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Fertility transition powered by women's access to electricity and modern cooking fuels

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Access to electricity and modern cooking fuels especially for women, leads to time savings in the home, improved health and better access to information. These factors increase women's well-being and enhances their ability to make reproductive choices, which is empirically expressed by falling birth rates. This study provides an international analysis of the relationship between access to modern energy and fertility, based on panel data synthesized from 155 Demographic and Health Surveys over 26 years. Controlling for other determinants, we find that access to electricity and modern cooking fuels, along with education, negatively affect fertility. Energy and education effects are complementary and strongest in regions with initially high fertility rates. Expanded access to modern energy and education would accelerate the demographic transition. Therefore, the energy demand and carbon emissions needed to achieve the SDG of energy access while ensuring gender equality and climate action would be lower in the long term than currently assumed.

Modern energy is a central pillar of human development and well-being[28, 40, 57]. Particularly for women, access to modern energy leads to less time spent on household chores[6, 64, 49], lower child mortality[1, 11, 55], better health[48, 6, 41, 62], access to information[49, 6] and education[65]. All these factors contribute to strengthening women's ability to make informed reproductive choices, a fundamental precondition for women's well-being[9]. Enhanced ability to make reproductive choices is in turn empirically reflected in falling birth rates[59].

Although access to modern energy has expanded globally in recent decades, in 2018 still 2.6 billion people had no access to clean cooking energy and 860 million had no access to electricity[24]. Moreover, almost half of the women aged 15-49 who lived in marriage or union worldwide had no control over their reproductive decisions[53], underlining the urgent need to better understand the factors that enable women to realize their reproductive rights.

If women's access to modern energy can improve their ability to make reproductive choices and this in turn leads to fewer children, then the impact of access to modern energy on fertility should be empirically detectable. Previous research has shown this effect for electricity for several countries[14, 15, 46, 44, 12, 18] (for a detailed overview of the existing literature see Supplementary Section E).

Building on these findings, we here provide an international analysis of the effect of women's access to energy on fertility and include access to modern cooking fuels as a novel explanatory variable. We use 155 Demographic and Health Surveys (DHS) from 44 low- and middle-income countries over 26 years (1990 - 2015), which we aggregate to 403 subnational regions. This allows us to examine changes over time while controlling for any relatively stable structural, historical, or geographic differences across regions and populations. This unique panel data set covers about ~45% of the world's population and about ~80% of the population of countries above the replacement fertility rate. Our indicator for fertility is the total fertility rate (TFR), defined as the average number of live births that a hypothetical cohort of women would have at the end of their reproductive period assuming uniform period fertility rates over the life cycle and no mortality.

Access to modern energy and fertility

In most research on energy and fertility, observed fertility declines are interpreted as a change in reproductive choices due to altered costs and benefits from household access to electricity[14, 15]. Such a theoretical framework implicitly assumes that the number of children is always a choice.

However, the majority of women in developing countries have little or no influence over the number of children they have[53]. We consider three complementary theoretical channels in which access to modern energy can affect fertility by enabling women to make unconstrained and informed reproductive choices (Figure 1).

First, access to modern energy reduces the burden of time-consuming domestic tasks associated with the use of traditional energy, which is often imposed on women and children. For example, collecting firewood can take up to 5 hours per day in some countries[23]. The resulting high requirements for child labor[50] favors or even requires a high number of children in households without access to modern energy, particularly in rural areas[7]. In such conditions, women lack alternative choices and tend to sustain a high fertility. How exactly women spend the time saved through improved access to energy varies[65, 43], but there is evidence that they use it at least in part for increased employment[16, 8, 64] and formal education[6]. Both are associated with reduced fertility[42, 34].

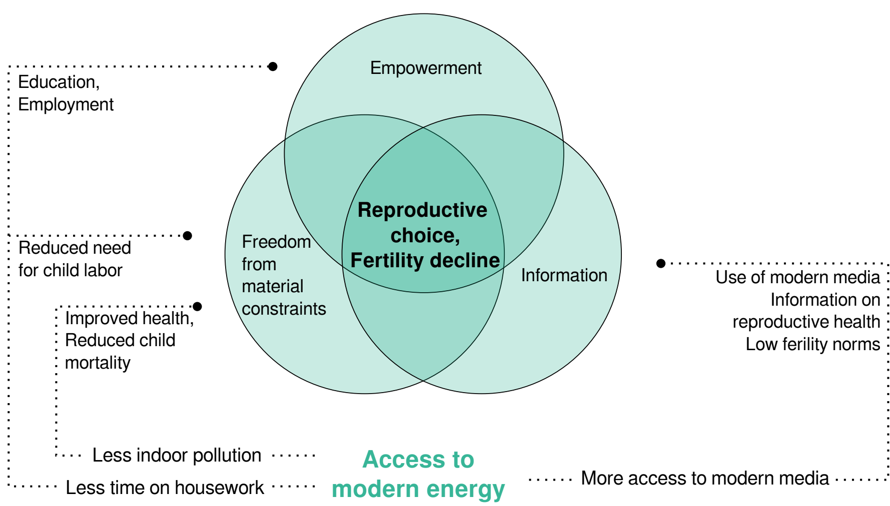

Figure 1: The three main theoretical channels through which expanded access to modern energy affects reproductive choice and fertility, based on literature and our own conceptualization.

