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The impacts of rural electrification on labor supply, income and health: experimental evidence with solar lamps in Tanzania

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Abstract

Energy, in particular electricity, is a viewed as a key component to economic development but nearly 1.3 billion individuals have no access to electricity. Grid expansion cannot currently meet the demands of many of these, including 530 million people in, primarily rural, sub-Saharan Africa. We provide experimental evidence on the impacts of non-grid small scale electrification through the use of a large scale randomized control trial. We offer randomized subsidies to 30 randomly selected households in each of 60 schools towards a solar lamp with a mobile phone charging point. We find that the lamps positively affect not only immediate outcomes such as expenditure on lighting and mobile phone charging, but also intermediate results including labor supply as well as final outcomes such as household income and well-being, effects that are robust even when controlling for multiple testing. Additionally, we find significant positive treatment effects on health in the sub-sample of households that did not previously own a solar lamp.

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1 Introduction

There is a general consensus that energy, in particular electricity, is a key input to economic development. Despite this consensus nearly 1.3 billion individuals around the world lack access to electricity. Of those, over 600 million reside in sub-Saharan Africa (IEA, 2013, 2014). In addition, based on current grid expansion plans and high population growth, it is estimated that 530 million people in, primarily rural, sub-Saharan Africa (SSA) will remain without grid connection for the next 30 years (IEA, 2014). In order to address these challenges the Sustainable Energy for All global initiative, launched in 2012, aims to extend electricity access to poor both through grid and non-grid small scale electrification, especially in SSA. All this is done in hope to unlock the development potential of electrification seen in the context of high-income countries. However, despite the apparent high potential, there is little robust evidence on the household level welfare effects of non-grid energy solutions, such as solar power. This paper aims to contribute evidence to this question.

The availability of electricity and other complementary investments, in particular lighting, is thought to affect development outcomes in a number of ways. The final outcomes of interests to policy makers are typically outcomes such as improved learning and education, increased labour supply and household income as well as better health. In turn, the pathways through which electricity affects the final outcomes can be characterized by a number of intermediate outcomes which themselves are also informative and of interest. These intermediate outcomes include, but are not limited to, additional productive hours for businesses, market work and study, improved productivity during existing work and study hours, improved access to information (via mobile phones, radios and internet), more efficient business practices through better access to communication technology and improvements in quality of life both as experienced subjectively and also objectively through improved indoor air quality as households switch from relatively dirty energy sources to a cleaner source. A number of papers have shown – mainly outside of SSA – that with improvements in grid electricity such improvements in intermediate and final outcomes do indeed materialize, but have also pointed out the importance of complementary enabling conditions for the full benefits of electrification to arise. These findings include increases in female employment (Dinkelman, 2011; Grogan and Sadanand, 2013) and improvements in education (Khandker et al., 2013, 2012) and health (Barron and Torero, 2014). Lenz et al. (2016) find that reductions in energy expenditure. All of these papers, however, focus on how grid connectivity influences outcomes and only one – from El Salvador (Barron and Torero, 2014), a considerably richer country than Tanzania – provides experimental evidence. Despite these positive findings of grid access relatively little robust evidence exists on comparative impacts of solar energy access on household welfare. A handful of studies (Furukawa, 2014; Kudo et al., 2015; Hassan and Lucchino, 2017) have explored the educational impacts of access to solar energy in rural contexts with mixed results. Encouragingly, a few recent studies on the immediate impacts of access to solar energy consistently find that solar lamps significantly reduce energy expenditures and lead households to substitute away from poor quality, high emission light sources (Grimm et al., 2016; Rom et al., 2016; Aklin et al., 2017). However, little robust evidence exists on the impacts on intermediate and final outcomes.

In this paper we provide, to our knowledge, the first comprehensive evidence of a positive impact of rural electrification in a Sub-Saharan African setting on wide range of welfare measures. In the experiment, households in rural Tanzania were randomly supplied with solar lamps (or rather differing subsidies to buy such lamps). The solar lamps offered are fitted with a USB charging point and with a daily charge the lamps have enough capacity to provide the household with bright light[1] for several hours and a small amount of power - enough to, for example, charge a mobile phone.

[1]The lamps on offer provide up to 160 lumens of usable light substantially more than a traditional kerosene lamp.

Using our experimental design we test how the supply of solar-powered lighting affects a range of intermediate as well as 'final' outcomes of interest. These outcomes include immediate outcomes such such as lighting and fuel expenditure, more intermediate ones such as labor market participation especially of women, business practices and indoor air pollution and final outcomes in the form of household income, health and subjective well-being. These variables were collected during an extensive household level survey.

Specifically, we find that, household expenditure on lighting decreases as does expenditure on phone charging, both of which are clearly directly impacted by the ownership of a solar lamp sold as part of the study. The total savings accumulated over a two year period would be enough to pay for the lamp, without taking any other benefits into account. Having more reliable access to mobile phones also increases use of mobile money. Adults work more outside of the household and in jobs in which they can earn money, a result which is confirmed in a separate time-use survey. This increase includes more females working in jobs to earn money. Comfortingly, adolescents do not increase their labour supply nor drop out of school more. Owning a lamp thus appears to create new opportunities by which households can increase their income, in part by exploiting the opportunity to charge others money for using the mobile phone charger. Not only do households report a higher income, but the respondents who have a solar lamp also report feeling happier with their current situation in life. In addition, we find significant reductions in indoor-air pollution and positive effects on respiratory health, significant in the sample which did not own a solar lamp at baseline. These findings are robust to adjusting for multiple hypothesis testing and strongly jointly significant.

2 Setting and Program Description

In partnership with GiveWatts, an NGO working in Kenya and Tanzania, we designed a randomized field experiment in which households in rural Tanzania were offered the chance to purchase solar powered lamps with solar panels. In our study the lamps were offered at different levels of subsidization at the household level. The lamps are fitted with a mobile phone charging point and with a daily charge the lamps have enough capacity to provide the household with light for several hours and a small amount of power - enough to, for example, charge a mobile phone.

It may seem that this is a rather limited intervention given that the solar panels and lamps offered in our study are only able to provide a clean source of lighting and a limited amount of power. However, it has been documented that even for rural households in sub-Saharan Africa with grid connections electricity consumption is generally quite low, typically in the range 50 and 100kWh per person per year. To put these numbers in context, annual consumption of 50kWh per person for a five person household would for example power a mobile phone, two compact fluorescent light bulbs and a fan for approximately five hours a day (IEA, 2014). These low levels of energy consumption despite grid connections lend support to the idea that decentralized energy solutions with minimal infrastructure investments can serve as a short run energy solution in rural areas where demand for energy and willingness-to-pay is low.

Our partner organization has been working with primary schools in rural Kenya since 2010 to provide solar power energy solutions to households in off-grid areas. Recently they have expanded their operations into the Northern part of Tanzania. The NGO operates based on the following protocol: first the NGO establishes a partnership with each school to facilitate the distribution of the lamps and collection of payments. The NGO officer then organizes a meeting with parents of children in the school to demonstrate how the lamps work and explain the price and payment structure of the lamps. The process of distributing the solar lamps and collecting payments from households is then managed jointly by the Parent Teacher Association in the school and a local agent from the NGO. The standard NGO model in Kenya provides the lamps at the recommended retail price of 3500 KSh ($37). Households are offered the lamps on credit and can repay over a number of months. The payment structure is such that households make an initial payment amounting to roughly a third of the total price and then pay the remainder of the cost in instalments over a 3 month period. The roll-out in Tanzania will follow a similar model and prices, with the major difference being that each of the four instalments are equal, at 20,000 TSh ($9.2). Repayment rates in Kenya are quite high with roughly 95% of lamps repaid in full. Despite the lamps being cost-effective when compared with alternative fuel sources, take up at full price is rather low at an average of 10% across GiveWatts program schools.

3 Experimental Design

We designed our experiment with two factors in mind. First was the ability to estimate a demand curve for solar lamps. By offering the lamps to households at differing price levels, we can gain a relatively crude impression of the demand curve for solar lamps. Second we can then use the variation in demand for lamps at different prices to induce variation in lamp ownership. Where people receive a high subsidy, we can use this for an intention-to-treat estimation for the effects of lamp ownership.

