Title

Impact of a rural solar electrification project on the level and structure of women's empowerment

Journal

Environmental Research Letters, 12(9)

ISSN

1748-9318

Authors

Burney, Jennifer
Alaofè, Halimatou
Naylor, Rosamond
et al.

Publication Date

2017-09-01

DOI

10.1088/1748-9326/aa7f38

Peer reviewed

Impact of a rural solar electrification project on the level and structure of women's empowerment

Environmental Research Letters

LETTER

Impact of a rural solar electrification project on the level and structure of women's empowerment

Jennifer Burney[1,4], Halimatou Alaofè[2], Rosamond Naylor[3] and Douglas Taren[2]

[1] School of Global Policy and Strategy, University of California San Diego, San Diego CA, United States of America
[2] Mel and Enid Zuckerman College of Public Health, University of Arizona, Tucson AZ, United States of America
[3] Center on Food Security and the Environment and Department of Earth System Science, Stanford University, Stanford CA, United States of America
[4] Author to whom any correspondence should be addressed.

E-mail: jburney@ucsd.edu

OPEN ACCESS

RECEIVED
6 February 2017

REVISED
21 April 2017

ACCEPTED FOR PUBLICATION
12 July 2017

PUBLISHED
11 September 2017

Keywords: photovoltaic, drip irrigation, energy access, Solar Market Garden, Benin, women's empowerment, Sustainable Development Goals

Abstract

Although development organizations agree that reliable access to energy and energy services—one of the 17 Sustainable Development Goals—is likely to have profound and perhaps disproportionate impacts on women, few studies have directly empirically estimated the impact of energy access on women's empowerment. This is a result of both a relative dearth of energy access evaluations in general and a lack of clarity on how to quantify gender impacts of development projects. Here we present an evaluation of the impacts of the Solar Market Garden—a distributed photovoltaic irrigation project—on the level and structure of women's empowerment in Benin, West Africa. We use a quasi-experimental design (matched-pair villages) to estimate changes in empowerment for project beneficiaries after one year of Solar Market Garden production relative to non-beneficiaries in both treatment and comparison villages ($n = 771$). To create an empowerment metric, we constructed a set of general questions based on existing theories of empowerment, and then used latent variable analysis to understand the underlying structure of empowerment locally. We repeated this analysis at follow-up to understand whether the structure of empowerment had changed over time, and then measured changes in both the levels and likelihood of empowerment over time. We show that the Solar Market Garden significantly positively impacted women's empowerment, particularly through the domain of economic independence. In addition to providing rigorous evidence for the impact of a rural renewable energy project on women's empowerment, our work lays out a methodology that can be used in the future to benchmark the gender impacts of energy projects.

1. Introduction

Gender equality and women's empowerment have been stated priorities of international development agencies for decades, based on both the intrinsic value of equality as an end in and of itself, and on the empirical evidence that empowerment of women and girls can be a means to other desired development ends, including improved child health and nutrition [1]. Gender equality has historically been the easier of the two concepts to quantify, since any desirable outcome measured at the individual level can simply be disaggregated by gender and relative metrics computed (e.g. [2]). Conversely, the notion of women's empowerment has remained more nebulous, because it is both multi-dimensional and context-dependent [3]. The international development community has struggled with how best to measure women's empowerment [4], and although numerous development projects purport to have empowerment as an objective and/or a pathway for impact, relatively few of them outside of the public health domain have actually measured or reported such impacts.

International development organizations have also long pursued energy projects, with large hydropower and electric grid investments dominating the portfolio in the mid and late 20th century. These projects were typically large, centralized, and geared towards industry

and urban consumers. This worldview—focused on the supply side of the energy equation—was enshrined in the Millennium Development Goals (MDGs) adopted in 2000, which notably did not include indicators for energy access, beyond the proportion of the population using solid fuels. Over the past decade, however, the development community has begun to rethink energy security as a problem of both physical supply and economic and physical access. Recognizing that what individuals require is in fact energy services—and that energy services can be different from grid infrastructure—a proliferation of both public projects and private investments in microgrids, solar home systems, and pay-as-you go pricing options has sprung up across the developing world, and in rural areas in middle-income emerging markets [5]. The post-2015 Sustainable Development Goals (SDG) framework reflects this shift, and has enshrined energy access as a standalone development target [6]. The SDG framework also explicitly recognizes that energy access alone might pit development against the environment, and thus calls for reliable access to affordable, clean energy.

There are many pathways through which reliable clean energy access might have a disproportionate impact on women by opening new opportunities for them [7–9]. Perhaps most straightforwardly, across many developing communities (and especially rural ones), households are fundamentally energy constrained. They rely on burning biomass as their main source of energy, and the responsibility for gathering the household's daily energy supply—wood, agricultural residues, and animal manure—typically falls to women and girls, who spend hours (and tremendous amounts of physical energy) gathering and transporting it [10]. The health benefits to women of cleaner-burning cookstoves have been well-established [11], but far less peer-reviewed research has focused on the gender impacts of other energy technologies. Large-scale electricity provision in Indian slums [12] and across the Rwandan countryside [13], as well as evaluations of distributed solar photovoltaic systems [14] suggest strong equity impacts for women, but the literature directly measuring impacts on empowerment is thin [9]. From an environmental perspective, the ability to quantify the full suite of impacts of renewables-based development projects—including empowerment—is necessary to make the case for clean versus conventional approaches.

