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The lighting transition in rural Africa — From kerosene to battery-powered LED and the emerging disposal problem☆

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ABSTRACT

People without electricity access, numbering today more than 500 million in rural Africa alone, have been using dim and sooty kerosene lamps and candles for their lighting purposes for decades. In the present paper, current lighting usage patterns are systematically assessed using detailed new survey data from seven countries across Sub-Saharan Africa. The data makes evident that a transition has taken place in recent years, both unnoticed by and without external support from governmental or non-governmental organizations: the rural population without electricity in Africa has replaced kerosene lights and candles by simple, yet more efficient and cleaner LED lamps powered by non-rechargeable batteries. Nevertheless, we also show that the discharged batteries are generally disposed of inappropriately in latrines or the nature. The toxic content of many dry-cell batteries and their accumulation at local litter hotspots may have harmful repercussions on health and the environment. We conclude by suggesting that rapid action is needed to, first, install an effective monitoring system on batteries that enter the continent and, second, put in place an appropriate waste management system.

Introduction

In rural Africa, over 500 million people – some 85% of the population – lack access to electricity (World Bank/IEA, 2015). They have to rely on traditional energy sources to meet their daily energy demands for simple services such as cooking, access to information, and lighting. To provide basic lighting services, people have been using candles or kerosene in wick lamps and hurricane lanterns for decades. The lighting quality of these sources is low. Moreover, kerosene usage is associated with soot emissions, which may impair lung function and increase infectious illnesses like tuberculosis, as well as the likelihood of asthma and cancer (O'Sullivan and Barnes, 2007; Lam et al., 2012a; Epstein et al., 2013). Besides these adverse health effects, the emitted carbon dioxide and black carbon negatively affects the climate (Lam et al., 2012b; UNEP, 2012) and high heavy metal concentrations add to the harmful pollution profile of kerosene (Akpoveta and Osakwe, 2014).

Still today, kerosene is largely seen as the dominant fuel in non-electrified areas among national governments and donor agencies active in the electrification sector.[1] Several initiatives exist that try to improve access to electric lighting technologies in order to eliminate kerosene use in these households (see for example Global LEAP, the *Lighting a Billion Lives* initiative, World Bank's *Lighting Global* platform, and LuminaNET). One obvious solution is facilitating grid electricity access, but also less cost-intensive options such as electric lighting powered by small Solar Home Systems (SHS) and quality-certified portable solar lamps are increasingly promoted (see, for example, Dutt and Mills, 1994 and Harish et al., 2013 for descriptions of this lighting transition over the past decades). Most of these solar lamps are equipped with light-emitting diodes (LED) that, over the last years,

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[1] As will be shown in this article, this is not necessarily the case anymore. One reason for this misperception is that official censuses do not account for LED lights that are powered by non-rechargeable batteries as a lighting option. The censuses are either not recent enough or do not differentiate between LED lamps powered by non-rechargeable batteries and other lighting options such as rechargeable lamps. See, for example the latest General Census of the Population and of Housing, Agriculture and Livestock in Senegal (ANSD, 2014) or the Lighting Africa Nigeria Consumer Insights Market Study (2013).

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have decreased massively in production costs with simultaneous increases in efficiency and lighting output and thus reductions in the consumption of energy (US DoE, 2012; McKinsey and Company, 2012).

In this paper, new evidence is presented suggesting that kerosene is often not the baseline situation in non-electrified areas in Africa anymore. The LED technology is not only enabling high-quality solar lamps to become affordable: also simple LED lamps powered by non-rechargeable dry-cell batteries have become accessible in most parts of the world without any external intervention from governmental or non-governmental organizations. Depending on number and quality of LEDs, lighting output of these products may come close to high-quality products promoted by the initiatives mentioned above like *Lighting Global* or *Global LEAP*. The downside of the massive increase in the usage of those LED lamps running on non-rechargeable batteries is a soaring consumption of dry-cell batteries in non-electrified areas. Dry-cell batteries contain heavy metals, which compromise people's health and the environment (Lighting Global, 2011; Järup, 2003).

Against this background, we systematically assess current lighting usage patterns of households without electricity and disposal habits of dry-cell batteries using detailed new rural household survey data.[2] The data has been collected as part of evaluation studies on the impacts of electrification projects between 2006 and 2014 in seven countries across Sub-Saharan Africa. The data underlying this analysis thus has three features that make it particularly useful for tracing the trend from traditional lighting sources to battery-powered LED lamps. First, it covers the time period in which this transition emerged. Second, it includes a decent sample of countries from both East and West Africa with different socio-economic and demographic backgrounds. Third, it contains rich information tailored to this topic given that it has originally been collected in electricity access evaluations with a clear focus on energy and lighting usage.