3.1 Sample Selection

The evaluation sample consists of 2067 households in the catchment area of 69 primary schools in the district of Magu in Tanzania. The selection of Magu district was based on the expansion plans of our partner organization and the timing of the project funding. Based on the program structure of our partner organization the sample selection required a two step selection where we first selected schools to be part of the study and then selected households connected to each selected school.

3.1.1 Selection of schools

The selection of schools was randomized based on a list of all public schools in Magu district provided by the Ministry of Education and Vocational Training (MoEV) in Tanzania. From the list we randomly selected 69 schools to participate in our study. Of the 69 schools 60 were randomly selected to receive the subsidy treatment. The remaining 9 schools serve as control schools, but were eligible for the standard GiveWatts program.

3.1.2 Selection of students and households

From each of the selected schools we collected student rosters. From the student rosters we randomly selected 30 students per school. All households of students selected for the study were sent a letter introducing GiveWatts and informing them of the possibility of participating in our study and asking one of the student's parents to come to the school for a baseline interview. The letters were distributed to the students during school hours. Some students were not present at the distribution of letters. If a student was not present the next student from the randomized student list was selected as a replacement. As it is unlikely that student absence is purely random we will attempt to measure the extent of this selection effect by this using grade data from the school, if available, along with attendance data prior to the implementation of the program. In spite of possible sample selection of those present, we feel these are the households who would be likely to purchase lamps in the first place and as such are a representative sample of the households of interest to the study in the Mwanza region, given that households would have to have children attending school to purchase a lamp any way.

3.2 Treatment Assignment

Our main treatment instrument is a subsidy for a solar lamp, inducing variation in take-up of purchasing solar lamps.

3.2.1 Assignment of treatment at school level

The 69 schools selected to be part of our study were assigned to one of the three following treatment categories, each with different percentage subsidies available:

1. High average subsidy: $S_1 = \{0, 50, 100\}$
2. Low average subsidy: $S_2 = \{0, 25, 100\}$
3. No subsidy (Control schools)

We randomly assigned 30 schools to treatment arm A, with a high average subsidy, and 30 schools to treatment arm B, with low average subsidy. The remaining 9 schools are assigned to control arm C, without any subsidies.

3.2.2 Assignment of treatment at household level

The treatment assignment of households, their level of subsidy, was determined by a random draw from the set of subsidies S assigned to the school. This randomization took place via a public lottery with the respondents following the baseline interviews. Based on their draw the respondents were presented with a voucher for their assigned subsidy s_i. They could then redeem the voucher by purchasing a lamp from GiveWatts through the school. The voucher was valid for 2 weeks from the date of the draw. During the entire experiment, households were able to buy lamps from GiveWatts at the full unsubsidized price, though no household in our sample decided to buy the lamp at the full price.

In all project schools GiveWatts followed their standard protocol in advertising the information meeting to all households in the school through the teachers and students. During the meeting there was a demonstration of how the lamps and solar panels work and parents were given information on the price and payment structure of the lamp. The introductory meeting was conducted at the school and led by a representative from GiveWatts.

4 Data Sources

The primary sources of data are a baseline survey conducted immediately before treatment assignment and a follow-up survey that was collected approximately 12 months after the baseline survey. Additional sources of data include a brief school survey, administrative data from the schools and administrative data from our partner organization, as well as a midline survey including student testing.

4.1 Baseline Survey

To measure the core outcome variables we conducted an extensive household level survey at baseline before program implementation for all households in the sample. The household survey was administered to a parent (or guardian) of the selected student at the school. The survey featured detailed questions on general household and individual characteristics. The questionnaire also included questions on fuel consumption and expenditures. The expenditure questions are intended to measure the household level savings due to reduced fuel expenditures following the repayment period. The questionnaire also contained a detailed module on economic activity and labour market outcomes for household members these include business activities, employment status, hours of work and earnings. The lamps may also provide household members with new income generating opportunities. Anecdotal evidence from conversations with our partner organization suggests that some households have used the lamps to sell mobile charging time to other households in the area or to rear animals such as chickens. In addition, the lamps may allow home-run businesses to stay open later into the evenings.

4.2 Midline Survey

We re-visted the communities approximately 5-6 months after the baseline survey and conducted midline surveys with about 10% of households in our sample.

4.3 Follow-up Survey

12 months after program implementation we conducted a second household survey for our initial sample households as well as re-testing the students in our sample. The household survey took place at the home of each household, allowing us also to obtain GPS coordinates

for each household's domicile. At follow-up we also administered a detailed time-use survey to the parents and the selected students. This allows us to analyze the impact of the solar lamps on intermediate outcomes such as hours spent on income generating activities and study time. Table 3 shows the average minutes spent at endline on different categories of activities for all adults as well as split by lamp purchase decision. On average the respondents inform us of 14.45 hours of activities per day. Adults in households with lamps spend more time carrying out both paid and unpaid work, while they spend less time on domestic tasks.

4.4 Other data sources

We collected administrative data from two sources: the study schools and from our partner organization. The data from the schools includes enrolment and attendance data. The data from our partner organization includes take-up data (lamp purchase data) and repayment data.

5 Estimation Strategy

We estimate the treatment effects using the following strategy:

$$Y_{i,t+1} = \alpha + \beta L_i + \pi Y_{i,t} + \epsilon_{i,t+1} \tag{1}$$

where $Y_{i,t+1}$ represents an outcome variable at endline, with $Y_{i,t}$ its baseline value and L_i is the ownership of a lamp. The first definition is a dummy equal to one when the household purchased a lamp at baseline when given the opportunity. The above OLS regression shows whether those with a lamp are better off in terms of the chosen outcome variable, but does not imply causality as results may reflect a number of possible sources of endogeneity. We therefore exploit the random variation in the subsidies assigned to the households in an Instrumental Variables (IV) setup. Here, we use the take-up estimation as a first stage to predict whether households purchase/own a lamp from our intervention and use these predicted values ($\hat{L}_i$) in a second stage. In Equation 2 we use a single dummy equal to one when the subsidy takes either the value 50% or 100% which can be found as the subsidy variable S_i below.[2]

$$L_{i,t} = \alpha + \beta S_i + \epsilon_i \tag{2}$$

$$Y_{i,t+1} = \alpha + \beta \hat{L}_i + \pi Y_{i,t} + \epsilon_{i,t+1} \tag{3}$$

We control for baseline variables where available in the second stage regression. Where these are not available, due to not being included in the baseline survey we use the specification seen below in equation

$$Y_{i,t+1} = \alpha + \beta \hat{L}_i + \epsilon_{i,t+1} \tag{4}$$

We also show results from the intention to treat (ITT) regressions, where we regress the outcome of interest on a dummy for a subsidy level of 50% or higher.

$$Y_{i,t+1} = \alpha + \beta S_i + \epsilon_{i,t+1} \tag{5}$$

For each family of outcomes, there are several variables measuring similar outcomes. For example, for labor supply, we know whether a person worked outside the household

[2] As noted in Section 6.2, take-up for the 25% subsidy variable is very low. Our instrument is therefore strongest if we construct the control group as those with either a zero or a 25% subsidy. Since all subsidies were assigned randomly, this is internally valid.

at all and how many hours they worked. To restrict the number of hypotheses tested, we therefore construct summary indices following Anderson (2008). Here we switch signs, such that an improvement in all variables is a change in the same direction, before demeaning and standardizing according to the control group. An index variable is then constructed as the mean of the variables each weighted by the inverse of the covariance matrix.

We also explore heterogeneity in treatment effects along three dimensions: whether a household owned any solar lamp at baseline, whether the respondent at baseline had completed primary education and whether a household earned above median income. In order to estimate this using instrumental variables, there is an additional first stage regression which includes the variable of heterogeneity $V_{i,t}$ on the right hand side in both first stage equations as well as in the interaction term in Equation 7.

$$L_{i,t} = \alpha + \beta S_i + \gamma V_{i,t} + \epsilon_{i,t} \tag{6}$$

$$L_{i,t} \times V_{i,t} = \alpha + \beta S_i + \gamma V_{i,t} + \nu_{i,t} \tag{7}$$

The predicted values for lamp ownership along with the interaction term with the variable of interest are then used in the second stage equation:

$$Y_{i,t+1} = \alpha + \beta \hat{L}_i + \gamma \widehat{L_i \times V_i} + \pi Y_{i,t} + \epsilon_{i,t+1} \tag{8}$$

In Equation 8 the baseline value for Y is included where available.