Here we present impact analysis of a rural solar electrification project on women's empowerment in the Kalalé district of Benin, West Africa. The centerpiece of the village electrification project, the Solar Market Garden (SMG), is a passive photovoltaic pumping and irrigation system shared within existing village women's agricultural groups. It was developed and refined by the Solar Electric Light Fund (SELF)[5], and is now implemented by a local community-based development organization (L'Association de Dévéloppement Economique Sociale et Culturel, et l'Autopromotion (ADESCA-ONG)).[6] After a pilot-scale evaluation between 2007-2010, SELF and ADESCA-ONG secured funding to install 8 new Solar Market Gardens in villages across Kalalé. Results from the two-village pilot study have been described elsewhere [15–17]; here we present analysis from the scale-up phase that began in 2013. We leveraged this expansion to study the impacts of this rural energy access project on economic development, food security, and women's empowerment. In addition to determining the best metrics for measuring levels of empowerment, we also developed a methodology to assess changes in the structure of empowerment itself over time—a key potential pathway for impact of rural energy and environment projects.

2. Project context and research design

The SMG was designed by solar technicians, community organizers, and farmers with the objective to expand agricultural production for local women's farming groups engaged in counter-season hand-watered horticulture far from the grid. In this monsoonal, semi-arid region, hand-watered horticulture is limited predominantly by energy—the labor required to fetch water by hand—with important consequences for both income and nutrition. By providing reliable energy access to pump irrigation water, and by sharing the bulk cost of the system among a group of farmers, the SMG was designed to cost-effectively expand productivity along three margins—increases in farmed area (extensive), higher yields via improved inputs and management practices (intensive), and facilitation of year-round production (temporal). This increase in production could be sold, consumed in the home, or donated in-kind (e.g. meals for kids at school), providing many pathways for impact on the economic well-being and food security of project beneficiaries and their households, and of other community members, who might reap various spillover benefits.

Along with these potential pathways for impact on core sustainable development outcomes related to poverty, food security, and nutrition, we hypothesized that women's empowerment might also be directly affected, although we were agnostic about the expected sign. Studies have shown that economic development is in general associated with increased empowerment [1], but the literature on interventions with women's groups has been mixed. In particular, the literature is unclear as to whether women's groups promote or facilitate empowerment themselves [18–20] and

[5] SELF is an American NGO based in Washington, DC (www.self.org). Its funding comes from charitable contributions and grants.

[6] ADESCA-ONG is a local NGO focused on development and solar energy access in Kalalé, Benin. Its funding comes from charitable contributions and grants.

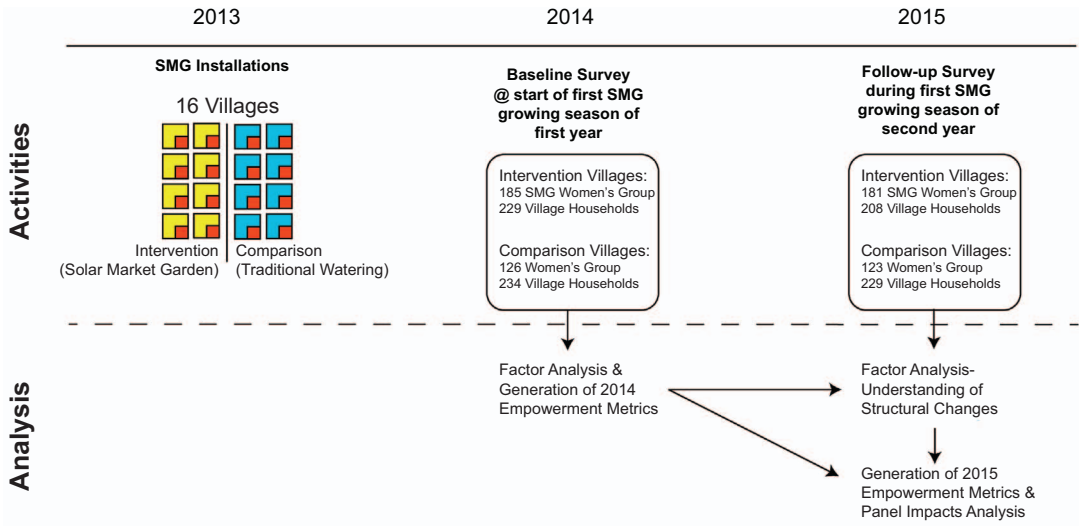

Figure 1. Outline of the SMG project timeline, including survey data collection (Activities), and the analysis presented here.

whether interventions targeting women or women's groups may have unintended negative consequences (for example, strain or even violence as a response by husbands or others to female economic empowerment or changing decision-making power in the household) [21, 22]. Our formative research included interviews with all women's groups in the district prior to selection of intervention and comparison villages; these interviews suggested a broad range of 'openness' between women and their husbands within and between villages, but almost all said their husbands were unaware of exactly how much money they were making, and that this information asymmetry was largely intentional on their part.