The transition to simple LED lighting powered by non-rechargeable batteries in non-electrified Africa exposed in the present paper provides insightful lessons on technology adoption in a resource-poor developing country context. Except for mobile phones, no other technology has made such deep inroads to the periphery of the continent without any external support. From a policy perspective, this is of importance for the design of the Sustainable Energy for All initiative, the UN-led global effort to reach all hitherto non-electrified regions with electricity by 2030. Even more importantly, our findings on escalating improper battery disposal strongly suggest different fields of intervention for both academia and policy, namely battery sales monitoring, health and environmental impacts and end-of-life battery management systems.

The remainder of this paper is organized as follows: in Section 2, we briefly introduce the data underlying this research. Section 3 delineates the lighting technology transition towards LED. This transition is then examined based on the general technology adoption literature and technology-specific economic and technical factors in Section 4. Section 5 shows the dry-cell battery disposal behaviour of rural households in the surveyed regions and summarizes the existing knowledge on environmental and health hazards related to this. Section 6 concludes.

The data

In general, cross-regional information on energy and lighting usage is hardly existent. The typical datasets available for multiple African countries – the Demographic and Health Surveys (DHS) or the Living Standard Measurement Studies (LSMS), for example – do not systematically contain information on lighting usage.[3] For the research question underlying this paper, we therefore rely on own data collected between December 2006 and December 2014 in Benin, Burkina Faso, and Senegal in Western Africa and Mozambique, Rwanda, Tanzania, and Zambia in Eastern Africa.

The data stem originally from impact evaluation studies commissioned by development agencies such as Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Netherlands Ministry of Foreign Affairs to evaluate the effect of their electricity access interventions on the socio-economic living conditions of the interventions' target populations. The interventions ranged from promoting pico-solar photovoltaics (PV) lamps to centralized grid extension projects. The surveys were mostly baseline surveys for upcoming projects, where the majority of households usually did not have any electricity source at their disposal. These surveys are used to assess lighting technology choices of non-electrified households, which is the central analysis of the present study. Of course, also in regions that are not systematically electrified, some households possess individual electricity sources, like solar systems, car batteries, and gensets. Households with these electricity sources are excluded when analysing the lighting transition among non-electrified households. In some countries, we additionally have data on regions with ongoing energy access interventions. Here, we observe also households who benefited from the respective energy access intervention. These households are used to analyse whether traditional lighting technologies are still used if households have access to modern electricity. Most surveys cover between ten and 50 rural villages from different areas of the countries. Total sample sizes range between 150 and 1500 interviews per survey. As can be taken from Table 1, the data stems from 11 surveys with an aggregate of over 9500 household observations. The table also indicates the sample selection process and location: The surveys are generally representative for the areas in which they were conducted, usually exemplary for the rural settings in the respective country. None of our surveys was conducted in peri-urban areas or the outskirts of cities.

In collecting the data, a lot of attention was dedicated to the way people use lighting as one major impact transmission channel of electrification (e.g. through night-time activities like home studying; see van de Walle et al., 2015 or Torero, 2015). The actual study implementation in all countries took place in cooperation with local specialized survey organizations. For more details on the survey methodology applied in the individual studies and the different data sets, the interested reader is referred to the published reports and peer-reviewed publications referenced in the right column of Table 1. Non-published reports and all data sets are available from the authors upon request. The data has furthermore been used in Peters and Sievert (2016) to give an overview on socio-economic impact potentials of rural electrification in Africa. None of the studies assesses in any detail the lighting transition covered in this article.

Lighting transition towards LED

Mankind has made dramatic transformations in the cost and provision of artificial illumination, starting with light from fire, over tallow candles (i.e. candles made from moulded animal fat) and ending at modern electric lighting of our times (see for example Fouquet and Pearson (2006) who illustrate this transformation for Great Britain). In Africa, this last step has not been made in many regions, since access to grid-based electricity is widely lacking. The most comprehensive set of currently available information on lighting usage in sub-Saharan Africa

[2] This paper does not focus on disposal of rechargeable batteries that are often built into solar lamps or rechargeable batteries used with SHS.

[3] The DHS surveys only elicit whether the interviewed household has access to electricity. No question is asked on the usage of lighting (The DHS Program, 2017). Among LSMS studies conducted in Sub-Saharan Africa since 2006, only four addressed lighting, one through a binary question on different lighting energy sources (Uganda) and the other three asking for the major lighting energy source (Ethiopia, Malawi and Tanzania, see World Bank, 2017).