6 Results

6.1 Balance at baseline

As seen in Table 1, the sample is balanced across treatment (consisting of those with a subsidy of 50% or higher) and control (consisting of those with a subsidy below 50%) across a number of socio-economic variables, such as household size, female employment, income, bank account ownership, kerosene expenditure, and prior solar lamp ownership. In Table 2, we also show that there are no significant differences across treatment and control for those families of outcomes, for which we have baseline data, namely labor supply, light and fuel expenditure and income (all measured by the respective summary indices).

6.2 First Stage

We explore the take-up of the lamp in more detail in a separate paper (Aevarsdottir et al., 2016), but present the simple take-up regression as the first stage here. In Table 4 it can be seen that the instruments are highly relevant and the F-statistic is over 800 for owning a lamp, clearly indicating we do not face a weak instruments problem. The first stage is similarly strong for the case of being able to show the purchased lamp. The subsidy has the desired effect in encouraging households to purchase a solar lamp independent of the instrument used. The results show that those with a 100% subsidy are predicted to buy the lamp with a probability of around 0.9 and households receiving the offer of a 50% subsidy buy the lamp with a probability of around 60%, while take-up is low for households with a 25% or no subsidy. We therefore use a dummy for subsidy level 50% or higher as our preferred instruments to examine the effect of lamp ownership on welfare outcomes.

6.3 Immediate Effects of solar lamp ownership

6.3.1 Energy and technology use

One would expect that purchase of a solar lamp means households can reduce their expenditure on lighting and fuel and Table 5 shows that this is indeed the case. We see that households saved money that would have been spent on lighting and kerosene otherwise. We find negative and significant effects on lighting expenditure during the last and in a typical week, of 200 and 500 Tanzanian shillings respectively, or a relative reduction of expenditure by half for typical lighting expenditure. If we take the value of 500 TSh, as in column (2) for a typical week's spending, a household would save enough to purchase the lamp at the full price over a period of 160 weeks, or roughly three years. Spending on kerosene specifically does not seem to be the bulk of spending on lighting[3] in the households in our sample, but we nonetheless observe a decrease in household spending on on this item, both in the last week and in a typical week to almost zero.

In addition to savings made on lighting, households in possession of a lamp from our intervention also have the opportunity to charge their mobile phone using the lamp, which 67% of lamp owners do. If households have no electricity at home, they typically have to travel to the nearest town or village centre where they pay 100-300 TSh to have their phone charged. If they live far from this centre, they often leave the mobile phone with the shopkeeper who is charging their phone for them. This means they not only face travel costs and time spent in order to get their phone charged this way, but they may also not have access to a mobile phone restricting any potential use of the phone. We estimate the immediate monetary savings from charging with the lamp both for last week and in a typical week (Table 5 columns (6) and (7)). The average spent last week by households at endline

[3] Though this could be because households were confused by the questions and did not want to double report an expenditure

was 400 TSh, so the effect size of 300 TSh reduced expenditures are not only statistically but also economically significant. The results for typical spending are larger still at around 500 TSh for the IV results in (7). Including a control for previous solar lamp ownership makes no significant change in the size of the coefficient which is indicative of the fact that it is unusual for solar lamps available on the market to include the opportunity to charge mobile phones.

Hence if we add the total expenditure reduction on lighting, fuel and mobile phone charging using a conservative estimates of 900TSh/week, the average household would save enough to purchase the lamp at full price over a period of two years. Given that the lamps have a warranty period of two years, the savings on lighting alone are worth the value of the lamp purchase, without even considering additional benefits that the lamp may bring.

Some households even recognised an opportunity to make additional money and charged money for others to charge their phone with the lamp they now own. 46 of the 760 households with a lamp received money for phone charging, averaging over 6600 TSh per month.

6.4 Intermediate effects of solar lamp ownership

6.4.1 Labour Supply

Owning a clean and marginally free source of light may allow household members to use their time during daylight hours to work outside the household, and shift the time they carry out tasks in the home to the morning or evening. Consistent with this, we find that lamp ownership significantly increases the labor supply of adults in general and women in particular both at the extensive and intensive margin. In Table 6, we find an increase of roughly 8 percentage points in the number of households with at least one adult working outside the home in the IV specification. This is equivalent to a 20% increase relative to households that do not own a lamp. The number of households with at least one adult earning income outside the house, which includes the sale of agricultural products produced on the household's own land as well as wage earning jobs outside the home, does not increase significantly. Turning to the intensive margin, we find positive increases in both the number of adults working outside the home and those earning income outside the home, equivalent to 10-20% compared to the control group. In the index for adult labour market participation we find a positive and significant impact of lamp ownership.

We obtain similar results from the time use survey, shown in Table 9 for all adults. In the IV specification in Table 9, we find that if adults are in households with solar lamps they work on average roughly 40 minutes more per day in jobs to earn money. This represents an increase of about 19% in time spent earning money. The positive impact of a lamp on unpaid work appears to cancel out a decrease in time spent on domestic tasks. Of the other categories in the time use questionnaire only community activities experience a change, which is a decrease of roughly 50% (but not significant), while time spent on care-giving, education, leisure and self-care are not affected by the lamp for adults.

Lamp ownership may be particularly beneficial for women in terms of allowing them to shift some of the housework to the evening and thereby free up time to work during the day. We test this in Table 7 and indeed find positive effects on the number of households with at least one woman working outside the home and on the number of women earning money outside the home. Lamp ownership increases the chance that a woman works outside the household by about 5 percentage points or 26% above the control group, while the number of women earning income outside the home by about 16%. The number of additional females earning is roughly one half of the increase in additional adults earning, indicating that men and women benefit equally from lamp ownership in terms of their labor supply. When we consider the time use of adult women (see Table 10) the results are very similar to those of the whole sample, with an increase of around 40 minutes paid work and roughly 24 minutes unpaid work on average. As with the adult sample as a whole the unpaid work and domestic tasks cancel out. Note that the control mean for females working is lower for both paid and unpaid working meaning that the increases seen for females are proportionally higher than for men. Adult women seem to spend a little more time on activities which can be seen as educational.

While it may be desirable for adult household members to work more outside of the household to earn money, it is less desirable for adolescents to use their time in this way, especially if labor market participation crowds out school attendance and enrolment. It is therefore comforting to see that we do not see any significant changes in adolescents either working or earning income outside the home or being enrolled in school. This is confirmed in the time use survey for under 18s, who do not change the amount of time spent on paid or unpaid work due to lamp ownership nor decrease their time spent on educational activities.

6.4.2 Mobile phone use

We previously saw that households are saving money on phone charging. In addition to saving money, they can now likely maintain access to their mobile phone while charging and can be more confident they will have a charged mobile when they need it. If households now have more reliable access to a mobile phone, this could increase their use of mobile money (Mpesa), which may be productivity enhancing. It is not clear whether this should take effect on the extensive margin, i.e. more people use Mpesa at all, or on the intensive margin, i.e. those with Mpesa increase their use of it. We test the effect of a lamp on the overall use of Mpesa in Table 11, where we find no increase in the number of households reporting that they use Mpesa. As part of the endline survey, we also asked about how much money a household saves with Mpesa as well as how much they send and receive. Savings[4] roughly double due

[4] We winsorize for the top 1 percentile to remove problems of unrealistically high values

to lamp ownership. The volume received clearly increases significantly, at roughly 40,000 TSh in the IV specification which is also economically significant with average household monthly income equal to around 83,000. Somewhat surprisingly given the previous results, the volume sent is not significantly different despite all coefficients being positive. In spite of the fact that households do not seem to be sending as much as they receive, there is clear evidence of an increased use of Mpesa on the intensive margin.

6.4.3 Air quality

Closely linked to the reduction in energy expenditure and therefore use of fossil fuels is the quality of the air inside the home. This was only measured in the endline survey when visiting the households' homes. We measure the PM2.5 particulates (particulate matter with a diameter of less than 2.5 micrometres, measured in $\mu g/m^3$), potentially harmful gases known as volatile organic compounds (VOCs, measured in parts per million or ppm) and an overall pollution index (calculated by the devices used, with the lowest pollution indicated by 0 and the highest by 9).