We used a quasi-experimental design to measure the baseline levels and overall structure of women's empowerment in Kalalé, across treatment and comparison villages; we then re-assessed both levels and structure of empowerment after one full year of SMG operation. Installations for the SMG scale-up phase began in 2013, with systems functional and first plantings taking place in late 2013 and early 2014. Each SMG is installed on land that was both traditionally allocated and formally titled to the women's agricultural group in the given village; most of the SMGs are centrally located within their villages, or within a 5-10 minute walk for the majority of group members. The solar photovoltaic system pumps water from a borewell (between 10 and 60 m deep); although it varies by village, between 25 and 40 group members share the SMG technology, with each woman farming her own ~120 m^2 plot and contributing to shared group plots.

We surveyed all members of village women's agricultural groups in eight treatment and eight matched-pair comparison villages in Kalalé, along with a random sample of 30 non-women's group households in each of the 16 villages at both the start of the project (just as the SMGs went into operation) and one year later, in early 2015; in all, 771 female respondents were surveyed at baseline and follow-up. (There was some attrition from baseline to follow-up (33 women, or 4.3%), that was spread across villages, with 6 the most from any one village. Around 2/3 of the attrition was comparison households within intervention villages; beyond this, however, there appears to be no structural differences in terms of who was most likely to drop out of the sample.) Household questionnaires included information on all household members, detailed income, production, consumption, and assets data, as well as information on access to services, dietary intake questions, and a set of questions (described further below) intended to assess women's empowerment. In addition, as part of the larger food and nutrition security assessment, women of childbearing age and the youngest household child under the age of five completed a biometric assessment (height, weight, and blood samples for anemia and vitamin A tests). The study was approved by the National Ethics Committee for Health Research (NECHR) of Benin. Ethical clearance was obtained from the Institutional Review Boards (IRBs) charged with the protection of human research subjects of the University of Arizona (UA). The analysis portion of the project was additionally approved by the IRB of the University of California, San Diego.

3. Methods

3.1. Measuring women's empowerment

International organizations that have sought to measure women's empowerment have struggled with: (a) the nebulous nature of the concept itself, (b) the desire to build pre-defined indices that can be applied over a broad range of contexts to facilitate comparative study, and (c) the recognition that empowerment can be extremely context-specific. As

a brief example of this history and tension, the United Nations, the World Bank, and the International Food Policy Research Institute have taken three different approaches to measuring empowerment. The UN has largely avoided setting out specific indicators for empowerment and has focused on gender equality and (reductions in) gender violence. Gender equality and women's empowerment were first enshrined jointly as Goal #3 of the MDGs, but the United Nations tracked only equality indicators—the ratio of females to males across all levels of education, literacy rates, non-agricultural employment, and national parliaments [23]. In 2015, the UN adopted the SDGs as successors to the MDGs; Goal #5 of the SDGs seeks to 'Achieve gender equality and empower all women and girls' [24]. Again, the SDG framework includes targets for equality of representation in government and managerial positions, as well as in access to technology; it also includes more nuanced verbiage on empowerment: Target 5.4 advocates for 'the promotion of shared responsibility within the household as nationally appropriate', and Target 5.a focuses on 'reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws' [24]. Nevertheless, the specific indicators for the SDG empowerment targets are largely equality metrics.

In contrast to the SDG approach, the International Food Policy Research Institute (IFPRI) developed the Women's Empowerment in Agriculture Index (WEAI) in 2012 [25]. The WEAI is an overall empowerment index constructed from five pre-specified domains of empowerment—decisions about agricultural production, access to and decision-making power over productive resources, control over use of income, leadership in the community, and time use. This pre-specified format is meant to facilitate both measurement of baseline levels of empowerment as well as changes over time in a broad range of developing agricultural communities. The tradeoff of the fixed index is that the given set of indicators comprising the index may not be equally relevant in all areas. Largely because of this, the World Bank has eschewed a fixed index approach and instead gathers indicators, both equity and empowerment related, that can be used in contextually-appropriate ways [26].

To construct our empowerment metrics, we draw from the concepts put forward in the WEAI and the SDGs, but take an approach more along the lines of the World Bank. Our questionnaire did not include a comprehensive time use survey, and we did not interview male heads of household so we are unable to construct within-household equity metrics, as described in the SDGs. But drawing on these ideas, along with the specific domains and sets of indicators used by the WEAI and included in the World Bank gender database, we included thirty-two empowerment-related questions in our household survey. We conducted latent variable analysis to understand the underlying structure of empowerment in Kalalé, and then built a locally-appropriate empowerment index for the region. These methods are described in detail below.

3.2. Questionnaire coding

The 32 questions included in the empowerment module of our household survey are shown in table 1. Original questionnaire codings are shown, along with the final binary coding for the particular dimension. Most of our codings are conservative ('sometimes' and other intermediate answers are coded as zeros, or *not* empowered in that particular dimension); we conducted our analysis with the alternative coding ('sometimes' and other intermediate answers coded as 'empowered'), and did not see meaningful differences.

3.3. Factor analysis

We used the 32 recoded question in a latent variable analysis–that is, we assumed that our variables likely had some underlying correlation structure and could be represented by a set of latent variables, or 'domains' that more accurately described the structure of empowerment than the simple collection of 32 variables. To find this structure, we first randomly divided our baseline (2014) data into training and test sets. We conducted exploratory factor analysis (EFA) with the training set; using the combination of selecting factors with eigenvalues > 1 (figure 2 (left, orange)) and the criteria that individual variables should load onto factors with loadings > 0.6, we arrived at a set of 6 underlying factors based on 22 variables. This initial model from the EFA is shown in figure 3.