Second, access to modern energy improves health and reduces child mortality[1, 11, 55]. Indoor air pollution caused by traditional cooking techniques leads to a heavy burden of respiratory disease and 2.8 million premature deaths annually[23], predominantly among women and children. High child mortality in turn constrains women's reproductive choices as they need to bear more children to achieve the same desired family size[54].

Third, electricity enables access to modern sources of information, for example via mobile phone, which can provide information on reproductive health and modern contraception[52], child health, nutrition, vaccination, and disseminate low fertility norms through television shows[32, 27]. This empowers women to make informed reproductive choices and avoid unwanted births.

The three channels of influence can reinforce each other. For example, improved access to energy can lead to time savings, which in turn can be used for the consumption of information and learning with modern information and communication technologies[37]. Better health and less indoor air pollution can also create better conditions for the education of girls and women's employment.

Historical trends, effects and mechanisms

Access to modern energy correlates strongly with fertility. This association is apparent in temporal trends over the past two and a half decades, with important differences between income groups (Figure 2).

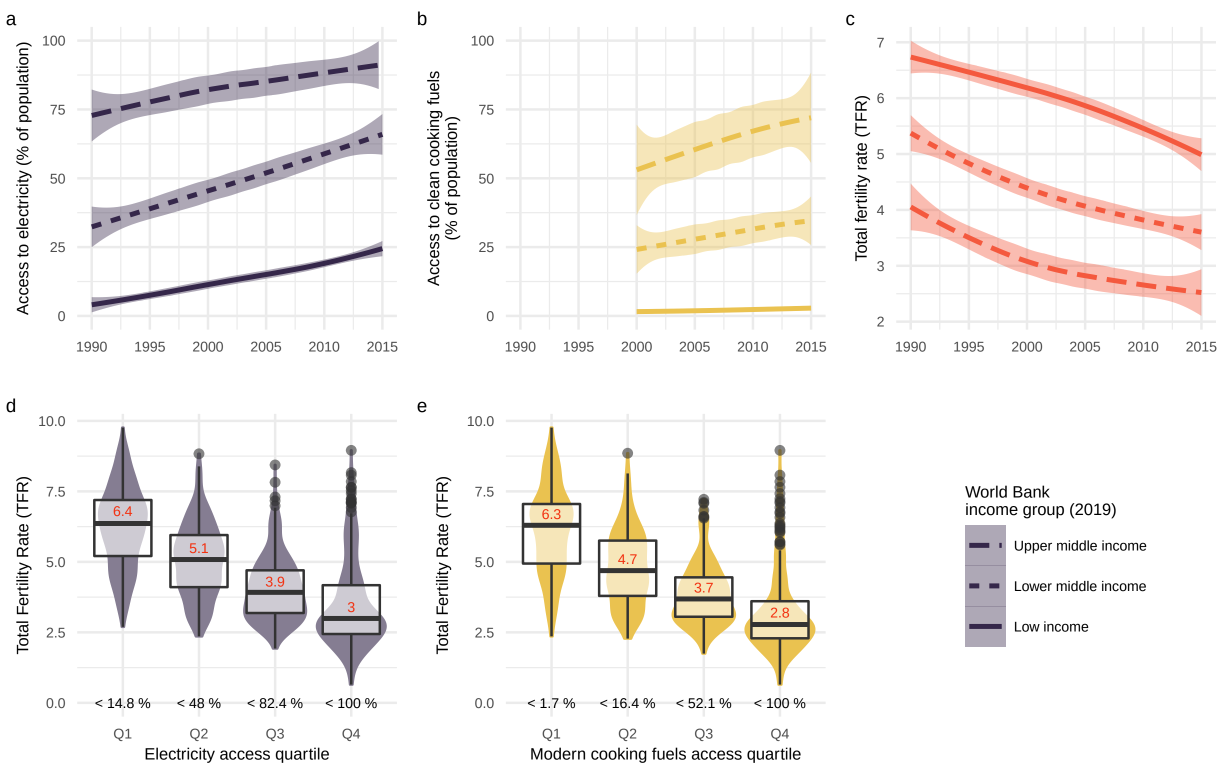

Figure 2: Trends in access to electricity, modern cooking fuels and fertility in 44 countries. Panel (a), (b) and (c) represent, respectively, the average access to electricity, access to clean cooking fuels, and the average total fertility rate over time in 44 countries, by country income groups, based on World Bank data (95% confidence interval as shaded area). Countries are aggregated by World Bank income groups (based on the 2019 classification). Note that the World Bank energy access indicators differ slightly from those used in this study (Supplementary Note 1). Panels (d) and (e) represent electricity access quartiles for 44 DHS countries from 1990 to 2015 and access to modern cooking fuels quartiles for 36 DHS countries from 1999 to 2015 (b). Numbers at the bottom show the 25% (Q1), 50% (Q2), 75% (Q3) and 100% (Q4) access quartiles. Violin plots indicate the country distribution of the Total Fertility Rate (TFR) within each quartile. Boxplots show the median TFR value (number in red), the interquartile ranges (boxes), and the 1.5x interquartile range (whiskers).

The total fertility rate (TFR) decreases with increasing access to electricity and modern cooking fuels for a pooled sample of annual observations of DHS regions (Figure 2). In regions with the lowest access to modern energy (first quartile) the TFR is more than twice as high as in regions with the highest access (fourth quartile). The differences are substantial, with a median of 6.4 children per woman in low-access regions compared to 3 in high-access regions. The median access across all regions is 48% for electricity and only 17% for modern cooking fuels (see also Supplementary Table 3).