The air in the households seems to be of universally bad quality, with the air index averaging around 8.5 across all households. Nonetheless, there is suggestive evidence that in some dimensions the lamps cause air quality to improve. In Table 12 we present the results for the PM2.5 measurements. In 2015 EU regulations state that PM2.5 should not exceed $25\mu g/m^3$ on average each year. The average in our sample is $163\mu g/m^3$. While pollution is still far above these levels even for households with solar lamps, we see significant reductions in particulate matters as well as the overall pollution index.

6.5 Final outcomes

6.5.1 Income

There are two ways in which the solar lamp could increase the household's income: (i) the phone charger could be 'rented' out to others to charger their phone; (ii) as a result of increased labor market participation.

In Table 13 we show estimation results for total household income, which is the sum of the income of all individuals in the household. We find that the coefficient on lamp ownership is positive and significant. This would suggest that adults are able to work more in jobs where they can earn money as a consequence of lamp ownership. When considering per capita income, we see even more significant income increases. Household income increases by about 25% due to the purchase of a solar lamp. A log income specification shows similar, but marginally insignificant results. Part of the income increase is covered by the ability to charge money for phone charging from others, which a small number of people exploited (46 of the 760 households with a lamp). This is shown in Table 13 columns (5) and (6), where we see that by construction nobody makes money from charging phones in the control group reflected in what is essentially a zero income from this source for these people as well. The additional income from charging for those with a lamp is 160 TSh, which implies increased income for those who use the lamp in this way of about 6000TSh a month (or the equivalent of charging twenty phones). However, given the small number of people who engage in this practice, it would seem reasonable to conclude that the majority of the income increase works through increased labor supply.

Comparing the reported income results with a back of the envelope calculation from the time use data, an increase of this magnitude appears feasible. If adults report 40 minutes more paid work per day, this amounts to 10,400 minutes per year (assuming they work 5 days per week for 52 weeks in a year). Working full time in a shop in Magu district pays in the region of 40,000 TSh per week. If we assume a 42 hour working week then these 10,400 minutes amount to 4.127 weeks and then roughly 165,000 TSh. This is suggestive of the fact that the increase in income stems from a change in labor market behavior rather than earning income for mobile phone charging, which very few households choose to do.

6.5.2 Subjective Well-being

In addition to income, access to lighting may improve people's sense of well-being. Specifically, people may generally feel happier or safer due to having a brighter and cleaner light source. For example, in qualitative surveys at midline it was brought to our attention that some lamp owners used their lamps to check on their animals at night to prevent theft. We test whether the lamp leads to respondents feeling more secure with the use of the survey question from endline, "How safe and secure, on a scale from 0 (very unsafe with constant risk) to 10 (perfectly safe), would you say your household is at home?" Lamp owners do not feel more or less secure than non-lamp owners, as can be seen in Table 14. Also in this table are the results for general satisfaction with life, based on the question "How satisfied, on a scale from 0 (very unhappy) to 10 (very happy) would you say your household is with its current situation?" Here we see a positive effect of around 0.4 points out of 10.

6.5.3 Health

Finally, if solar lamps improve indoor air quality (as seen in Tables 12 and 16), then it is also possible that we see improvements in health, and in particular respiratory health. We examine this in Tables 15 and 16, where we estimate the local average treatment effect (together with the OLS and the ITT) on respiratory disease, measured by the percentage of household members experiencing coughing in the last week, month and six months. We find negative, but noisily estimated, effects for all three variables and for the overall index.

7 Heterogeneous treatment effects

We now explore three dimensions of heterogeneity that could be important for how solar lamp ownership induced by our experiment might affect household welfare in Table 16. In particular, we estimate local average treatment effects for the full family of outcomes comparing those who already owned a solar lamp at baseline versus those who did not, those with complete primary education versus not and those with above (versus below) median income at baseline.

For previous lamp ownership, we find significant differences only for the income from charger summary index and the respiratory illness summary index. The former effect suggests that people are more likely to use the charging function of the lamp in a significant way if they already have a clean and reliable light source (none of the lamps found in households prior to our study have a charging function).

When it comes to respiratory illnesses, we find significant improvements in health only in the sample that did not previously own a solar lamp. While this might suggest that indoor air pollution was already lower in households that previously owned a solar lamp, such an interpretation is not consistent with the results in column (6), which show that indoor air pollution improved more (though not significantly so) in such households. This suggests that other mechanisms were also at play in the health improvement.

Turning to education, we find that overall and female labor supply increases substantially (significantly so for the latter) for households with more education, perhaps because these households have better earning opportunities they can now take advantage of. Consistent with this, we also find similar patterns for the income summary index and income from the phone charging facility with significant treatment effects confined to the sample with higher education. Similarly, it is households with higher income at baseline that are significantly more likely to make money from the charging facility.

8 Adjusting for multiple hypothesis testing

Since the analysis in this paper is exploratory and examines the causal effect of solar lamp ownership on a large number of outcome variables, we here submit the results to tests for joint significance and adjustments for multiple hypothesis testing.

For this exercise, we focus on the ten primary outcomes of interest; lighting/fuel and phone expenditure, overall and female labor supply, business practices, indoor-pollution, income (overall and only from the charger), subjective well-being and health, and, specifically, the indices that summarize these family of outcomes. Following Young (2016), we present two types of tests, namely tests of joint significance and tests that control for multiple hypothesis testing. The former provide information on whether all treatment effects are zero or – in the case of rejection – whether some unspecified subset is not. The latter method tells us for each specific coefficient whether it is significantly different from zero, adjusting for the fact that the probability of falsely rejecting a null increases mechanically as the total number of hypotheses tested increases. Here, we present adjustments that control the family wise error rate, i.e. the probability of at least one false rejection in a family of hypotheses, and the false discovery rate, i.e. the share of false rejections (see Anderson, 2008). In implementing these tests, we calculate both 'conventional' Neyman-Pearson statistics based on asymptotic arguments and exact statistics based on randomization inference (Fisher, 1935).

To conduct randomization inference, we first state the Fisherian null hypothesis of no treatment effect for any participant and outcome, namely that the outcome would be the same regardless of treatment status, $y_i(t_i) = y_i(0)$. Note that in our context, this is effectively a statement about the intention-to-treat estimate, i.e. it relates treatment assignment, namely subsidy level, to outcomes, without saying anything about the relationship between treatment and 'dosage' (see Imbens and Rosenbaum, 2005) induced by the treatment, namely lamp ownership. In other words, the Fisherian null makes no statement about the coefficients in the first stage regression and we therefore construct our test statistics on the basis of the underlying ITT regressions (see Young, 2016).[5]

Following Imbens and Rosenbaum's notation, there are N (equal to the number of participants) instrument settings h_j, $j = 1, ..., N$. The resulting instrument is $z = ph$, where p is the particular permutation matrix implied by the randomly drawn subsidy levels in the original experiment. To calculate the exact p-values of the ITT estimator, we draw a permutation matrix P from the set of all possible permutations, Ω, set the instrument setting to $Z = Ph$ and then calculate the T-statistics for the ITT coefficients for each of the 10 indices summarizing the different families of outcomes. We repeat this process $L = 10,000$ times.

From this, we calculate the two-sided p-value by taking the absolute value of the T-statistic and recording the share of permutations with a higher statistic. The one-sided p-value is calculated analogously by recording the share of T statistics smaller than the original one for H1: $\beta < 0$ (in the case of labor supply, business practices, income and subjective well-being) and larger than the original one for H1: $\beta > \beta_0$ (in the case of expenditure, air pollution, and respiratory illnesses).

To test joint significance of all treatment effects, we calculate the Wald statistic for each permutation with the p-value given by the share of permutations with a Wald statistic larger than the one associated with the original treatment assignment. That is,

$$p_{joint} = \frac{1}{L}\sum_{k=1}^{L}\mathbb{I}(\mathbf{T}(\mathbf{P_k})'\mathbf{V}(\mathbf{T}(\boldsymbol{\Omega}))^{\mathbf{-1}}\mathbf{T}(\mathbf{P_k}) > \mathbf{T}(\mathbf{p})'\mathbf{V}(\mathbf{T}(\boldsymbol{\Omega}))^{\mathbf{-1}}\mathbf{T}(\mathbf{p}))$$

where $\mathbf{V}(\mathbf{T}(\boldsymbol{\Omega}))$ is the covariance matrix of T over the universe of potential permutation matrices.