We then used the test half of the data set to conduct a confirmatory factor analysis (CFA) on the 6-factor, 22-variable model. We named the six domains based on the variables that loaded onto them (figure 3)–(1) Decision Making, (2) Physical Mobility, (3) Male Involvement, (4) Economic Security, (5) Self Confidence, and (6) Group Membership. Table 3 shows the various fit indices for this initial specification of our structural model (with agreed-upon criteria shown for reference in the table notes). We used modification indices to understand where our model could be improved: where two variables were highly correlated within the same domain, we removed the variable with a lower EFA factor loading. This process resulted in a final structural equation model with 16 variables in the 6 domains. The final variables are shown in table 2, with the modified model fit indices in the second column of table 3 and final eigenvalues shown in figure 2 (right).

Table 1. Summary of empowerment questions asked as part of a comprehensive household survey of both beneficiary and comparison households within and between villages, at the start and one year after project implementation.

Q#	English version of prompt	Original coding	Binary recoding
	In your household, who has the last word on decisions regarding:	1: Head of Household 2: Respondent 3: Another member of the household	0 (No): 1,3,6,96,98 1 (Yes): 2,4,5
1	Whether you will work to make money?	4: Respondent and head of household	
2	Whether you will use a method of contraception?	5: Respondent and other household members	
3	Decisions on kids' schooling?	6: A group of household members	
4	What to do if a member of household is sick?	96: others out of household	
5	How to discipline children?	98: Don't know	
6	Whether to have another child or not?	99: N/A	
	Are you habitually authorized to go to the following places:	1: Yes, alone 2: Only if accompanied 3: Not at all	0 (No): 2,3 1 (Yes): 1
7	Local market for purchases?		
8	Health center or traditional doctor?		
9	Visit friends in the village?		
10	Religious sites?		
11	Other villages/cities?		
	Do the adult male members of your household help you:	0: Not at all 1: Very rarely 2: From time to time	0 (No): 0,1,2 1 (Yes): 3,4
12	Prepare meals?	3: Regularly	
13	Clean the house?	4: Always	
14	Do laundry?		
15	Make purchases for house?		
16	Taking care of kids?		
17	Do you feel like an important member of your household?	0: No / Never 1: Sometimes / A little 2: Always / Yes	0 (No): 0,1 1 (Yes): 2
18	Do you think the members of your household listen to you and respect your opinion?	0: No / Never 1: Sometimes / A little 2: Always / Yes	0 (No): 2,3 1 (Yes): 1
19	If you have a problem at home, do you feel confident enough to resolve it on your own?	0: No / Never 1: Sometimes / A little 2: Always / Yes	0 (No): 2,3 1 (Yes): 1
20	Do you have money of your own that you alone manage?	0: No 1: Yes	0 (No): 0 1 (Yes): 1
	Do you take care of the finances needed to buy:	0: No 1: Yes	0 (No): 0 1 (Yes): 1
21	Fruits and vegetables?		
22	Clothing for yourself?		
23	Healthcare/treatment for yourself?		
24	Beauty products for yourself?		
	If you need help, can someone in your family always:	0: No 1: Yes 98: Don't know	0 (No): 0,98 1 (Yes): 1
25	Ensure shelter for a few nights?		
26	Give you some money if necessary?		
	Are you a member of:	0: No 1: Yes	0 (No): 0 1 (Yes): 1
27	A religious organization?		
28	A social organization?		
29	A women's organization?		
30	A labor organization?		
31	A political organization?		
32	When there is a local or national election, do you vote?	0: Never 1: Sometimes 2: Always	0 (No): 0,1 1 (Yes): 2

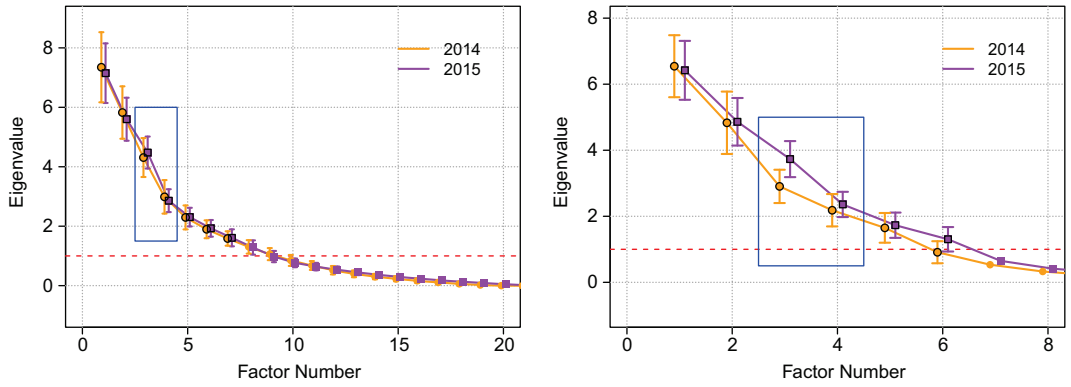

Figure 2. Scree plots of the initial EFA and the final model (after CFA and revision), for independent analyses of baseline (2014) and follow-up (2015) data. 95% confidence intervals for the factors were obtained by conducting 500 bootstrap repetitions. Independent analysis on both years of data resulted in the same overall number of factors, and with similar overall relative importance, with one notable exception. In both years, decision making and physical mobility were the two most important factors (i.e. they accounted for most of the variation in the sample), but in baseline the third-most important factor was male involvement, while in follow-up it was economic independence (blue boxes, see figure 3). The change in importance of economic independence to the overall structure of empowerment is highly statistically significant.