Table 1
Studies and surveys used in this paper.

Country	Survey date	Sample size	Share of HHs with electricity	Sample selection	Location	References
Benin	2007	419	31% grid electricity, 24% other	14 villages, 12 of which selected for electrification and 2 electrified comparison sites	Average rural area, partly remote villages, partly well connected.	Peters and Harsdorff (2010)
Burkina Faso	2010 2012	1200 922	26% solar panel, 7% other 45% solar panel*	40 villages representative for Kénédougou province	Rural area with slightly above-average income opportunities due to cotton farming	Bensch et al. (2013a)
Mozambique	2008	140	33% solar panel	1 village selected by for pico-hydro project	Remote rural area with above-average income opportunities due to gold mining	Bensch et al. (2010)
Rwanda I	2007/08	633	30% grid electricity*	12 villages, 5 of which selected for electrification and 7 electrified comparison sites	Average rural areas	Bensch and Peters (2010); Bensch et al. (2011a)
Rwanda II	2011 2012	307 307	none 42% pico-solar PV*	15 villages, random sample in the country's off-grid periphery	Very remote rural areas	Grimm et al. (2017); Grimm et al. (2013)
Rwanda III	2011 2013	1486 1318	1% solar panel; 2% other 34% grid electricity*; 3% solar; 2% other	50 villages, representative sample of rural areas with electrification activities	Representative for rural Rwanda	Peters et al. (2014); Lenz et al. (2016)
Senegal I	2009	797	40% solar panel*; 2% other	41 villages in Peanut Basin and Casamance selected by electrification project	Remote rural areas	Bensch et al. (2013b)
Senegal II	2011	482	18% solar panel; 5% other	21 villages in Peanut Basin and Casamance selected by electrification project	Remote rural area; partly above average soil fertility	Bensch et al. (2011b)
Senegal III	2014	390	16% solar panel, 2% pico-solar PV; 5% other	10 villages in Thiès area selected by electrification project	Average rural area, relatively well connected, only 100 km away from capital Dakar	Langbein et al. (2014)
Tanzania	2014	1000	15% solar panel; 16% pico-solar PV; 10% other	Two villages selected by electrification project at Lake Victoria	Remote villages, above-average income opportunities due to fish production	Bensch et al. (2017)
Zambia	2011	180	34% solar panel; 17% other	Two villages selected by electrification project located close to planned small hydro power plant	Remote rural area with above-average incomes due to large farming and tourist facilities	Neelsen et al. (2011)

Note: *Asterisks refer to electrification rate figures that have been boosted by donor-driven interventions. “Other” electricity sources include gensets, car batteries, and biodigesters. Some households own multiple electricity sources.

(UNEP/GEF, 2013; IFC, 2011) shows that in 2008 households without electricity still used mainly kerosene and candles (see Table 2).

Households are considered as electrified if they have access to electricity in the form of grid connections, generators, SHS, and smaller-sized plug-and-play pico-solar PV systems (see also OECD/IEA, 2010). In 2008, LED technology was not yet widely available and batteries still comprised a negligible share of two to 14% of the households' total lighting expenses. Except for Zambia, where households almost exclusively used candles, national average monthly consumption figures ranged between 5 and 9 l of kerosene, 3 and 13 candles and 0.8 to 1.2 batteries.

Table 3 shows data on lighting sources used by non-electrified households originating from our more recently conducted surveys. Because the underlying surveys were conducted in rural areas rather distant from urban agglomerations, our LED usage rates tend to underestimate the country-wide usage rates, whose calculation would require including non-electrified areas closer to the existing infrastructure and urban centres.[4]

The surveys we conducted until 2008 confirm the UNEP data presented in Table 2. The surveyed households in Benin, Mozambique, and Rwanda solely used the traditional lighting sources kerosene and candles. Battery-run torches were available in some of the surveyed communities (not shown in the table), but battery consumption was prohibitively expensive since efficient LED light was not yet available. In all surveys conducted after 2009, we observe sizable usage rates for LED lights powered by non-rechargeable dry-cell batteries. In particular, in Western African countries dry-cell batteries have replaced kerosene and candles to a very large extent.

For countries in other African regions, traditional lighting sources are still prevalent, but on the decline. In Rwanda, for example, kerosene and candles are still widely used, but dry-cell battery LED usage is increasing steadily. This can be taken not only from the binary usage indicators but also from the shares in total lighting hours shown in the right column of the table. It seems that lamps run with non-rechargeable batteries increase their share in total lighting over time in all countries, even though part of this observation may be confounded by inter-country differences that exist at any point in time. Complementary data on people's satisfaction with the different lighting types shows that people are more satisfied with battery driven lighting sources: in surveys with higher usage levels of lamps powered by non-rechargeable batteries, interviewees expressed a higher level of satisfaction (not shown in the table).

