2 h, the benefits are eradicated, and a system utilizing appropriately sized panels and battery used instead. This example highlights the need for careful sizing of mini-grid systems and that the sizing will be a key factor in determining the most appropriate combination of panels, batteries, and supporting equipment.

There are other issues that should be considered in the case of a combined PV/diesel powered mini-grid. There is potential for locally produced biofuel that could reduce the impact of the generator further or increase the hours that it could operate. However, since the main impacts result from the combustion of the fuel, rather than the production of diesel, the benefits may be marginal. This would require significant further analysis and will depend heavily on the biomass system used to create the biofuel. There are also benefits to having a generator that can be switched on quickly if there is a need to provide power at short notice or to compensate for when local weather conditions may have reduced the power available from the PV/battery system. These social benefits have not been factored into this environmental analysis.

Significant assumptions have been made for this study relating to the lifetime of components. As one of the key impact generators for mini-grids, the effect of the lifetime of the PV panels is worth exploring. A reduction in PV panel life would increase its contribution to total impact (assuming the mini-grid life remained at 20 years) and may (if sufficiently reduced) overtake the poles as the main issue of concern for all sized grids, not just those sized for e-cooking or higher loads. This would in turn suggest that (a) there is a driver for a more robust PV panel design as well as a more efficient design and (b) that

diesel generators may be appropriate for use in a supporting capacity for less powerful mini-grid applications. In addition, the cost implications for frequent PV panel replacement could make mini-grids financially less attractive. By contrast, an extension to PV panel life to match the life of the poles and overhead cables would result in an increase in the small impact from batteries and inverters. The poles and cables are already assumed to last longer than the mini-grid (30 and 25 years, respectively). Any reduction in their lifespan (perhaps due to weather conditions or damage by animals) would increase their existing large contribution to the total impact. The batteries and inverter have a predicted life of 10 years. Increasing or decreasing this life span would affect their small contribution to the total impact, but it is unlikely to cause them to become an issue of concern.

Supplementary Materials: Supplementary Materials are available online at <https://www.mdpi.com/article/10.3390/en14144227/s1>.

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Appendix A

Items coloured green are included in the mini-grid model; the remainder have not been modelled. Details of how each item was modelled in Simapro can be found in the Supplementary Materials.

Table A1. Bill of materials for the mini-grid.

Malawi Mini-Grid BOM				
Section	Description	Unit	Qty	Comments
Power Components				
	PV panels	m ²	76.6	14.1 kWp at 16% efficiency. Modified from ecoinvent as a single crystal PV panel (GLO), market, Cut off U
	Battery	kWh	41.1	Lithium Iron Phosphate (LIB)
	Inverter	kW	5	Taken as multiples of the 2.5 kW inverter from ecoinvent, (GLO) Cut off U
	Converter	kW	11.6	Taken as multiples of 2.5 kW inverter from ecoinvent, (GLO) Cut off U
	Shipping container	m	1	Standard 20 ft container, Dimensions 5.89 × 2.35 × 2.36
Poles				
	9 m poles 140–160 mm	ea	75	Buried 1.5 m deep, no concrete
	Stay blocks	ea	50	Standard wooden block with hook, 1 m deep
Cables/Conductors				
	50 mm AAC conductor	m	6000	Aluminium core
	16 mm twin figure 8	m	1000	Copper core
	2 × 16 mm armored cable	m	80	From generation to first poles, 2 runs
	Stay wire 7/12	m	500	Steel
	4 mm ² single core cable red 100 m	ea	2	Assume a copper core

Table A1. Cont.

Malawi Mini-Grid BOM				
Section	Description	Unit	Qty	Comments
	4 mm ² single core cable black 100 m	ea	2	Assume a copper core
	2.5 mm ² single core cable red 100 m	ea	8	Assume a copper core
	2.5 mm ² single core cable black 100 m	ea	8	Assume a copper core
	2.5 mm ² single core cable green 100 m	ea	10	Used for earthing
	1.5 mm ² single core cable red 100 m	ea	30	Assume a copper core
	1.5 mm ² single core cable black 100 m	ea	15	Assume a copper core
	1.5 mm ² single core cable green 100 m	ea	15	Assume a copper core
	Bare copper cable	ea		
Overhead Materials				
	Bobbin insulator	ea	100	Ceramic
	D-Iron, 2 bolts, 2 nuts, 2 washers, complete with bobbin	ea	110	60 for hoses, 50 for use with poles with angles or junctions
	M16 × 200 GI bolt, nut, washer	ea	48	For the D-iron through pole
	M16 × 260 GI bolt, nut & washer	ea	100	For the bobbin through the pole
	LV Stay insulator	ea	100	Ceramic
	M16 Stay rod complete	ea	50	Steel
	Guy grip	ea	110	Steel
	PG clamp 50 mm AL/AL	ea	150	Overhead line
	PG clamp 50 mm AL/CU	ea	150	House connections
	Cable lug 16 mm	ea	240	Steel
Distribution Board				
	4-Way distribution board		60	
	DB space covers	ea	120	
	63A 2-Pole mainswitch RCCB 30mA	ea	60	2 poles confirmed
	5A MCB	ea	60	
	Earth rod 4ft	ea	60	
PVC				
	20 mm PVC conduits	bundle	18	25 pieces in a bundle
	20 mm PVC couplings	ea	2200	
	20 mm PVC nipples	ea	2000	
	20 mm PVC saddles	ea	800	
	Round boxes	ea	900	
	Round box covers	ea	700	
	PVC boxes 175 × 150mm	ea	60	
	PVC boxes 75 × 75mm	ea	240	

Table A1. Cont.

Malawi Mini-Grid BOM				
Section	Description	Unit	Qty	Comments
Electrical Fittings				
	Batten lampholder	ea	128	Ceramic
	LED bulb 5 W	ea	128	Indoor light bulbs
	Wall glass fitting	ea	56	Outside light bulb holder
	LED bulb 10 W	ea	56	Outside light bulb
	Double sockets	ea	60	
	Switch: 1 gang 1 way	ea	184	Every light gets a 1 gang one way switch—option for 2 gang below
	Switch: 2 gang 2 way	ea	30	Enough for half the houses if needed
Consumables				
	Self-tapping screws 1" 8G for PVC boxes	packet	10	
	Insulation tape	roll	10	
	Hacksaw blades	ea	10	
	2" nails	kg	4	

Table A2. Expected lifetimes of mini-grid components.

Item	Lifetime, Years
Minigrid	20
PV panel	20
Battery	10
Inverter	10
Converter	10
Shipping container	25
Poles and stays	30
Overhead equipment	20
Heavy duty cabling	30
Light duty cabling	25
PVC components	15

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