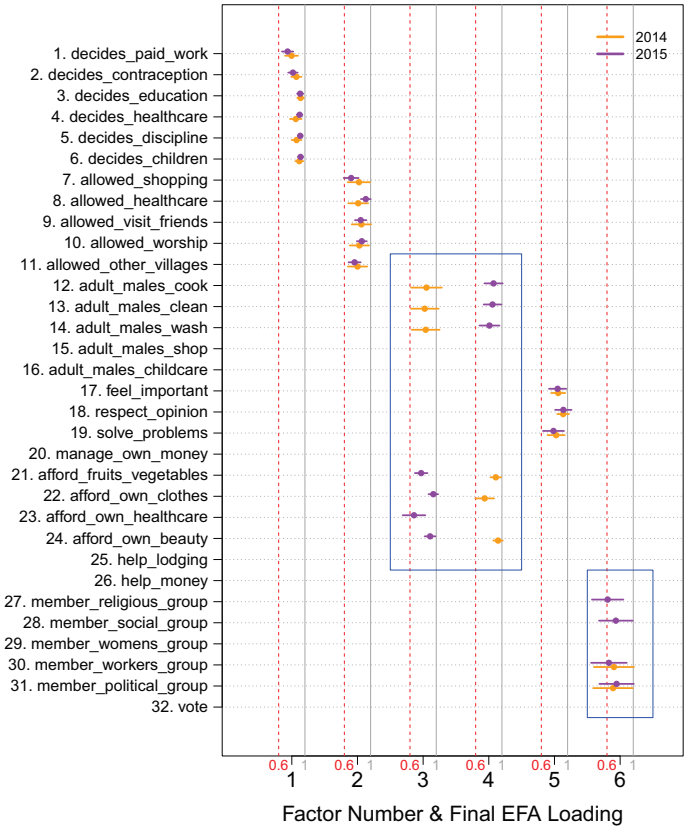

Figure 3. Factor loadings for independent EFA analyses on baseline (2014) and follow-up (2015) data. Based on these factor loadings we named the underlying domains: Decision Making, Physical Mobility, Male Involvement, Economic Independence, Self Confidence, and Group Membership. To estimate the 95% confidence interval for the factor loadings, we repeated the EFA with 500 bootstrap resamplings. The individual loadings stay fairly consistent between the two time periods, with the exception of the switch in order between male involvement and economic independence (blue box) and the increased loadings for religious and social group membership in 2015.

Finally, using the entire dataset, we then constructed two sets of empowerment indicators based on this final model. For the first set we simply constructed the individual domain scores by adding the final indicators within each domain (table 2 (left)), and then the total empowerment score by adding the domain scores. This set of score variables can be used as an overall benchmark, with changes indicating a net movement from not empowered to empowered (or the other way around) in one of the explanatory

Table 2. The six domains for empowerment as determined by exploratory factor analysis (latent variables analysis), with final composition after confirmatory factor analysis and model refinement for both 2014 and 2015 data.

Domain	2014 Final model	2015 Final model
DECISION MAKING	decides healthcare + decides education + decides children	decides paid work + decides education + decides children + decides discipline
PHYSICAL MOBILITY	allowed shopping + allowed healthcare + allowed visit friends	allowed worship + allowed visit friends
MALE INVOLVEMENT	adult males cook + adult males wash	adult males clean + adult males wash
SELF CONFIDENCE	feel important + respect opinion + solve problems	feel important + respect opinion
ECONOMIC INDEPENDENCE	afford fruits vegetables + afford own clothes + afford own beauty	+ afford own clothes + afford own healthcare
GROUP MEMBERSHIP	member workers group + member political group	member workers group + member political group

Table 3. Fit indices for initial and final (refined) confirmatory factor analysis, 2014 and 2015. Ideal thresholds for these statistics, indicating a good structural equation model, are indicated beneath the table.

	2014 Initial	2014 Refined	2015 Initial	2015 Refined
CFI	0.880	0.976	0.863	0.973
TLI	0.858	0.968	0.842	0.961
RMSEA	0.088	0.043	0.081	0.046
p(RMSEA)	0	0.937	0	0.770
SRMR	0.054	0.035	0.065	0.040
GFI	0.846	0.966	0.839	0.971
AIC	2157	4555	5212	6744
BIC	2384	4769	5462	6941

CFI = Comparative Fit Index (>0.9).
TLI = Tucker Lewis Index (>0.95).
RMSEA = Root Mean Square Error of Approximation (<0.06).
SRMR = Standardized Root Mean Residual (<0.08).
GFI = Goodness of Fit Index (>0.9).

variables. The second set of indicators is a relative empowerment indicator, used to assess whether an individual is relatively empowered or disempowered within the sample. For these indicators we recoded each woman's domain and total empowerment scores to 1 if it was above the sample mean, and zero for below.