Finally, it has to be noted that lighting is not the only purpose non-rechargeable batteries are used for in the surveyed households. Radios are another main battery consumer. In line with the higher prevalence

Table 2
Lighting consumption among households without electricity in selected sub-Saharan African countries in 2008.
Source: based on UNEP/GEF (2017).

	Population without electricity, in %	Share in total lighting cost among non-electrified households, in %		
		Kerosene	Candles	Batteries
Benin	75	87	5	7
Burkina Faso	85	81	15	4
Ethiopia	83	77	8	14
Ghana	40	90	4	6
Kenya	84	89	4	6
Mozambique	88	81	15	4
Rwanda	95	83	13	4
Senegal	58	17	81	2
Tanzania	86	78	17	5
Zambia	82	17	81	2

Note: The data for the different countries is modelled by the UNEP/GEF en.lighten initiative based on technology mix and price data from Ethiopia, Ghana, Kenya, Tanzania, and Zambia (UNEP/GEF (2013)). Households are considered as electrified if they have access to electricity in the form of grid connections, generators, Solar Home Systems (SHS), and smaller-sized plug-and-play pico-solar PV systems.

[4] Usage rates of SHS and pico-solar systems have also increased considerably over time, as can be taken from Table 1.

Table 3
Lighting consumption of the population without electricity in our survey samples.
Source: own data.

		Population without electricity, in %	Lighting usage rates among non-electrified households, in %			Share in total lighting hours, in %	
			candles	kerosene	batteries	fuel-run lamps	lamps run with non-rechargeable batteries
Benin	2006	54	12	100	98	99	0
Burkina Faso	2010	67	0	29	100	32	63
	2012	49	0	10	99	22	76
Mozambique	2008	51	87	57	8	99	0
Rwanda I	2007/8	67	11	81	15	100	0
Rwanda II	2011	100	24	57	50	63	36
	2012	58	23	45	44	58	42
Rwanda III	2011	97	26	65	24	82	15
	2013	62	32	39	45	73	26
Senegal I	2009	58	44	18	99	35	65
Senegal II	2011	78	21	9	97	11	89
Senegal III	2014	79	0	1	98	2	95
Tanzania	2014	64	8	60	66	47	51
Zambia	2011	53	69	16	82	56	43

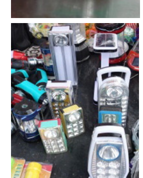
Note: Households are considered as electrified if they have access to electricity in the form of grid connections, generators, Solar Home Systems (SHS), and smaller-sized plug-and-play pico-solar PV systems.

of battery-based lighting in our West African study countries, around 80% of non-rechargeable battery consumption accrues to lighting there, whereas this share averages slightly below 50% for the more recent surveys in the East African countries.

So far, we have handled LED lights as a homogenous lighting source. Yet, LED lights are used in different shapes ranging from hand-crafted lights with one diode to fairly bright ready-made multi-diode lamps. In Table 4, we show the typical LED lamps we have encountered in the different countries, next to classical kerosene lamps and pico-solar PV lamps that tend to use higher-quality LEDs and do not run on non-rechargeable batteries. Since pico-solar PV lamps are normally considered as a modern electricity source and require considerably higher investments, we do not analyse pico-solar PV lamp adoption here in detail. We differentiate between three different LED lamp types powered by non-rechargeable batteries: hand-crafted LED lights, simple LED flashlights, and ready-made battery-run LED lamps. Ready-made LED lamps exist in various forms. Some of them, for example, mimic the appearance of hurricane lamps and may have several dozens of diodes. Hand-crafted LED lights are especially used by the poorest households. These are typically one or two diodes that are removed from ready-made torches or lamps and connected by wires to dry-cell batteries. In Rwanda, for example, they are then wrapped in banana leaves in a makeshift manner and installed at room walls or on a stick that can be carried around.