Table 1: Results of fixed-effect models analyzing the effect of access to modern energy on the total fertility rate.

	Total Fertility Rate			
	M1	**M2**	**M3**	**M4**
Women with access to electricity (%)	-0.018^{***}		-0.008^{**}	
	(0.003)		(0.004)	
Women with access to modern cooking fuels (%)		-0.013^{***}	-0.012^{***}	
		(0.004)	(0.004)	
Women with access to electricity and modern cooking fuel (%)				-0.013^{***}
				(0.004)
Years of education (Women)	-0.320^{***}	-0.315^{***}	-0.283^{***}	-0.320^{***}
	(0.053)	(0.061)	(0.064)	(0.062)
Percentage of urban households (%)	0.0002	−0.007	−0.006	−0.006
	(0.003)	(0.006)	(0.006)	(0.006)
GDP (100$ per capita)	-0.007^{**}	0.0003	0.001	0.0002
	(0.003)	(0.004)	(0.004)	(0.004)
Mean age at marriage of women	0.065	0.043	0.058	0.049
	(0.068)	(0.081)	(0.081)	(0.081)
Conflict indicator (deaths/10000)	-0.009^{***}	-0.010^{***}	-0.010^{***}	-0.010^{***}
	(0.003)	(0.003)	(0.003)	(0.003)
Adjusted $R2$	0.37	0.29	0.3	0.29
Number of countries/regions	44 / 403	36 / 319	36 / 319	36 / 319
N	1356	940	940	940

Regression coefficients of fixed-effects models with cluster robust standard errors in parentheses. Clustering of standard errors on the sub-national region level. The dependent variable is the total fertility rate in the region. The indicator for access to modern energy is the percentage of women aged 15-49 who have access to electricity (M1, M3), access to modern fuels for cooking (M2, M3) or access to both at the same time (M4). The sample size for the models M2, M3 and M4 is smaller because fewer DHS surveys collected information on access to modern cooking fuels. The models control for region and time fixed effects. With different specifications in terms of controls variables, the coefficient for access to electricity ranges from -0.025 (+- 0.003) to -0.017 (+- 0.003), and the coefficient for access to modern cooking fuel ranges from -0.016 (+-0.005) to -0.013 (+-0.004). The coefficient for the average years of education ranges from -0.375 (+- 0.054) to -0.306 (+- 0.050) when the energy indicator is access to electricity and ranges from -0.315 (+- 0.061) to -0.303 (+- 0.057) when the energy indicator used is access to modern cooking fuels (Details in Supplementary Tables 24 and 25). P-values: 0.1 > * > 0.05 > ** > 0.01 > ***

We tested the hypothesis that expanding women's access to electricity and modern cooking fuels reduces total fertility rates (Table 1), using fixed effects panel regression models. The models are based on changes within regions over time to ensure that our results are not affected by any relatively stable structural, historical or geographical differences between regions and the populations considered. Female education is considered as an additional explanatory variable as it has been widely recognized as a major driver of fertility[35, 26, 31, 17]. To isolate the effect of access to modern energy from other known influences, we controlled for time trends and for changes in the level of urbanization, conflict, average age at marriage and national GDP as a proxy for income (for a detailed description see the Method section and Supplementary Note 2).

Across the 403 regions, we find that a one percentage point increase in the share of women with access to electricity led to a reduction of the TFR by 0.018 children, holding all other variables constant (Table 1, M1). Likewise, the TFR decreased by 0.013 children for every one percentage point increase in the access to modern cooking fuels (Table 1, M2). The results are robust to the inclusion of both variables in a single model to account for dependencies between the variables (Table 1, M3) and to the use of a combined energy indicator (Table 1, M4) that measures the percentage of women with access to both electricity and modern cooking fuels. The effect of electricity access is weaker in model M3, suggesting a relationship between the modern energy indicators. The sample size is lower for the models that include access to modern cooking fuels as explanatory variable, because this information was not collected in all regions and survey waves.

The effect of modern energy access on fertility can be substantial. According to World Bank data, between

1990 and 2015, the average access to electricity rose from 31% to 57% in the countries in our sample and the TFR dropped from 5.6 to 3.8 children per woman[66]. Our model suggests that a quarter of this decrease in TFR is due to expanded access to electricity, illustrating its important role in fertility decline. As a comparison, according to our models, improvements in education have contributed 45% to the observed reduction in the total fertility rate (Supplementary Method 6).

Following our theoretical framework and building on previous literature[14, 19, 36], we explore the extend to which improved health, access to information, increased female labor force participation as a proxy for time savings, and the use of modern contraception explain the observed effects of expanded access to modern energy on fertility. We find that access to television is a particularly important short-term mediating channel, explaining 33% of the observed electrification effects on fertility (Supplementary Table 12). This result closely mirrors previous findings on Indonesia[14] and India[27] and suggests that modern information and communication technologies may have played an important role in fertility transitions during the period 1990-2015. Although our dataset did not have information about mobile phone use, in particular in earlier years, we could expect that mobile phone usage also may play an important role in fertility transitions, by allowing the fast diffusion of information about reproductive and sexual health and empowering women to make independent decisions[52].

Changes in child mortality (Supplementary Table 10) and the use of modern contraception (Supplementary Table 11) are found to only explain a small part of the energy effects, possibly due to the short time horizon of our analysis. Similarly, we do not find evidence that female labor force participation mediates energy effects on fertility (Supplementary Table 11).