3.4. Changes over time

To estimate the impacts on empowerment over time, it is necessary to construct indicators for the follow-up time period (2015). The dominant practice is to simply assume the same factors and factor loadings, and to construct the factors in follow-up as in baseline. This approach is useful in that it references the individual baseline and is easily interpretable, but the same concern holds as for any index: it is possible that the very structure of empowerment changes over time, and that the latent variable model from baseline is no longer as good for follow up. As a result of this concern, some practitioners have begun recommending that independent factor analysis be conducted on follow-up data to verify the structure [27]. We pursue both approaches and define two sets of follow-up variables. The first set uses the baseline definitions to create the follow-up metrics; the second repeats the entire EFA/CFA process independently on the follow-up data.

To estimate impacts we run regression analysis using the model specification:

$$E_{it} = a_i + \beta_r r_t + \beta_{wg} wg_i + \beta_{wg*r}(wg_i * r_t) + \beta_{treat}(wg_i * treat_i * r_t) + \epsilon_{it} \quad (1)$$

where E_{it} is the empowerment score (either total or for an individual domain) for respondent i at time t. The a_i are respondent fixed effects, and r_t, wg_i, and $treat_i$ are binary variables for, respectively, the survey round ($r_t = 0$ for baseline, 1 for follow-up), whether or not the respondent is in a women's group, and whether the respondent was in a treated village or not. The estimated coefficients then give the average change in empowerment from baseline to follow-up for all respondents ($\hat{\beta}_r$), for being in a women's group versus not ($\hat{\beta}_{wg}$), and the impact of being in a women's group over time ($\hat{\beta}_{wg*r}$). Finally, $\hat{\beta}_{treat}$ gives the SMG project impact on empowerment (women in treated women's groups, over time). For total scores we use OLS regression; for the relative empowerment scores (binary), we use logistic regression. We estimated treatment effects using both constructions of the follow-up (2015) indicators.

4. Results

4.1. Factor analysis and structural changes

Scree plots showing the eigenvalues of the underlying factors (latent variables) derived from our EFA are shown in figure 2, with initial EFA for each year shown on the left and final structure (after CFA and model refinement) on the right. We began EFA allowing an arbitrarily large (20) number of underlying factors and then refined down to 6 based on the criteria defined above. The factor eigenvalues can be thought of as the amount of the covariance within the entire set of included variables that is explained by the individual factor (or the group of variables that comprise that underlying quantity). An eigenvalue greater than 1 means that the factor (combination of variables) explains more of the overall variance than a single variable.

For both baseline and follow-up, decision-making power and physical mobility were the largest explanatory factors, and self confidence and group membership were the smallest. However, the intermediate factors—male involvement in household tasks and economic independence, switched in terms of order of importance, with economic independence becoming more important in explaining sample variation over time. The 95% confidence intervals on both factor eigenvalues (figure 2) and individual factor loadings (figure 3) were calculated by conducting 500 bootstrap resampling of the EFA. As shown in figure 2, in addition to changing its relative rank importance, the eigenvalue for economic independence in follow-up (purple) is both significantly larger than in baseline (the third orange value) and significantly larger than the fourth eigenvalue (male involvement) in follow-up.

Within the individual factors, loadings did not change in a statistically significant manner for most variables, but a few did change rank order within a given factor, resulting in different set of variables in the independent construction of follow-up indicators (table 2), but not much of a difference in overall explanatory power of the different factors, beyond the changes described above.

4.2. Project impact

The SMG project had statistically and practically significant impacts on women's empowerment for project beneficiaries over the first year of use. Table 4 shows the impact over time of the project on total empowerment scores and on odds ratios, with the follow-up metrics constructed using both of the techniques described above. The marginal impact of being a project beneficiary was almost 2 points (1.947), or about two questions in table 2. Our model (equation (1)) accounts for the selection bias of being in a women's group in general, the time trends of the whole sample, and the time trends for women's group members versus non-women's group members (both treatment and comparison). It is noteworthy that over time, there appears to be no net offset for being in a women's group versus the regular village sample, but that on average the entire sample is less empowered over time, and in general members of women's groups over time also report lower levels of empowerment. Against this backdrop, the project impact (a marginal 2 point change over a baseline of 9 points), is even more important.

The odds ratios (table 4) give the likelihood of a respondent falling within the upper half of the distribution of empowerment scores–a relative metric compared to the total score itself. In this formulation we again see that project beneficiaries are 2.7 times more likely to be in the upper half of the distribution after access to the SMG. The versions of the models that use the 2015-specific empowerment construction (columns 3 and 4 of table 4) can be thought of as endogenizing some of the structural changes to empowerment; it thus makes sense that the magnitudes of the changes are slightly lower.

Tables 5 and 6 show the impacts of the SMG project on the individual domains of empowerment (in both tables, follow-up (2015) scores are constructed using the baseline (2014) factor analysis). The domain scores show that overall, women in Benin tend to have some decision-making power and the freedom to visit friends, shop, etc. (physical mobility); they also tend to feel respected and empowered to solve problems (self confidence). Through SMG access, beneficiaries were more likely to have improvements in the domains of economic independence (being able to provide for some of their own needs), male help with domestic tasks, self confidence, and participation in other groups. These impacts offset for project beneficiaries an overall decrease in these domains over time (for the whole sample).