[5] An alternative would be to apply randomization inference to a non-parametric version of the the LATE estimator as in Imbens and Rosenbaum (2005).

To adjust for multiple hypothesis testing, we ask to what extent we can be confident that solar lamp ownership has a beneficial effect on welfare. In other words, we apply the adjustments to the p-values calculated from the appropriate one-sided hypotheses in each case.

We report the results in Table 17. In the first row, we re-estimate the ITT regressions for the summary indices as a system of seemingly unrelated regressions (the coefficients are identical to the single equation estimation). The system estimation allows us to easily implement a conventional test Wald test of joint significance across the ten regressions. We strongly reject the null that all coefficients are zero. We come to the same conclusion when considering the test statistic that is constructed on the basis of randomization inference (last two rows of the table).

In the second and third row, we report the conventional and exact Fisher p-values for each summary index. The two sets of p-values are very similar and lead to the same conclusions about the significance of the coefficients, indicating that our sample size is large enough for the asymptotic analysis to be valid.

In the third and fourth row, we adjust the one-sided exact p-values of the intention-to-treat effects to control the family-wise error rate. In particular, we follow Anderson in using the Westfall and Young (1989) free-step down resampling method (see Romano and Wolf, 2005, for alternative methods), which controls the probability of making at least one type I error as the number of hypotheses tested increases.[6] Applying this method, we see that the p-values increase substantially. For the p-values that were smallest originally, the adjustment is effectively equal to the Bonferroni correction (i.e. multiplying the p-values by the total number of hypotheses tested), whereas the increase is less stark for the p-values

[6] We use this method, rather than the simpler Bonferroni method, because of its increased power arising from the fact that it calculates exact p-values, respects the covariance structure of the data, and removes hypotheses that have been rejected from the testing algorithm.

that were larger originally. In sum, we continue to reject the null against the one-sided alternative at the 5% level in the case of phone expenditure and at the 10% level for light and kerosene expenditure, labor supply, income generation from charger and subjective well-being. The p-value of the ITT coefficients of female labor supply, use of mobile money, and indoor-pollution increases to .108, and these effects therefore turn marginally insignificant. The effect of solar lamp subsidization on respiratory illnesses continues to be insignificant.[7]

We would argue that controlling the probability of one or more false rejections is too conservative for the exploratory analysis we are undertaking here. In other words, we want to know whether solar power adoption has overall positive effects on a number of dimensions, but not specifically whether any one of them is positively affected. We therefore present our preferred correction in column (5) and (6) of the table where we present sharpened q-values that control the false discovery rate, i.e. the proportion of falsely rejected null hypotheses over a family of tests. Setting the false discovery rate to .1, i.e. we would find it acceptable to falsely reject one of the ten hypotheses, we would reject all ten one-sided null hypotheses.

In sum, we conclude that the finding that solar ownership has significant positive effects on a range of intermediate and final outcomes is robust to adjusting for multiple (and joint) hypothesis testing.

9 Conclusion

In this paper, we have shown experimental evidence on the impact of electrifying rural households, or rather taking the first step along the way of electrification, namely providing

[7] While the Westfall and Young (1989) accounts for dependence in the data, it does not take account of the logical sequence of a set of hypotheses. That is to say, we would deem it more likely that the rejection of the null that income is not positively affected by lamp ownership is correct if we find that intermediate outcomes related to this final outcome, such as labor supply, are positively affected. In future work, we will explore these relationships in Bayesian framework.

a source of lighting and the ability to charge mobile phones with a solar lamp. We see effects on a number of immediate, intermediate and final outcomes. Households report reduced expenditure on lighting, fuel and mobile phone charging. The fact that more activities can now take place in the evening frees them up to participate in the labor market during the day and we see positive effects on labor supply for adults and in particular women. With more reliable phone charging, we also see an increase in the use of mobile money (at the intensive margin: more transfers and higher balances). At endline, households with a solar lamp report 25% higher income than those without. For a small number of households part of this income increase comes from the fact that they offer the charger to others for a fee. We present evidence from the household survey and a time use survey that adults are increasing their labor market participation to an extent which is well aligned with the income increases. Additionally, we find significant positive treatment effects on respiratory health in the sample of households that did not previously own a solar lamp.

It therefore seems that solar lamps are a cost-effective way to improve welfare. With the expenditure savings alone, the lamps would have paid for themselves after two years. Yet, in Aevarsdottir et al. (2016), we find that few households are willing to purchase the lamps at full cost (see also Grimm et al. (2016)). Understanding why willingness to pay for electrification is so low therefore seems an important issue.

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10 Tables and Figures

Table 1: Balance

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	hh size	female empl	hh income	mobile money	kerosene	nonsolar	education	income median
50% or more	-0.00172	0.00458	20167.2	0.0132	38.94	0.00277	-0.0224	0.00712
	(0.145)	(0.0187)	(20718.4)	(0.0242)	(48.28)	(0.0247)	(0.0231)	(0.0145)
Constant	8.457***	0.168***	91231.4***	0.616***	439.8***	0.433***	0.700***	0.0907***
	(0.0977)	(0.0126)	(13926.3)	(0.0162)	(32.45)	(0.0166)	(0.0155)	(0.00977)
Observations	1629	1629	1629	1629	1629	1629	1626	1629

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

OLS regressions for control variables on the treatment dummy equal to one when the subsidy is equal to 50% or 100%
Standard errors in parentheses
All regressions include school fixed effects
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
"hh size" is the number of household members, "female empl" is a dummy for whether any female works outside the household, "hh income" is yearly income in TSh, "mobile money" is a dummy for owning a mobile money account, "kerosene" is spending on kerosene in the previous week, "nonsolar" is a dummy equal to one if a household did not own any solar powered objects previously, "education" is a dummy equal to one if the respondent at baseline has education of at least 8 years, "income median" is a dummy equal to one if the household has above median income.

Table 2: Balance for Indices

	(1) Light & Kerosene Index	(2) Labour Index	(3) Female Lab Index	(4) Juv. Lab. Index	(5) Income index
50% or more	-0.0289	-0.0163	-0.0150	0.00855	0.0210
	(0.0356)	(0.0406)	(0.0422)	(0.0285)	(0.0424)
Constant	-2.78e-10	-8.62e-09	0.00555	6.67e-10	7.11e-08
	(0.0239)	(0.0273)	(0.0284)	(0.0192)	(0.0285)
Observations	1629	1629	1608	1629	1629

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

OLS regressions for control variables on the treatment dummy equal to one when the subsidy is equal to 50% or 100%
Standard errors in parentheses
All regressions include school fixed effects
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
The included variables are the indices for the set of variables we have information for at baseline. The indices are used in the following tables, where the individual components of each index can be found, and are constructed according to Anderson (2008).

Table 3: Time use descriptives - Adults

	(1) All	(2) No lamp	(3) Lamp	(4) Diff.	(5) P-value
Paid work	244.5	235.4	258.9	23.64**	0.0239
	(240.8)	(238.2)	(244.2)	(10.46)	
Unpaid work	170.6	163.7	181.5	17.99**	0.0455
	(206.9)	(204.7)	(210.1)	(8.992)	
Domestic tasks	225.0	232.0	214.1	-17.69*	0.0514
	(208.9)	(209.6)	(207.5)	(9.078)	
Caregiving	14.09	13.37	15.24	1.888	0.3529
	(46.74)	(41.73)	(53.76)	(2.032)	
Community	10.28	10.19	10.42	.2370	0.9309
	(62.82)	(59.91)	(67.21)	(2.732)	
Education	3.836	2.908	5.307	2.402	0.1383
	(37.27)	(31.77)	(44.60)	(1.620)	
Leisure	249.4	247.9	251.7	3.948	0.6067
	(176.3)	(176.2)	(176.5)	(7.668)	
Self-care	191.9	194.0	188.4	-5.499	0.4438
	(165.1)	(162.8)	(168.7)	(7.179)	
Day length	867.1	865.5	869.8	4.334	0.1466
	(68.64)	(67.13)	(70.94)	(2.985)	
Obs	2230	1368	862		

Standard deviations in parentheses for columns (1)-(3)
Standard errors in parentheses for column (4)
In column (5) the p-value is reported for the null hypothesis that the difference in column (4) is equal to zero
All variables are measure in minutes