The fertility transition describes the decline in birth rates that can be observed in all countries across the world as they transition from mostly large family agrarian to small family industrial societies. Typically, the transition follows a non-linear pattern. After an initial strong drop in fertility, many countries experience a gradual reduction in the pace of the transition once fertility levels approach the replacement rate[60]. While the overall pattern of the fertility transition is often similar, there are large differences between countries and regions[3, 30].

To test whether the absolute fertility level had an influence on the strength of the effect of modern energy access, we included an interaction term between the modern energy access variables and the regional baseline fertility level, i.e., the fertility level in the first available survey year (Supplementary Figure 4). The interaction term allows the effects of modern energy access to vary with the baseline fertility level.

We find considerably larger effects of expanded access to modern energy in areas with a higher baseline fertility level (Figure 3, panels (a) and (b)). The interaction effects are significant for all modern energy access indicators (Supplementary Table 6). Using the combined energy indicator as a reference, our results suggest that a one percentage point increase in access to modern energy in a region with a TFR of 6 in the first DHS wave is estimated to lead to reduction of the TFR by 0.06 children (0.066 - 0.022 x 6). Accordingly, the effect of expanding access to modern energy was about 82% larger in areas with a TFR of 6 than in areas with a TFR of 3.5 children per woman.

The effect of modern energy access on fertility was particularly strong in countries in sub-Saharan Africa, where baseline fertility levels were relatively high (Figure 3, panel (c)). Similarly, we find a more pronounced effect in low-income countries in South Asia, such as Pakistan. The exemplary focus on Nigeria (Figure 3, inset) reveals large differences in the marginal effect of modern energy on fertility decline among the regions in Nigeria. This underlines the importance of using the rich sub-national variance in our data set to uncover underlying heterogeneities in the data.

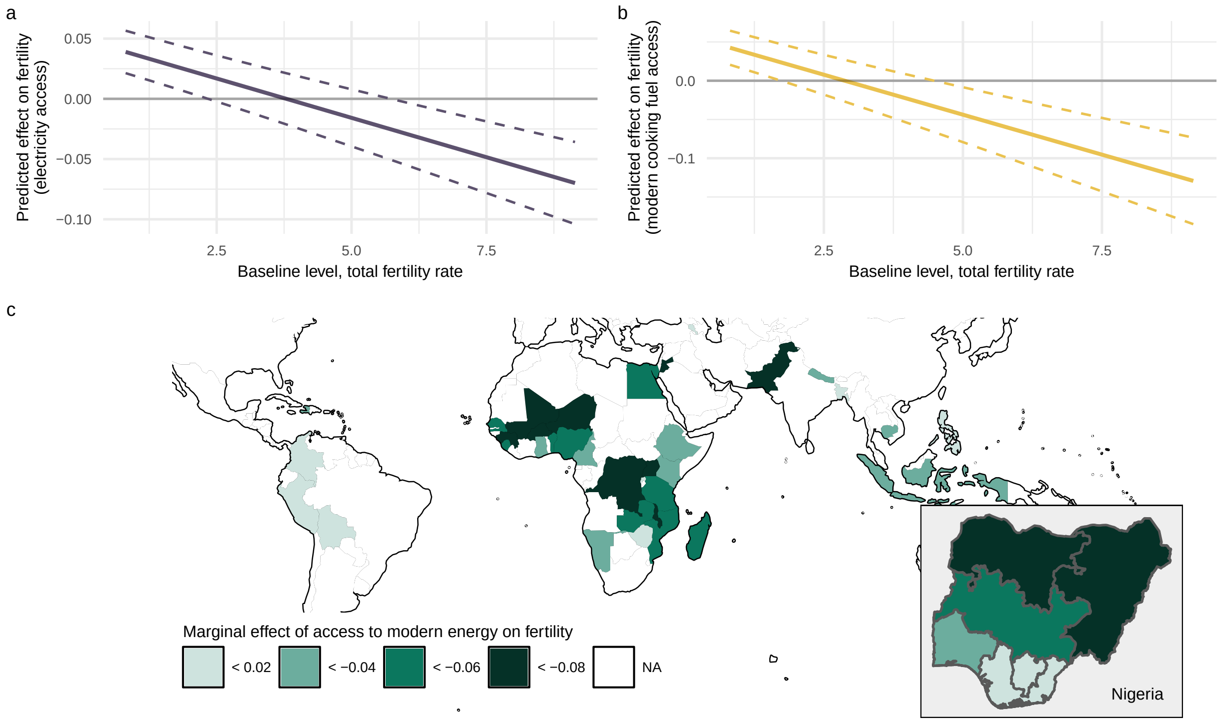

Figure 3: Marginal effects of access to modern energy on fertility. Panels (a) and (b) represent the marginal effects on fertility of, respectively, access to electricity and access to modern cooking fuels, by baseline levels of total fertility rate. The baseline level is the level of fertility in the first year available in our data. The solid line corresponds to the marginal effect and the dotted lines delimitate the 95% confidence intervals. Panel (c) represents the marginal effect of access to both forms of energy on fertility in 36 countries. The inset depicts the spatial distribution of marginal effects within Nigeria to illustrate within-country differences in the relationship. Panels (a), (b) and (c) correspond respectively to models M5, M6 and M7 (Supplementary Table 6) which include an interaction between access to modern energy (electricity, modern cooking fuels or access to both) and the baseline levels of fertility in the region.