Table 4. Regression results showing the impact of the Solar Market Garden project on total women's empowerment. Results shown for both total score (columns 1 and 3) and binary empowerment status, defined as 1 if total score is above the sample median (columns 2 and 4). The first two models use the same construction of the empowerment domains and indicator for both pre (2014) and post (2015); the third and fourth models use the independent factor analysis construction of empowerment for each year. The last row of the table shows the coefficients for total project impact: project beneficiaries were more likely to have higher empowerment scores after follow-up.

	Total empowerment			
	2014 Model for 2015		2015 Model for 2015	
	Score *OLS* (1)	Status *logistic* (2)	Score *OLS* (3)	Status *logistic* (4)
Constant	8.933***	19.033	9.171***	19.156
	(2.030)	(12,108.580)	(1.893)	(12,456.070)
Women's Group	0.132	0.982	0.329	1.736*
	(0.719)	(0.840)	(0.671)	(0.902)
Round (Post)	−0.783**	−1.165**	−0.614*	−0.827*
	(0.389)	(0.455)	(0.363)	(0.467)
Women's Group*	−0.295*	−0.114	−1.865***	−1.252***
Round (Post)	(0.177)	(0.196)	(0.165)	(0.198)
Women's Group*	1.947***	2.728***	1.479***	1.488***
Treatment Village*	(0.450)	(0.546)	(0.419)	(0.534)
Round (Post)				
Observations	1545	1545	1545	1545
R^2	0.552		0.595	
Adjusted R^2	0.099		0.184	
Residual Std. Error (df = 767)	2.680		2.500	
F Statistic (df = 777; 767)	1.217***		1.449***	
Log Likelihood		−451.326		−464.943
Akaike Inf. Crit.		2458.652		2485.886

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 5. Regression results estimating impact of Solar Market Garden project on individual women's empowerment domain scores.

	Dependent variable:					
	Decision making (1)	Physical mobility (2)	Economic independence (3)	Male involvement (4)	Self confidence (5)	Group membership (6)
Constant	2.536***	3.316***	0.498	−0.115	2.608***	0.089
	(0.830)	(0.739)	(0.917)	(0.384)	(0.947)	(0.395)
Women's Group	0.183	−0.316	−0.066	0.039	0.360	−0.069
	(0.294)	(0.262)	(0.325)	(0.136)	(0.335)	(0.140)
Round (Post)	0.015	0.196	−0.632***	−0.156**	0.083	−0.288***
	(0.159)	(0.142)	(0.176)	(0.074)	(0.182)	(0.076)
Women's Group*	0.402***	−0.279***	0.030	0.056*	−0.455***	−0.049
Round (Post)	(0.072)	(0.064)	(0.080)	(0.033)	(0.082)	(0.034)
Women's Group*	0.144	0.083	0.737***	0.251***	0.436**	0.298***
Treatment Village*	(0.184)	(0.164)	(0.203)	(0.085)	(0.210)	(0.087)
Round (Post)						
Observations	1545	1545	1545	1545	1545	1545
R^2	0.509	0.489	0.500	0.521	0.546	0.536
Adjusted R^2	0.012	−0.030	−0.007	0.036	0.086	0.066
Res. Std. Err. (df = 767)	1.096	0.975	1.210	0.506	1.250	0.521
F Statistic (df = 777; 767)	1.025	0.943	0.986	1.074	1.187***	1.140**

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$.

5. Discussion

The Solar Market Garden—a distributed photovoltaic irrigation system—was designed to help farmers surmount the energy barrier to year-round horticulture production in the Sudano-Sahelian climate. By providing reliable renewable energy access for irrigation water, the SMG enables enhanced production, sales, and consumption of these high-value micronutrient crops. For the first time here, we show that this distributed energy project focused on economic and food security outcomes also directly impacted

Table 6. Odds ratios for impact of Solar Market Garden project on individual women's empowerment domains.

	Dependent variable:					
	Decision making (1)	Physical mobility (2)	Economic independence (3)	Male involvement (4)	Self confidence (5)	Group membership (6)
Constant	18.597	20.811	−20.173	−24.144	18.045	−20.480
	(11 193.040)	(12 534.300)	(7604.186)	(19 745.950)	(12 425.500)	(20 669.160)
Women's Group	1.092	−0.185	0.614	1.299	2.217**	−1.056
	(0.753)	(0.967)	(0.835)	(1.809)	(0.970)	(1.119)
Round (Post)	−0.822	0.949**	−2.304***	−2.136***	−0.112	−2.302***
	(0.500)	(0.473)	(0.452)	(0.676)	(0.459)	(0.595)
Women's Group*	2.081***	−0.759***	0.632***	0.628**	−1.515***	−0.568*
Round (Post)	(0.233)	(0.192)	(0.186)	(0.298)	(0.196)	(0.326)
Women's Group*	1.865***	−0.308	1.657***	3.436***	2.315***	2.810***
Treatment Village* Round (Post)	(0.626)	(0.549)	(0.521)	(0.822)	(0.534)	(0.642)
Observations	1545	1545	1545	1545	1545	1545
Log Likelihood	−357.322	−467.280	−510.646	−197.965	−469.804	−230.824
Akaike Inf. Crit.	2270.644	2490.559	2577.292	1951.931	2495.609	2017.648

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

women's empowerment. Beneficiaries were both more likely to improve their overall empowerment score—reflecting new decision making power, mobility, economic independence, self-confidence, equity at home, or group participation—and were more likely to be in the upper half of empowerment scores in the sample.