Table 4: First stage

	(1)
	Lamp
50% or more	0.683***
	(0.0179)
Constant	0.114***
	(0.0120)
Obs	1629
F-stat	1465.3

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Impacts on expenditure: lighting

	(1) Light LW	(2) Light Typ.	(3) Kerosene LW	(4) Kerosene Typ.	(5) Light & Kerosene Index	(6) Phone LW	(7) Phone Typ.	(8) Expenditure Index
OLS								
Lamp	-269.6***	-485.9***	-53.24***	-65.28***	-0.162***	-243.5***	-316.6***	-0.228***
	(74.69)	(187.3)	(16.58)	(19.37)	(0.0389)	(25.75)	(69.60)	(0.0369)
Baseline value	0.102***	0.00897**	0.0210**	0.00109	0.120***			
	(0.0191)	(0.00370)	(0.00845)	(0.000962)	(0.0269)			
Control Mean	756.767	1060.773	81.968	93.670	0.026	381.181	469.323	0.006
Observations	1627	1627	1629	1629	1627	1627	1627	1627
ITT								
50% or more	-135.0*	-337.0*	-51.67***	-62.63***	-0.0958**	-203.6***	-289.8***	-0.202***
	(74.35)	(186.1)	(16.46)	(19.22)	(0.0387)	(25.76)	(69.16)	(0.0367)
Baseline value	0.103***	0.00892**	0.0223***	0.00114	0.123***			
	(0.0192)	(0.00370)	(0.00845)	(0.000962)	(0.0270)			
Control Mean	702.798	1007.922	81.915	94.233	0.000	370.215	466.360	0.000
Observations	1627	1627	1629	1629	1627	1627	1627	1627
IV								
Lamp	-197.8*	-493.5*	-75.52***	-91.72***	-0.140**	-298.2***	-424.3***	-0.295***
	(108.6)	(272.3)	(24.07)	(28.16)	(0.0565)	(37.48)	(101.2)	(0.0537)
Baseline value	0.102***	0.00897**	0.0206**	0.00104	0.120***			
	(0.0191)	(0.00370)	(0.00846)	(0.000964)	(0.0269)			
Control Mean	725.326	1064.306	90.541	104.709	0.016	404.309	514.878	0.034
Observations	1627	1627	1629	1629	1627	1627	1627	1627

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports results of OLS regressions of the outcome variables on lamp ownership, where the baseline value is included where data is available. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4

-Outcome variables in columns (1)-(6) are expenditure over the period of 1 week, either last week "LW" or in a typical week "Typ.". Columns (1) and (2) are any expenditure on lighting, (3) and (4) are for kerosene for all uses, while (6) and (7) are for charging mobile phones. Column (6) is an index of the expenditure on lighting and fuel variables and Column (8) is an index of the expenditure on phone variables constructed as in Anderson (2008)

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 6: Impacts on adult labour supply

	(1) Anyone work outside hh	(2) Anyone earning income	(3) Number working outside hh	(4) Number earning income	(5) Labour Index
OLS					
Lamp	0.0514**	0.0212	0.0604	0.0553	0.0749*
	(0.0237)	(0.0223)	(0.0373)	(0.0550)	(0.0407)
Baseline value	0.260***	0.0714***	0.282***	0.0912***	0.192***
	(0.0249)	(0.0227)	(0.0246)	(0.0222)	(0.0247)
Control Mean	0.370	0.717	0.504	1.244	0.007
Observations	1628	1628	1629	1629	1628
ITT					
50% or more	0.0566**	0.0278	0.0630*	0.111**	0.0929**
	(0.0236)	(0.0222)	(0.0370)	(0.0546)	(0.0404)
Baseline value	0.260***	0.0723***	0.283***	0.0924***	0.193***
	(0.0248)	(0.0227)	(0.0245)	(0.0221)	(0.0247)
Control Mean	0.367	0.714	0.505	1.219	-0.000
Observations	1628	1628	1629	1629	1628
IV					
Lamp	0.0829**	0.0406	0.0922*	0.162**	0.136**
	(0.0345)	(0.0324)	(0.0541)	(0.0800)	(0.0592)
Baseline value	0.259***	0.0714***	0.281***	0.0915***	0.191***
	(0.0249)	(0.0227)	(0.0246)	(0.0222)	(0.0247)
Control Mean	0.358	0.710	0.495	1.201	-0.016
Observations	1628	1628	1629	1629	1628

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership and the baseline value. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4
-The outcome variables in columns (1) and (2) are dummies for any individual working outside the household (i.e. not on land owned by the household) and any individual earning income (i.e. not just working for subsistence) respectively. Columns (3) and (4) are the number of individuals doing these tasks. Column (5) is an index of the previous variables constructed as in Anderson (2008).
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 7: Impacts on female labour supply

	(1) Any female work outside hh	(2) Any female earns income	(3) N. females work outside hh	(4) N. females earning income	(5) Female Lab Index
OLS					
Lamp	0.0155	0.000434	0.0138	0.0225	0.0248
	(0.0205)	(0.0253)	(0.0233)	(0.0321)	(0.0443)
Baseline value	0.274***	0.0545**	0.255***	0.0673***	0.187***
	(0.0269)	(0.0258)	(0.0268)	(0.0232)	(0.0260)
Control Mean	0.214	0.469	0.230	0.520	0.033
Observations	1588	1588	1629	1629	1588
ITT					
50% or more	0.0423**	0.0401	0.0415*	0.0584*	0.0915**
	(0.0203)	(0.0251)	(0.0231)	(0.0318)	(0.0439)
Baseline value	0.274***	0.0545**	0.256***	0.0679***	0.187***
	(0.0269)	(0.0258)	(0.0267)	(0.0232)	(0.0260)
Control Mean	0.203	0.451	0.219	0.504	0.004
Observations	1588	1588	1629	1629	1588
IV					
Lamp	0.0618**	0.0586	0.0607*	0.0855*	0.134**
	(0.0298)	(0.0368)	(0.0339)	(0.0466)	(0.0644)
Baseline value	0.272***	0.0538**	0.254***	0.0672***	0.186***
	(0.0270)	(0.0258)	(0.0268)	(0.0232)	(0.0261)
Control Mean	0.196	0.446	0.213	0.494	-0.009
Observations	1588	1588	1629	1629	1588

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports results of OLS regressions of the outcome variables on lamp ownership and the baseline value. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4

-The outcome variables in columns (1) and (2) are dummies for any female working outside the household (i.e. not on land owned by the household) and any female earning income (i.e. not just working for subsistence) respectively. Columns (3) and (4) are the number of females doing these tasks. Column (5) is an index of the previous variables constructed as in Anderson (2008)

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 8: Impacts on juvenile labour supply

	(1) Number working outside the home	(2) Number earning income outside the home	(3) Number enrolled	(4) Juv. Lab. Index
OLS				
Lamp	-0.0133**	-0.0142	0.0564	0.0851**
	(0.00663)	(0.00992)	(0.0365)	(0.0344)
Baseline value	0.00101	0.0585**	0.323***	0.210***
	(0.00438)	(0.0236)	(0.0201)	(0.0297)
Control Mean	0.023	0.041	0.543	-0.016
Observations	1629	1629	1629	1629
ITT				
50% or more	-0.0102	-0.00599	0.0252	0.0431
	(0.00658)	(0.00985)	(0.0363)	(0.0342)
Baseline value	0.000806	0.0584**	0.324***	0.210***
	(0.00438)	(0.0236)	(0.0201)	(0.0297)
Control Mean	0.022	0.038	0.554	-0.000
Observations	1629	1629	1629	1629
IV				
Lamp	-0.0149	-0.00876	0.0368	0.0631
	(0.00963)	(0.0144)	(0.0531)	(0.0500)
Baseline value	0.00104	0.0583**	0.323***	0.210***
	(0.00438)	(0.0236)	(0.0201)	(0.0297)
Control Mean	0.024	0.039	0.550	-0.007
Observations	1629	1629	1629	1629

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership and the baseline value. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4
-The outcome variables in columns (1) and (2) are dummies for any juvenile (14-17 years old) working outside the household (i.e. not on land owned by the household) and any juvenile earning income (i.e. not just working for subsistence) respectively. Columns (3) and (4) are the number of juveniles doing these tasks. Column (5) is an index of the previous variables constructed as in Anderson (2008)
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 9: Intermediate impacts related to income generation: adult time use