The effects of education and energy combined

In our models, the region's level of education of women had a strong impact on fertility (Table 1), which is consistent with the long-standing literature on the role of female education on sustained fertility decline. It has been shown that increasing education can change plans, intentions and timing of having children by raising womens' status and autonomy and increasing contraceptive practice[35, 26, 31, 17].

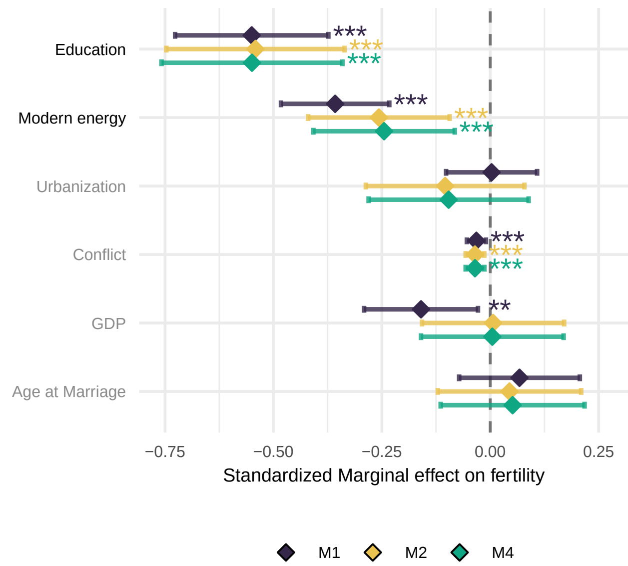

Figure 4: Standardized coefficients of different factors on fertility in three models. The modern energy indicator corresponds to access to electricity (purple), access to modern cooking fuels (yellow) or access to both at the same time (green). The explanatory variables are indicated in black, the controls in grey. The variables were normalized by subtracting the mean value and dividing it by the standard deviation, in order to make the coefficients for the explanatory variables comparable. The models from which these coefficients are derived are the same as those in Table 1, but with standardized variables. P-value levels : $0.10 > * > 0.05 > ** > 0.01 > ***$

We find that with every additional year of schooling for women in a region, the TFR was reduced by 0.32 children per woman (Table 1, M4). This means, all else being equal, that an additional three years of schooling lead on average to a reduction in fertility by about one child per woman. Taken together, energy and education showed strong effects on fertility in our models. In standardized terms, improvements in education and modern energy access (combined indicator) by one standard deviation resulted in a fertility decline of 0.55 and 0.24 standard deviations, respectively (Figure 4).

Improvements in modern energy access and education may occur simultaneously, for example in the context of large-scale development initiatives, and the influence of both factors on fertility may be interdependent. We investigated this by examining the interaction between access to modern energy and the baseline education level in a region and a variable that captures changes in female education over time. The models also control for the non-linearity of the fertility response by including the interaction between modern energy access and the baseline fertility level. We find no significant interaction between modern energy access and changes in women's education, suggesting that the effects of education improvements and expanded modern energy access are additive (Supplementary Table 8).

However, we observe a negative interaction term between access to modern energy and the baseline education level, indicating a complementarity between the two factors. The higher the baseline level of education, the stronger (more negative) the effect of modern energy access on fertility (Extended Data 1, panels (a) and (b) and Supplementary Table 7). For example, improved energy access is estimated to lead to a 2 times stronger reduction in fertility in a region with an average baseline education level of 10 years compared to a region with a level of 6 years of schooling.

There are different possible explanations for this complementarity. Women with higher education may benefit more from expanded access to modern energy, for example because they may be better able to understand and effectively use information disseminated through modern communication and media channels, such as mobile phones[52] or television[32, 27], or because they may be better able to operate modern cooking and electrical appliances effectively.

To estimate the magnitude of potential fertility reductions under different scenarios of expanded access to modern energy, we performed a simulation focused on sub-Saharan Africa, the world region with the highest expected population growth by the end of the century[60]. Our simulations are based on a model where the effects of electricity access and education on fertility depend on the baseline levels of fertility (Supplementary Table 9). These simulations project future fertility based on energy and education scenarios, all other factors being held constant.

We developed three scenarios for the expansion of access to modern energy and women's education in sub-Saharan Africa based on two electrification scenarios of the International Energy Agency[22] (see Methods). The first scenario ("Baseline") envisages an increase in electrification coverage from the current 45% to 65% by 2040. The second, more ambitious scenario ("Universal access") assumes full electrification by 2040. With regard to women's education, both scenarios are based on a continuation of existing country trends. Our third scenario ("Universal access + Education") expands on the second scenario by adding to current country-specific education trends one and a half standard deviations of the average percentage increase in educational attainment in sub-Saharan Africa. Like the IEA scenarios, our simulations only consider electricity access, not access to modern cooking fuels (Supplementary Method 7).