One of the most interesting results of this analysis is that the SMG—likely through expanding women farmers' market and economic activity—is associated with a change in the very structure of empowerment in Kalalé; after implementation, economic independence becomes a statistically more important determinant of relative empowerment. The methods we have used here to structurally model women's empowerment in an agnostic manner—and to then quantify any changes in that factor analysis over time—should become standard practice given that empowerment is context-dependent. That is, the actual magnitudes of SMG impact on the level and structure of women's empowerment in northern Benin may not be directly comparable to other projects, because the very structure of empowerment can be different across contexts or, as we have shown here, in the same population over time.

It remains unclear why the overall time trends for total empowerment, and for the domains of economic independence, male involvement, and group membership, are negative. Given the study setup, built around a difference-in-differences project evaluation, we are unable to discriminate between three possibilities: (1) intervention-induced changes on the entire sample (i.e. Hawthorne effects), (2) real social changes around them that have altered women's perceptions of their own empowerment (e.g. if the Kalalé district is being 'left behind', and so women perceive their own status as lower in a relative sense as time passes), and (3) true declines in empowerment that might be associated with larger regional trends towards, for example, increased religiosity. The inability of our quasi-experimental setup to answer this question further points to the need for systematic, repeated measures of women's empowerment over time.

Here we provide a methodology and a set of practices that could be used to both document women's empowerment more broadly, and to benchmark the empowerment impacts of different kinds of development projects, including those focused on energy and environment as pathways. The strength of the methods presented here is that they could be used broadly across contexts; nevertheless a careful understanding of the right set of underlying questions to ask across different socioeconomic and cultural environments is needed, and these methods should be compared to existing qualitative approaches to understanding empowerment.

Women stand to gain from reliable and affordable energy access, but conventional methods of expanding energy access could also mean increased environmental damages. Such damages (for example, in impact studies of biomass-based cooking) may in fact have disproportionate negative impacts on women. It is thus critical to understand how renewable energy projects compare to conventional energy projects on all dimensions, including women's empowerment, to create informed and equitable development policy.

Acknowledgments

We would like to thank the members of the Kalalé SMG groups, the ADESCA-ONG team, and village representatives for their support in carrying out this research.

References

[1] Duflo E 2012 *J. Econ. Lit.* **50** 1051
[2] United Nations Gender Inequality Index 2016
[3] Kabeer N 2005 *Gender Dev.* **13** 13
[4] Malhotra A, Schuler S R and Boender C 2002 Measuring Women Empowerment as a Variable in International Development *Report* (Washington, DC: The World Bank)
[5] Alstone P, Gershenson D and Kammen DM 2015 *Nat. Clim. Change* **5** 305
[6] United Nations 2015 United Nations Sustainable Development Goals: 17 Goals to Transform Our World. Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all
[7] Khlin Gunnar, Sills Erin O, Pattanayak Subhrendu K and Wilfong Christopher 2011 Energy, Gender and Development What are the Linkages? Where is the Evidence? A background paper for the World Development Report 2012 on Gender Equality and Development SR125 (Washington, DC: World Bank)
[8] Cabraal R A, Barnes D F and Agarwal S G 2005 *Ann. Rev. Environ. Resour.* **30** 117
[9] World Bank 2011 *World Development Report 2012: Gender Equality and Development* (Washington, DC: The World Bank)
[10] Howells M, Alfstad T, Victor D, Goldstein G and Remme U 2005 *Energy Policy* **33** 1833
[11] Lim SS *et al* 2013 *Lancet* **380** 2224
[12] Parikh P, Fu K, Parikh H, McRobie A and George G 2015 *World Dev.* **66** 468
[13] Lenz L, Munyehirwe A, Peters J and Sievert M 2017 *World Dev.* **89** 88
[14] IdInsight (idinsight.org) 2015 D. Light Solar Home System Impact Evaluation *Technical Report*
[15] Burney J, Woltering L, Burke M, Naylor R L and Pasternak D 2010 *Proc. Natl Acad. Sci.* **107** 1848
[16] Burney J A and Naylor R L 2012 *World Dev.* **40** 110
[17] Alaof H, Burney J, Naylor R and Taren D 2016 *Food Nutr. Bull.* **37** 164
[18] Westermann O, Ashby J and Pretty J 2005 *World Dev.* **33** 1783
[19] Swain R B and Wallentin F Y 2009 *Int. Rev. Appl. Econ.* **23** 541
[20] Gugerty M K and Kremer M 2008 *Am. J. Polit. Sci.* **52** 585
[21] Kabeer N 2001 *World Dev.* **29** 63
[22] Schuler S R, Hashemi S M and Badal S H 1998 *Dev. Pract.* **8** 148
[23] United Nations 2015 United Nations Sustainable Development Goals: 17 Goals to Transform Our World. Goal 5: Achieve gender equality and empower all women and girls
[24] United Nations 2000 United Nations Millennium Development Goals. Goal 3: Promote Gender Equality and Empower Women
[25] Women's Empowerment in Agriculture Index (WEIA) 2012
[26] World Bank Gender Data Portal (Accessed June 2015)
[27] Osborne J W *et al* 2012 *Pract. Assess. Res. Eval.* **17** 2