	(1) Paid work	(2) Unpaid work	(3) Domestic tasks	(4) Caregiving	(5) Community	(6) Education	(7) Leisure	(8) Self-care	(9) Day length
OLS									
Lamp	23.64**	18.00**	-17.70*	1.888	0.237	2.402	3.948	-5.499	4.334
	(10.46)	(8.992)	(9.079)	(2.032)	(2.732)	(1.620)	(7.668)	(7.179)	(2.985)
Control Mean	235.219	163.553	231.787	13.355	10.186	2.906	247.763	193.904	865.457
Observations	2230	2230	2230	2230	2230	2230	2230	2230	2229
ITT									
50% or more	30.66***	12.20	-15.93*	0.757	-4.171	0.723	-2.263	-4.069	-0.377
	(10.33)	(8.895)	(8.978)	(2.010)	(2.699)	(1.602)	(7.581)	(7.098)	(2.952)
Control Mean	231.668	165.459	231.542	13.772	12.005	3.535	250.226	193.462	867.289
Observations	2230	2230	2230	2230	2230	2230	2230	2230	2229
IV									
Lamp	43.62***	17.36	-22.67*	1.077	-5.935	1.029	-3.219	-5.789	-0.537
	(14.73)	(12.65)	(12.77)	(2.859)	(3.847)	(2.279)	(10.79)	(10.10)	(4.202)
Control Mean	227.496	163.799	233.710	13.669	12.572	3.436	250.534	194.016	867.341
Observations	2230	2230	2230	2230	2230	2230	2230	2230	2229

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports results of OLS regressions of the outcome variables on lamp ownership. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4

-The outcome variables are categories of time use in the last week measured in minutes for the sample of all adults.

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 10: Impacts on Female adult time use

	(1) Paid work	(2) Unpaid work	(3) Domestic tasks	(4) Caregiving	(5) Community	(6) Education	(7) Leisure	(8) Self-care	(9) Day length
OLS									
Lamp	28.85***	20.80**	-18.96*	1.828	2.811	3.172**	3.458	-9.211	6.078*
	(11.12)	(9.101)	(9.854)	(2.789)	(3.171)	(1.275)	(8.635)	(8.541)	(3.400)
Control Mean	160.689	111.588	323.848	19.069	7.766	0.759	229.715	191.512	858.750
Observations	1509	1509	1509	1509	1509	1509	1509	1509	1508
ITT									
50% or more	29.43***	14.32	-16.64*	2.439	-1.805	3.185**	-0.345	-6.707	0.769
	(10.98)	(8.998)	(9.736)	(2.755)	(3.132)	(1.259)	(8.530)	(8.438)	(3.362)
Control Mean	159.610	113.661	323.441	18.763	9.593	0.661	231.186	190.746	860.769
Observations	1509	1509	1509	1509	1509	1509	1509	1509	1508
IV									
Lamp	42.21***	20.54	-23.86*	3.498	-2.588	4.568**	-0.495	-9.620	1.103
	(15.76)	(12.89)	(13.96)	(3.952)	(4.496)	(1.807)	(12.23)	(12.10)	(4.821)
Control Mean	155.556	111.688	325.733	18.427	9.842	0.222	231.234	191.670	860.663
Observations	1509	1509	1509	1509	1509	1509	1509	1509	1508

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports results of OLS regressions of the outcome variables on lamp ownership. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4

-The outcome variables are categories of time use in the last week measured in minutes for the sample of adult females.

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 11: Intermediate impacts related to income generation via improved business practices: mobile money

	(1) Use mobile money	(2) Savings	(3) Volume received	(4) Volume sent	(5) Mobile Money Index
OLS					
Lamp	0.00987	18975.7*	27426.1**	7267.1	0.0192
	(0.0240)	(10412.2)	(13328.4)	(16110.0)	(0.0144)
Baseline value	0.296***				
	(0.0244)				
Control Mean	0.534	45075.299	22266.770	24681.307	0.770
Observations	1627	879	879	879	879
ITT					
50% or more	0.0302	28203.6***	29372.9**	13964.7	0.0313**
	(0.0238)	(10307.1)	(13219.8)	(15980.0)	(0.0142)
Baseline value	0.296***				
	(0.0244)				
Control Mean	0.525	40048.156	20326.846	21276.810	0.764
Observations	1627	879	879	879	879
IV					
Lamp	0.0443	40534.9***	42215.4**	20070.5	0.0450**
	(0.0349)	(14884.9)	(19020.7)	(22982.4)	(0.0205)
Baseline value	0.295***				
	(0.0244)				
Control Mean	0.520	35804.120	15906.857	19175.416	0.759
Observations	1627	879	879	879	879

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership, where the baseline value is included where data is available. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 12: Intermediate impacts related to health and well-being: air quality

	(1) Particulate Matter 2.5	(2) Volatile Organic Compounds	(3) Pollution Index
OLS			
Lamp	-7.316	-0.0389	-0.102
	(5.045)	(0.201)	(0.0848)
Control Mean	166.4	0.7	8.6
Observations	1334	1331	1334
ITT			
50% or more	-8.773*	0.137	-0.178**
	(5.010)	(0.200)	(0.0841)
Control Mean	167.3	0.6	8.6
Observations	1334	1331	1334
IV			
Lamp	-12.72*	0.199	-0.258**
	(7.270)	(0.290)	(0.122)
Control Mean	168.7	0.6	8.6
Observations	1334	1331	1334

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4
The first panel reports results of OLS regressions on dummies for different groups of households: did not purchase a lamp but who already owned a solar lamp at baseline, purchased a lamp and did not already own a solar lamp at baseline, and those that purchased a lamp and already owned a lamp at baseline. The excluded group is households who did not purchase a lamp and did not own one at baseline. The second panel reports IV results.
-Particulate matter is measured in μg/m^3 for particulate matter of size 2.5 micrometers in diameter or smaller. Volatile Organic Compounds (VOCs include organic compounds with an initial boiling point less than or equal to 250°C at standard atmospheric pressure) are measured in parts per million (ppm). Pollution index is calculated as a combination of PM2.5 and VOC measures by the devices which report a value between 0 (Very low) and 9 (Very high).
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 13: Final outcomes : Income

	(1) Household income	(2) Household Income per capita	(3) Log Household income	(4) Log Household Income per capita	(5) Income Index	(6) Make money from charger	(7) Income from charger	(8) Charger Index
OLS								
Lamp	103212.1	15681.2	0.591*	0.520*	0.0720	0.0334***	222.5***	0.386***
	(85279.4)	(12059.0)	(0.320)	(0.273)	(0.0448)	(0.00586)	(58.22)	(0.0698)
Baseline value	2.104***	2.222***	0.0984***	0.106***	0.212***			
	(0.211)	(0.203)	(0.0283)	(0.0293)	(0.0261)			
Control Mean	866302.0	111573.8	8.7	7.3	0.0	0.0	0.0	-0.1
Observations	1555	1555	1555	1555	1555	1629	1629	1629
ITT								
50% or more	146747.0*	22248.6*	0.437	0.397	0.0854*	0.0164***	103.2*	0.187***
	(84661.8)	(11967.7)	(0.318)	(0.271)	(0.0445)	(0.00586)	(58.00)	(0.0697)
Baseline value	2.102***	2.222***	0.0994***	0.107***	0.212***			
	(0.211)	(0.203)	(0.0283)	(0.0293)	(0.0260)			
Control Mean	844662.5	108663.4	8.8	7.4	0.0	0.0	47.5	-0.0
Observations	1555	1555	1555	1555	1555	1629	1629	1629
IV								
Lamp	214511.8*	32537.1*	0.639	0.580	0.125*	0.0240***	151.0*	0.274***
	(123886.2)	(17522.9)	(0.465)	(0.396)	(0.0651)	(0.00852)	(84.62)	(0.101)
Baseline value	2.097***	2.211***	0.0983***	0.106***	0.211***			
	(0.211)	(0.204)	(0.0283)	(0.0293)	(0.0261)			
Control Mean	823601.1	105525.9	8.7	7.3	-0.0	0.0	30.2	-0.0
Observations	1555	1555	1555	1555	1555	1629	1629	1629