Table 4 furthermore displays the brightness performance of lamps currently available on the African market in terms of their luminous flux measured in lumen, the total intensity of emitted visible light. It can be seen that the lighting output of LED lamps may vary heavily, which depends on the number of diodes as well as on the performance of diodes and dry-cell batteries. Hand-crafted torches typically use a small number of inefficient diodes with low-capacity non-rechargeable batteries and thus barely provide more light than a candle or a tin wick lamp, i.e. around 10 lm. Ready-made LED lamps with several dozen diodes can easily emit as much as 50 to 100 lm and more. For comparison, a 12 W electric compact fluorescent lamp (CFL), the typical energy saver lamp used in grid connected rural households, emits around 600 lm. This points to a gap with grid-powered lighting, although the difference in illuminance is lower, since LED lamps emit

Table 4
Product range of typical portable lighting devices.
Sources: Luminous flux data comes from O'Sullivan and Barnes (2007), Mills (2003), Adelmann (2014), Grimm et al. (2017), Lighting Global (2015) and own market research.

	Tin wick lamp	Glass cover hurricane latern	LED lamps powered by non-rechargeable batteries			Pico-solar photovoltaics LED task lamp
			Single or multiple diode hand-crafted light	LED Flashlight	Ready-made battery-run LED lamp	
			 		 	
Energy carrier	Kerosene	Kerosene	Dry-cell batteries	Dry-cell batteries	Dry-cell batteries	Solar (stored in rechargeable batteries)
Luminous flux (in lumen)	11	8–82	~10	10–150	10–150	25–200

more directed light compared to incandescent light bulbs and energy savers, which are designed to provide ambience light.

Economics of LED adoption

The question of why the poor adopt a certain technology and why they do not is of utmost importance for the successful design of development policy. The literature highlights many prominent examples of technologies that are not easily adopted by the population even though they are perceived as highly beneficial for the poor: insecticide-treated bednets (Cohen and Dupas, 2010), improved cookstoves (Bensch et al., 2015; Lewis and Pattanayak, 2012), water purification (Ashraf et al., 2010), and fertilizers (Duflo et al., 2011), to name but a few. These technologies require small investments, which seem to be clearly worthwhile from an outsider's perspective, because the pay-off is high. Research that explores the observed low adoption rates suggests that consumers often do not invest because they lack the information about the benefits, they have a low appreciation for benefits that materialize only in the long run, they are unwilling or unable to cover the investment costs or the technology is not suitable for local customs. Beyond demand-side factors, the literature also stresses the importance of supply-side and policy factors such as supply chains, subsidy aspects, regulation, and innovation policies (see, for example, Rehfuess et al., 2014 and Foxon and Pearson, 2008).

Against this background, what are the driving factors behind the autonomous diffusion of the LED technology? The major difference with the abovementioned technologies probably is that lighting is a priority of people living in rural areas. In our surveys, electric lighting is by far the most important reason stated for why households want electricity.[5] Moreover, unlike those other technologies that require a certain investment, the different sorts of LED lamps depicted in Table 4 allow households to perfectly adapt their lighting consumption to their financing capacities. In other words, the investment can be scaled almost continuously. Very poor households replace kerosene wick lamps or candles by hand-crafted LED lamps, for which the investment costs are below one $US (see Grimm et al., 2017). As capacity to pay increases, households may then switch to multi-diode ready-made lamps that are available from 1 to 2 $US up as the number of diodes increases. The lighting transition is thereby embedded in a more complex pattern of fuel switching behaviour. It involves a general trend towards cleaner and more efficient fuels with a simultaneous reliance on multiple fuels at each step of the transition (van der Kroon et al., 2013; Arnold et al., 2006).

Moreover, usage of LEDs is cheaper or at least not more expensive than kerosene and candles. In a laboratory test with a set of dry-cell batteries and LED lamps from local markets in Liberia, Adelmann (2014) finds that the non-rechargeable-battery-powered LED lamps and kerosene lanterns perform similarly with costs of around one $US per kilolumenhour (klmh), i.e. the costs for providing 1000 lm of light for one hour are one $US. Based on our survey data from the years 2010 to 2014, we find that the costs paid by households to run LED battery lamps for one hour tend to be lower (between 0.017 and 0.035 $US PPP on average) than for kerosene lamps (around 0.03 to 0.06 $US PPP). In general, while there has been a strong improvement in the efficacy of LED lamps and a simultaneous decrease in LED and battery costs due to technological advancements and scale economies (US DoE, 2012; McKinsey and Company, 2012), kerosene prices have soared over the observation period. The retail price of kerosene increased 240% between 2000 and 2012 in the developing world, from an average price of roughly 0.50 $US per liter in 2000 to about 1.20 $US per liter in 2012. In high-cost markets, kerosene costs can be as high as 1.80 $US to 2.10 $US per liter (Hesser, 2013). It remains to be explored in how far the recent plunge in oil prices will affect end-customer kerosene prices. While this may have slowed down the transition towards LED lighting, a trend reversal is unlikely given the dynamic developments in the LED market.