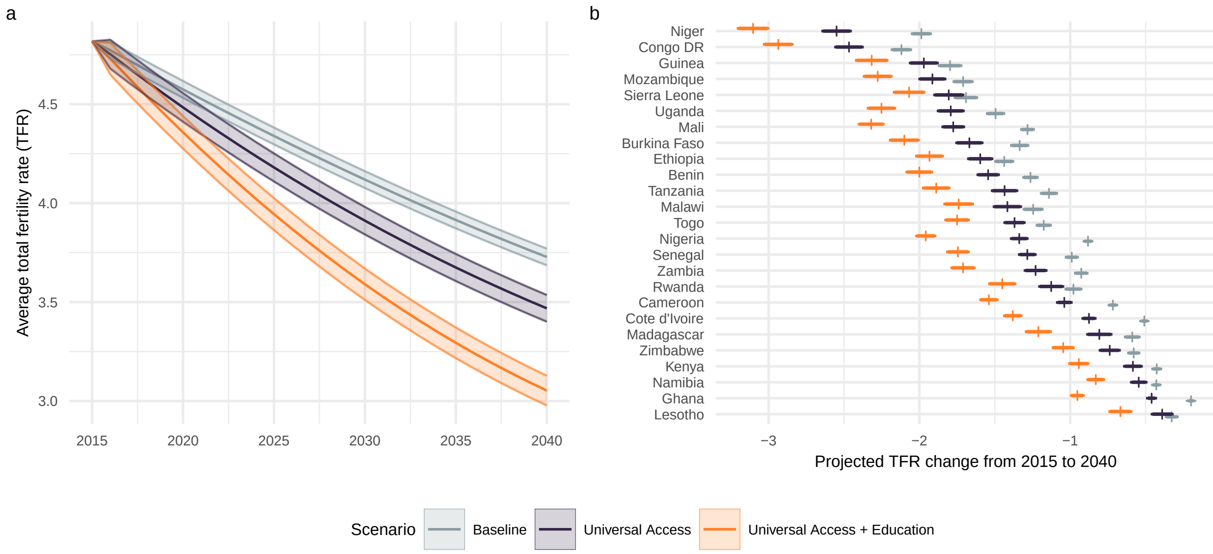

Figure 5: Predicted fertility decline from 2015 to 2040 in 25 sub-Saharan African countries under three scenarios of access to electricity and female education. Panel (a) depicts the average total fertility rate in the 25 countries, with the shaded area corresponding to the 95% confidence intervals. Panel (b) shows the fertility decline between 2015 and 2040 for each of the sub-Saharan African countries simulated, with error bars corresponding to 95% confidence interval. In the 'Baseline' scenario, all countries reach a level of 65% access to electricity in 2040. In the 'Universal Access' scenario, all countries reach 100% in 2040. Both scenarios assume a continuation of past trends in female educational attainment. In the 'Universal Access + Education' scenario, countries achieve full access to electricity by 2040 and improve their previous trends in the educational level of women by 1.5 standard deviations. The model used for this simulation and the methodology employed are detailed in Supplementary Table 9 and Supplementary Method 7, respectively.

According to our simulation, the average TFR in sub-Saharan Africa would drop to 3.5 children per woman in 2040 in the "Universal Access" scenario, which is 6% lower than the "Baseline" scenario (Figure 5). Under the combined "Universal Access + Education" scenario, the average TFR would be 19% lower (3.0 children per woman) than in the "Baseline" scenario, suggesting a large potential for combined education and energy interventions.

Although our predictions are based on a simple extrapolation, they are consistent with other projections for the region. For example, the medium variant of the UN's TFR forecast of 3.6 children per woman in 2040[60] lies between our estimates for the three scenarios. The fertility reductions differ from one country to another due to the different baseline fertility levels of the countries (Figure 5, panel (b)). Based on our models, countries with high baseline fertility levels like Niger are expected to experience a larger fertility decline, especially in the "Universal Access + Education" scenario.

Discussion

Fertility transitions are complex and multi-causal phenomena[39] embedded in broad structural, socio-economic and technological change[13]. Overall, our results suggest that access to modern energy, along with education are powerful drivers of this transition.

Modern energy and education are fundamental resources that enable women and girls to be better informed about reproductive health, relieve them of the need to have many children to do time-consuming housework and help them overcome patriarchal family and community structures that restrain the realization of their reproductive rights. All this contributes to strengthening their ability to make reproductive choices, which tends to lead to a fertility decline[59].

Further efforts are needed especially at the interface between energy research and reproductive health research. There is a need for studies that go beyond energy access and examine the impact of the use of energy appliances on fertility, which will become more important in the future, such as improved cooking stoves, off-grid solar devices like lamps or mobile phones. A better understanding of the timing of energy's role in fertility transitions would also be a step forward and could be based on household panel data in which the same household is repeatedly interviewed over long periods of time. Such analysis could also help enhance the understanding of the mid- to long-term mechanisms through which expanded access to electricity and modern cooking fuels affects fertility, which we could not investigate in this study. Field research and qualitative approaches provide complementary methods to investigate less tangible social and cultural factors that can act as barriers or amplifiers of the effects of modern energy on women's empowerment[56, 51] and their fertility.

Currently, models assessing future energy and carbon costs of tackling energy poverty[2, 4, 47] all use population projection scenarios that do not systematically account for interdependencies between energy and population. Our results suggest that if energy access expands rapidly, these scenarios will overestimate population growth and thus future total energy demand (and associated emissions) to end energy poverty. If lower energy demand due to reduced population growth were to outweigh growth due to per capita increases, determined policies to end energy poverty could even have a net positive effect on climate change mitigation. However, such synergies can only be brought to light if population projection models would endogenize modern energy access or if energy-consistent population scenarios were used, as was done with education, for example, in the work of K.C. et al (2017)[29].