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership, where the baseline value is included where data is available. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4
-Outcome variables in columns (1)-(4) are earned income in the last 12 month for the household in column (1), per capita in column (2) and logged versions of both these variables (where 1 is added to account for zeros). Columns (6) and (7) report whether the household has used the charger on the lamp to earn income and how much income they have earned from this. Column (5) is an index of the earned income variables and column (8) is an index of the income from charger variables constructed as in Anderson (2008)
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 14: Final outcomes : Subjective Well-being

	(1) Security (0=worst, 10=best)	(2) Happiness (0=worst, 10=best)	(3) Subjective Well-Being Index
OLS			
Lamp	0.00215	0.257***	0.0718**
	(0.0958)	(0.0917)	(0.0347)
Control Mean	7.4	4.3	0.0
Observations	1627	1627	1627
ITT			
50% or more	0.0403	0.259***	0.0826**
	(0.0951)	(0.0910)	(0.0345)
Control Mean	7.3	4.2	0.0
Observations	1627	1627	1627
IV			
Lamp	0.0590	0.379***	0.121**
	(0.139)	(0.133)	(0.0505)
Control Mean	7.3	4.2	-0.0
Observations	1627	1627	1627

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first panel reports results of OLS regressions of the outcome variables on lamp ownership, where the baseline value is included where data is available. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4.
-The outcome variable in column (1) measures how safe and secure the respondent feels on a scale of 0 (worst) to 10 (best). The outcome variable in column (2) measures respondent's reported life satisfaction on a scale of 0 (worst) to 10 (best). Column (3) is an index previous variables constructed as in Anderson (2008)
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 15: Impacts on health: Respiratory illness

	(1) Share in Household Coughing last week	(2) Share in Household Coughing last month	(3) Share in Household Coughing last 6 months	(4) Respiratory Illness Index
OLS				
Lamp	-0.0599	-0.118	-0.110	-0.0132
	(0.195)	(0.295)	(0.459)	(0.0387)
Control Mean	0.7	1.6	3.6	-0.0
Observations	1629	1629	1629	1629
ITT				
50% or more	-0.190	-0.233	-0.0632	-0.0304
	(0.193)	(0.293)	(0.456)	(0.0384)
Control Mean	0.7	1.7	3.6	-0.0
Observations	1629	1629	1629	1629
IV				
Lamp	-0.278	-0.340	-0.0924	-0.0444
	(0.283)	(0.428)	(0.667)	(0.0562)
Control Mean	0.8	1.7	3.6	0.0
Observations	1629	1629	1629	1629

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports results of OLS regressions of the outcome variables on lamp ownership, where the baseline value is included where data is available. The second panel reports intention to treat (ITT) regressions on a dummy indicating whether the household received a subsidy of 50% or more on the full price of the lamp. The third reports the instrumental variable results using the predicted values for Lamp obtained in the first stage reported in Table 4.

-The outcome variables in column (1)–(3) report the share of household members with a cough in the last week, last month and last six months. Column (4) is an index previous variables constructed as in Anderson (2008)

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 16: Analysis of heterogeneity of impacts

	(1) Light & Kerosene	(2) Phone Exp.	(3) Labour	(4) Female Labour	(5) Mobile Money	(6) Pollution	(7) Income	(8) Income fr. charger	(9) Well-Being	(10) Respiratory Illness
Lamp at Baseline										
Lamp	-0.199**	-0.250***	0.196**	0.149	0.0244	-0.109	0.136	-0.0196	0.136*	-0.173**
	(0.0887)	(0.0839)	(0.0928)	(0.101)	(0.0338)	(0.190)	(0.103)	(0.104)	(0.0787)	(0.0879)
Lamp × Solar at baseline	0.1000	-0.0763	-0.103	-0.0259	0.0351	-0.259	-0.0177	0.318**	-0.0243	0.219*
	(0.115)	(0.109)	(0.121)	(0.131)	(0.0425)	(0.248)	(0.133)	(0.135)	(0.102)	(0.114)
$\beta_1+\beta_2$	-0.0988	-0.326***	0.0934	0.123	0.0595**	-0.368***	0.1178	0.2981***	0.1112*	0.0459
	(0.0735)	(0.0697)	(0.0771)	(0.0837)	(0.0258)	(0.161)	(0.0838)	(0.0863)	(0.0654)	(0.0731)
Education										
Lamp	-0.249**	-0.248**	0.0552	-0.101	0.0401	0.0197	0.0661	0.115	0.106	-0.0864
	(0.101)	(0.0962)	(0.105)	(0.114)	(0.0426)	(0.218)	(0.116)	(0.119)	(0.0904)	(0.100)
Lamp × above primary	0.165	-0.0686	0.134	0.354**	0.00706	-0.374	0.101	0.0760	0.0317	0.0480
	(0.122)	(0.116)	(0.127)	(0.138)	(0.0487)	(0.264)	(0.140)	(0.143)	(0.109)	(0.121)
$\beta_1+\beta_2$	-0.0847	-0.316***	0.189***	0.253***	0.0471**	-0.354**	0.167**	0.191**	0.137**	-0.0384
	(0.0684)	(0.0649)	(0.0711)	(0.0781)	(0.0236)	(0.147)	(0.0782)	(0.0801)	(0.0609)	(0.0677)
Income										
Lamp	-0.206**	-0.273***	0.166**	0.0918	0.0665**	-0.201	0.129	0.0328	0.106	-0.00635
	(0.0803)	(0.0762)	(0.0843)	(0.0910)	(0.0293)	(0.175)	(0.0913)	(0.0943)	(0.0717)	(0.0799)
Lamp × $\geq$ median income	0.131	-0.0450	-0.0585	0.0850	-0.0407	-0.116	-0.0160	0.266**	0.0295	-0.0757
	(0.113)	(0.107)	(0.119)	(0.129)	(0.0411)	(0.245)	(0.129)	(0.133)	(0.101)	(0.113)
$\beta_1+\beta_2$	-0.0757	-0.317***	0.107	0.176*	0.0257	-0.316*	0.1127	0.2983***	0.1354*	-0.0820
	(0.0797)	(0.0754)	(0.0771)	(0.0912)	(0.0288)	(0.171)	(0.0917)	(0.0935)	(0.0710)	(0.0792)

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

-The first panel reports the instrumental variable results regressing the outcome on the predicted values for Lamp obtained in the first stage reported in Table 4, a dummy for solar lamp ownership at baseline and an interaction of these two variables. The second panel reports the instrumental variable results regressing the outcome on the predicted values for Lamp obtained in the first stage reported in Table 4, a dummy if the household completed primary education and an interaction of these two variables. The third panel reports the instrumental variable results regressing the outcome on the predicted values for Lamp obtained in the first stage reported in Table 4, a dummy if the household had above median income at baseline and an interaction of these two variables.

-The outcome variable in each column is the index variable for each family of outcomes.

-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

Table 17: Adjusting for multiple hypothesis testing

	(1) Light & Kerosene	(2) Phone Exp.	(3) Labour	(4) Female Labour	(5) Mobile Money	(6) Pollution	(7) Income	(8) Income fr. charger	(9) Well-Being	(10) Respiratory Illness
ITT										
50% or more	-0.0958**	-0.202***	0.0929**	0.0915**	0.0313**	-0.178**	0.0854*	0.114**	0.0826**	-0.0304
	(0.0387)	(0.0367)	(0.0404)	(0.0439)	(0.0142)	(0.0841)	(0.0445)	(0.0455)	(0.0345)	(0.0384)
Conventional p-value	0.013	0.000	0.022	0.037	0.035	0.035	0.055	0.012	0.017	0.429
Exact p-value	0.016	0.004	0.017	0.037	0.028	0.054	0.052	0.016	0.017	0.451
Family-wise error rate p-value (one-sided)	.0898	.0379	.0898	.1077	.1077	1077	.1077	.0898	.0898	.4570
Sharpened q-values (one-sided)	.008	.001	.008	.016	.016	.016	.016	.008	.008	.032
P-value of joint significance (SUR estimation)	0.000									
Exact p-value of joint significance	0.000									

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
-The first row reports the intention-to-treat results.
-The outcome variable in each column is the index variable for each family of outcomes.
-The control mean in OLS is households without lamps, in ITT and IV it is households with less than 50% subsidy.

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