Beyond cost considerations, people in non-electrified areas have an outright antipathy against kerosene, which seems even stronger than the antipathy against firewood (Grimm et al., 2013). According to focus group discussions, which we conducted complementarily to the structured surveys presented above, people strongly dislike kerosene because it is perceived as dirty, smelly, and also unhealthy. As part of these discussions, different anecdotes have been shared on kerosene-induced smoke and its implications for family members, including recurring eye problems or kids asking for battery lamps because of the smoke (Grimm et al., 2013). More generally, kerosene is frequently considered as “outdated” or “old-fashioned” (Lighting Africa, 2013). LED lamps, on the other hand, are perceived as clean and more convenient.

As a consequence, LED lamps are now widely available in rural areas and can usually be found even in remote rural shops that sell basic necessities. While supply of other fuels to non-electrified populations is often insufficient or unreliable (Elias and Victor, 2005), both LED lamps and batteries tend to be continuously available, which further nurtures their adoption. The lamps are mass-fabricated, mostly in China followed by India (Lighting Africa, 2012), with some producers such as NIWA and fosera initiating smaller production units on the African continent. The market for batteries seems more consolidated with Guangzhou Tiger Head Battery as one of a few Chinese battery manufacturers with distribution operations in the region; major local non-rechargeable battery manufacturers are Kenya-based Eveready East Africa, SIGELEC from Senegal and Energizer South Africa.[6]

Dry-cell battery disposal and disposal hazards

Separate waste collection or end-of-life recycling does not exist in rural Africa, neither for household waste nor for hazardous waste. Even in urban Africa, basic recycling and waste disposal facilities are either lacking or tend to be poorly managed and to rely on ill-adapted imported technology (Mudhoo et al., 2015; Nnorom and Osibanjo, 2008; Achankeng, 2003). Similarly, even for higher-value Waste Electrical and Electronic Equipment (WEEE) one observes ineffective or lax implementation of existing regulations in Africa as well as in other developing countries (Nnorom and Osibanjo, 2008; Orlins and Guan, 2016). At the same time, even full-fledged recycling systems in industrialized countries achieve fairly low recycling rates. The EU Batteries Directive passed in 2006, for example, requires member countries to achieve minimum collection rates for portable batteries of 25% in 2012 and 45% in 2016. The actual average collection rate across the 29 concerned countries reached 32% in 2011 (Perchards and Sagis, 2013), a time when the same figure was below 15% in Canada (CM Consulting, 2012). It can be assumed, though, that in these countries non-recycled batteries end up at least in the municipal solid waste collection system and are accordingly not disposed of in a completely unprotected way as today in many parts of Africa.

Our data in Table 5 shows that in Africa battery waste is frequently disposed of in nature, latrines, or open burning sites. Toxics are released to different degrees into the different components of the local environment, namely general soil, farming land, water, and air. Table 5 covers most of the countries included in the previous lighting usage analysis.[7] There is no reason to believe that waste management will be much different in other rural areas in Africa, and the patterns we observe in Table 5 are probably transferable to other countries. None of the different modes of disposal can be considered as appropriate, although dumping dry-cell batteries in latrines is probably even worse than

[5] This can also be seen in electricity consumption patterns in newly electrified areas where many households use little electricity for anything else but lighting (World Bank IEG, 2008).

[6] See also Tetsopgang and Kuepouo (2008) for a case study on countries of origin of discarded batteries in Yaoundé, Cameroon.

[7] Since dry-cell battery consumption was very low at the time of our early surveys before the battery and waste management topic had gained relevance, we only started eliciting information on battery disposal in the surveys after 2011.

Table 5
Mode of disposal of dry-cell batteries.
Sources: own data; population data on district or province level used to calculate population density figures have been taken from the most recent censuses of the different countries.

		Mode of dry-cell battery disposal, in %				Monthly consumption of batteries among battery users		Household size	Population density in survey areas, in people/km^2
		Nature	Garbage (non-managed)	latrines	other[a]	Non-electrified	electrified		
Burkina Faso	2012	61	33	6	0	8.9	8.5	8.0	50
Rwanda II	2012	2	3	86	9	4.3	3.7	5.1	450
Rwanda III	2013	10	7	82	1	6.4	5.5	5.1	450
Senegal	2014	64	28	7	1	14.1	14.5	14.6	150
Tanzania	2014	15	69	14	2	6.7	5.8	5.7	10

[a] Other main modes of dry-cell battery disposal are throwing the batteries in ditches or giving them to friends or children.

informal garbage disposal or dumping them into nature, because concentration levels become high (Lighting Global, 2011). According to our qualitative interviews with rural households, there is some vague awareness of the toxic character of dry-cell batteries. For example, people in Rwanda often explain that they dump batteries into latrines in order to protect their children.