Recognizing the multiple benefits of modern energy for women's lives opens new avenues for development policies and the simultaneous achievement of several Sustainable Development Goals, including SDG 1 on poverty reduction, SDG 3 on good health and well-being, SDG 5 on gender equality, SDG 7 on affordable and clean energy and SDG 13 on climate action. This would represent an alternative to public policy population control programs and patriarchal institutions that both deny women their reproductive rights[9]. Such developmental programs would not target fertility decline per se, but rather target female well-being, empowerment and reproductive choice and where decline in fertility is a consequence of the latter[33]. However, for such programs to be successful, various political, social and cultural barriers would need to be overcome[38].

Methods

Data

Our analysis is based on Demographic and Health Survey (DHS)[20] data as primary source of information. Since its creation in 1986, the DHS Program has collected more than 400 surveys in over 90 countries all over the world with a focus on low- and middle-income countries. The DHS data are individual-level data and are nationally and sub-nationally representative of the sampled population. We used the "Individual Recode" files of the DHS surveys, meaning that the sample consists of women between the ages of 15 to 49.

The representative surveys contain information on various indicators of population, health and nutrition, including information on fertility. Especially in more recent surveys, respondents were asked about whether their household has access to electricity and the primary source of energy used for cooking. We could not use all available DHS data in our study because for some countries either information was collected only once, but not consecutively, or the data did not contain our variables of interest, energy access and fertility. In particular, information on access to modern cooking fuels was only included in the DHS from the year 2000 on. The final sample used for our analysis is based on 2.17 million individual DHS records from 44 countries, representing 45% of the world's population.

Creating a panel from the DHS household survey data required a number of preprocessing steps. In a first step, we collected the raw data for all available DHS surveys. In a second step we harmonized the definition of regions. The DHS data are typically representative at the sub-national admin 1 level, which corresponds, for example, to a district or province in a country (Supplementary Table 1). However, the regional subdivision of countries changes from time to time, which is also reflected in the DHS surveys. The harmonization of regions' definition over time was a necessary step to increase the sample size but also to avoid that our results are affected by changes in administrative subdivisions in some DHS regions over time. The harmonization was carried out on the basis of the IPUMS-DHS information on integrated geography[25] and the DHS spatial repository[21], and allowed to maximize the number of years for each region. We also created a data set that maps the original and harmonized region names and indices for 254 DHS surveys. The data as well as the instructions on how to construct the harmonized regional data set are publicly available on a git repository. Further details about the DHS regions and their harmonization over time is provided in Supplementary Method 1, Supplementary Table 1 and Supplementary Figure 1.

In a third step, we aggregated the data collected from individual respondents to 403 harmonized sub-national DHS regions over 26 years (from 1990 to 2015). We used individual weights provided in the DHS data to correct for the disproportionate sampling necessary to the data collection (Supplementary Method 2). Since the respondents interviewed in DHS survey are not the same from one wave to the other, the aggregation to the sub-national level was necessary to obtain longitudinal data. This enabled analyzing the effect of changes in energy access on fertility within regions over time, while removing time-invariant heterogeneity in the estimation of our regression coefficients. While data from the individual respondents (2.17 million records) is used for the aggregation, the sub-national regions represent the unit of analysis in our study (n=1356). The dataset containing information about access to modern cooking fuels is smaller (36 countries and 319 regions over 17 years from 1999 to 2015), as the indicator was not widely used in the DHS surveys before the year 2000.

We used two additional data sources to complement the main regional panel data with country-level variables. We use the World Bank open data repository[66] to obtain information on the national GDP per capita and the Uppsala Conflict Data Program[58] to add a conflict indicator. The rest of the variables used were calculated directly from the DHS. A table of descriptive statistics of the panel data set is provided in Supplementary Table 3.

Note that due to gaps in the data collection, survey waves were not conducted in all countries at all times. The panel of the DHS regions is hence unbalanced (Supplementary Figures 2 and 3). We ran additional models in which we controlled for these gaps in the data (Supplementary Table 18). We also employed complementary data sources for descriptive analyses and robustness checks. Data from the World Bank open data repository[66] was used to build a second country-level panel data set that contains comparable variables to the DHS data. The country-level data allowed us to test whether the patterns we observed at the sub-national level also apply in a cross-country analysis. We found that the effect of electrification on fertility is negative and significant, and that the effect size is similar in magnitude to the effect size reported in Table 1, model M1 (Supplementary Table 16).

Research design and estimation

We modeled the total fertility rate (TFR) in each sub-national region i and survey wave t as a linear function of the percentage of women having access to modern energy in that region and a set of k time-varying region characteristics. In the analysis, we test whether regions that have seen larger expansions in energy access and education are also the ones with the strongest reduction in fertility under control of other socioeconomic processes and structural changes. The linear fixed effects panel model takes the form:

$$TFR_{i,t} = \beta 1 e_{i,t} + \beta_k x_{k_{i,t}} + \alpha 2_i + \alpha 3_{t'} + u_{i,t} \tag{1}$$

with β_1 representing the marginal effect of modern energy access on fertility. It shows the change in fertility in a region arising from a 1 percentage point increase in modern energy access the same year. The model controls for region fixed effects $\alpha 2_i$ to account for unobserved heterogeneity between the regions. To account for the clustering of observations, all standard errors are clustered at regional level. In addition, we include time period fixed effects $\alpha 3_{t'}$ (5 year intervals) to control for time trends in fertility change that are common across all regions. In additional models, we control for the number of years since the last survey wave (t-1) in our regressions to account for gaps in the panel (Supplementary Table 18).