One main driver for how batteries are disposed of is the population density. If population density is high, there is little space to dispose of garbage informally and people use latrines. Acceptability of littering public space also decreases with population density. In addition, there seems to be regional variation in social norms as to whether specific places are declared as (non-managed) garbage sites.

The table also specifies the amount of batteries used among non-electrified and electrified households. It becomes obvious that – while consumption data strongly correlates with household size – electrified households continue using batteries for lighting (see as well Table A1 in the Appendix). This shows that people only shift gradually to cleaner and more efficient lighting.[8] The continued use of traditional lighting among electrified households is particularly strong among those with solar systems, which often do not suffice to enlighten the whole household.

The extent of the dry-cell battery problem can be exposed by extrapolating the consumption data of rural Rwanda, for which we have detailed data on all parts of the country. Using the battery consumption figures from Table 5 and official figures on the rural population together with the official rural electrification rate of 5% (NISR, 2014; IEA, 2014), we calculate that in total 67,000,000 non-rechargeable dry-cell batteries are disposed in latrines and nature in the countryside of Rwanda every year. This corresponds to more than 2500 dry-cell batteries per square kilometre.

For densely populated regions like Rwanda, this poses a severe risk for local food chains and thus public health. Yet, little is known about the specific contents, in particular heavy metal contents, of dry-cell batteries sold in Africa. Similarly, evidence is lacking on the dose–response relationship between the accumulation of toxic substances in dry-cell battery waste and the health and environmental risks among the exposed people and local ecosystem. In the following, we briefly summarize the status quo of science in this field for the two main non-rechargeable dry-cell battery types, zinc carbon and alkaline-manganese, also known as alkaline.[9] Generally, both contain lead, cadmium and mercury, which the World Health Organization rates among the "ten chemicals of major public health concern"(WHO, 2017).

Lead is often found in high concentrations in zinc carbon batteries, less so for alkaline batteries (Recknagel et al., 2014). Concentrations are considered high in this context as compared to limit values of the EU batteries directive of 2006, which we use as reference in the absence of similar legislations in sub-Saharan Africa. Lead is a carcinogen and a recognized toxicant for causing adverse effects on children. High levels of exposure may affect the kidneys, gastrointestinal tract, reproductive system, and the nervous system (Schwartz and Stewart, 2007; Gottesfeld and Pohkrel, 2011; Lighting Global, 2011). Likewise, *Cadmium* is carcinogenic and a recognized developmental and reproductive toxicant. Long term exposure is associated with renal dysfunctions and bone defects; it is toxic to plants, animals and micro-organisms (UNEP, 2010). Surveys among dry-cell batteries from the international market came to the conclusion that cadmium is less prevalent and if so, again, rather in zinc carbon batteries (Barrett et al., 2012; Recknagel et al., 2014). Finally, *mercury* is a recognized developmental toxicant that may cause brain and kidney damage and affect the nervous system (Bernhoft, 2012). While many countries in the developing world have banned or restricted the use of mercury, it is still found in alkaline batteries (Uram et al., 2010).

To conclude, dry-cell batteries often contain elevated levels of toxic heavy metals. Little is known about these levels among dry-cell batteries produced for the African market. The extent to which inappropriate disposal of the batteries poses a health or an environmental threat is also not yet clearly understood but can be said to strongly depend on the number of batteries that accumulate locally.

Conclusion and policy implications

The evidence presented in this paper indicates that lighting usage in non-electrified areas is undergoing a widely unnoticed transition from candles and kerosene lamps to LED lamps powered by non-rechargeable dry cell batteries. In Western African countries, in particular, LED lamps are used by the vast majority of rural households, but these lamps are on the rise in other parts of the continent as well. Even though we also find increasing penetration rates for solar lanterns and solar home systems, the growth of lighting powered by non-rechargeable batteries is likely to continue in rural off-grid areas for many years. On the one hand, forecasted solar sales volumes will not be sufficient to reach the large non-electrified population in Africa (Navigant Research, 2014). On the other hand, and as evidenced in this article, households continue to use battery-powered LEDs for some time once electrified. Further LED efficiency improvements will ceteris paribus reduce battery consumption, but it will likely further spur demand for battery-driven LED lamps at the same time.

From a public policy perspective, this is a transformation to be welcomed, since LED lighting is brighter, cleaner, and preferred by rural dwellers as compared to kerosene. Interesting lessons on technology adoption can be learned, also for other technologies that the international community seeks to disseminate in developing countries. The virtue of simple LED lamps explaining their advance in Africa is not only that they are in line with the target group's strong preferences for improved lighting but probably also the scalability of the investment that needs to be made. People can almost continuously decide on the size of their lighting device according to their capability to invest. The

[8] This concurrent use of traditional and modern fuels can be seen as a livelihood strategy through which households cope with irregular income flows, protect themselves from unstable markets for energy service provision (e.g. because of blackouts) and hold onto their cultural practises, while benefitting to some extent from modern fuels (van der Kroon et al., 2013).

[9] Zinc carbon is still widely used in sub-Saharan Africa due to its low cost. Yet, it is gradually replaced by its improved version, alkaline, which has a higher capacity and shelf life and is less prone to leak (Battery University, 2017).

relative lumpiness, even of small-scale investments, is frequently an impediment for the adoption of other technologies.

Our findings, furthermore, provide insights into patterns of fuel switching behaviour. The particular focus on lighting helped to complement existing evidence on the more intensively studied topic of cooking fuels. The findings further exemplify how households individually develop coping strategies to meet at least basic demands in essential energy services also in absence of grid electricity or solar panels. If energy consumption of the required appliances is small enough, households, for example, rely on infrequent battery replacement in order to use electric lighting or infrequent cell-phone charging to improve telecommunication. Finally, our findings on LED usage have implications for socio-economic impact potentials of electrification programmes as promoted by the SE4All initiative. If LED lamps are the baseline lighting technology instead of fuel-based lamps, households to be electrified by the centralized grid or through decentralized solutions will experience fewer impacts on lighting quality and air pollution.

The analysis moreover revealed that considerable numbers of inappropriately discarded non-rechargeable dry-cell batteries accumulate and that little is known about the implications this has on local livelihoods. It therefore behoves governments to monitor the dry-cell batteries that are imported to their countries, i.e. to systematically take samples and test them on their toxicity, but also to better account for the use of LED lighting powered by non-rechargeable batteries in official surveys. Existing systematic instruments such as the *UNEP Toolkit for Identification and Quantification of Mercury Releases* (UNEP, 2015) may serve as a blueprint. These tests should be complemented by research that examines health and environmental impacts of inappropriate dry-cell battery disposal; as a consequence limit values for toxic substances may need to be introduced.

Even if the heavy metal content of the batteries is found to be low, the mere amount of batteries that accrues and that is stored in high concentrations in people's backyards will possibly create a public health problem, in particular in densely populated areas. Hence, not only the continued promotion of cleaner and more sustainable energy solutions has to be warranted, also some sort of battery waste management system will probably need to be installed. If prices of raw materials that can be extracted from used dry-cell batteries rise, private actors will seek to exploit dry-cell battery recycling potentials in Africa. Policy should promote this market development by getting the framework conditions right for private recycling investments. It is, however, questionable whether such investments will become profitable in remote areas of developing countries in the next few years. The subject of massively increasing battery usage in rural Africa should consequently move up the agenda of the international community and national governments, also for waste management reasons. A joint attempt should be made to increase the effectiveness and scope of waste collection system based on existing experiences (see, for example, Shaharudin et al., 2015; Lin and Chiu, 2015). These efforts should ideally integrate solar lanterns and solar home systems (and even extend to other types of e-waste) considering their increasing market shares and the toxicity of the installed rechargeable batteries. More generally, extra attention has to be given to end-of-life aspects as part of a sustainable provision of cleaner energy access.

Appendix A

Table A1
Basic lighting information on the population with electricity in our survey samples.

		Usage rates among households for lighting, in %			Share in total lighting hours, in %		
		Candles	Kerosene	Batteries	Fuel-run lamps	Lamps run with non-rechargeable batteries	Electric lamps
Benin	2006	7	67	88	42	0	58
Burkina Faso	2010	0	15	99	10	21	69
	2012	0	4	97	4	13	83
Mozambique	2008	78	46	16	84	0	16
Rwanda I	2007/8	39	22	14	11	0	89
Rwanda II	2011	–	–	–	–	–	–
	2012	5	13	30	7	16	77
Rwanda III	2011	49	37	41	47	18	35
	2013	58	17	14	11	2	87
Senegal I	2009	38	4	98	7	8	85
Senegal II	2011	29	3	96	10	37	53
Senegal III	2014	0	1	93	0	26	74
Tanzania	2014	10	27	52	12	21	67
Zambia	2011	76	13	94	34	21	45

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