As additional control variables, we collected information on a range of time-varying factors that might potentially affect access to modern energy and education and might at the same time influence fertility outcomes. We include measures for urbanization, age at marriage, economic development and conflict. Details on the selection of control variables are provided in Supplementary Note 2. To account for potential delays between the expanded access to modern energy and its effect on fertility and for possible reverse causality in our estimation, we reran our main models with lagged right hand-side variables (Supplementary Table 14 and Supplementary Method 4). Again, all our results remain robust suggesting that the identified relationships are indeed informative. All additional robustness checks are detailed in Supplementary Section D (Supplementary Tables 14-27).

Interaction analysis

In order to explore how the effects of modern energy access on fertility vary across different contexts, we ran interaction models in which we let the energy access variable interact with other characteristics of the regions (Supplementary Tables 6-8). In particular, we tested whether the relationship between energy access and fertility is different depending on whether the baseline fertility of the region is higher or lower, which would speak for a non-linear relationship. To measure the baseline fertility level, we used each region's absolute TFR level in the first survey wave for which data for the region is available (Supplementary Figure 4). More details on the interaction analysis can be found in Supplementary Method 5.

In addition, we analyzed differences in the effects of improved modern energy access on fertility by education level and changes, which has been identified as one of the main determinants of fertility outcomes in the literature. We considered both the role of the baseline level of education in a region and changes in education that co-occur with changes in modern energy access to test whether the effect of expanded access to modern energy differs between regions that either had an ex ante higher level of education or that have experienced significant educational improvements over the period considered. This allowed us to study under what conditions the relationship between access to modern energy and fertility is particularly strong.

Measurement

The fertility of a population is a measure that highly depends on its age structure. A relatively younger population will have, all else being equal, a higher fertility rate than a relatively older population. The fertility measure we used as our primary outcome variable is the total fertility rate (TFR), which is commonly used in demographic studies because it is independent of the age structure of the population considered. The TFR represents the average number of live births that a hypothetical cohort of women would have at the end of their reproductive period assuming uniform period fertility rates over the life cycle and no mortality. We calculated the TFR upon a one year basis, meaning that we took into account the births that occurred in the past year preceding the interview. The $TFR_{i,t}$ of the region i in the year t is expressed as live births per woman and the formula for its calculation is:

$$TFR_{i,t} = \sum_{a} 5 \times ASFR_{i,t,a} \tag{2}$$

with the $ASFR_{i,t,a}$ the Age-Specific Fertility Rate of region i in the year t, for the age group a. The ASFR corresponds to the fraction of women of a given age group that has given birth in a certain period of time, here one year. Age groups are segments of a population within a specified range of ages. In our analysis we used five-year age groups. The ASFR was calculated as the following:

$$ASFR_{i,t,a} = \frac{Nbirth_{i,t,a}}{Nwomen_{i,t,a}} \tag{3}$$

where $Nbirth_{i,t,a}$ is the number of births in the region i, in the year t and in the age group a and $Nwomen_{i,t,a}$ is the number of women in the region i, year t and age group a. Since the calculation of the TFR requires splitting the sample into age groups, the TFR is a measure whose uncertainty particularly depends on the sample size over which it is calculated. As a robustness test, we ran a weighted regression with weights corresponding to the sample size in each region-year. Our results remain robust to this specification (Supplementary Table 23).

The DHS collects information on two variables reflecting access to modern energy: first, whether a woman has access to electricity and second what her primary type of cooking fuel is. Based on this information, we calculated for each region the share of women with access to electricity and the share of women using modern forms of energy as a fuel for cooking. We defined modern energy for cooking as any energy derived from electricity, liquefied petroleum gas (LPG), natural gas, kerosene and biogas. All traditional biomass is excluded, namely firewood, charcoal, agricultural crops and animal dung as well as coal. Despite the fact that coal does not require collection, we excluded it from modern fuels because of its particularly negative impacts on health. We ran a robustness test where coal was included as a modern cooking fuel. We find that this does not affect our results (Supplementary Table 20).

We used GDP per capita, based on purchasing power parity (PPP) in constant international dollars, at the country level as a proxy for income because the DHS does not provide information on wealth that is comparable across countries, nor on income. In addition, we measured the number of conflict-related deaths per 10.000 inhabitants in each country using information from the UCDP data set[58].

Mediation analysis

Following our theoretical framework, we test whether child mortality, use of modern contraception, female labor participation and access to information are potential channels through which access to modern energy affects fertility. For this, we perform a mediation analysis[14, 19]. In a first step, we regress the potential intermediate outcomes on the energy access variables to test whether these have an effect. In a second step, we re-run our main models including the intermediate outcome as an additional control to explore whether the coefficient for access to energy changes upon inclusion of the additional variable and whether the potential intermediate outcome has a significant effect on fertility. While this test is indirect, it can provide evidence for the existence of mediating channels explaining the relationship between energy access and fertility. However, given the short time frame considered in our analysis, caution is warranted in the interpretation since some of the considered channels may affect fertility only over a longer time horizon.

Simulation and policy experiments

We ran simulations for 25 sub-Saharan African countries in which we projected the fertility decline until 2040 using three electricity access scenarios that are based on scenarios developed by the International Energy Agency (IEA) for sub-Saharan Africa[22]. Like the IEA scenarios, our simulations only consider the electrification rate, not access to modern cooking fuels. Our "Baseline" scenario is based on the IEA "Stated Policies Scenario" and extrapolates current trends in energy expansion in sub-Saharan Africa to the future. It results in an increase from 45% of average electricity access in 2015 to 65% in 2040.

Our second scenario "Universal access" is based on the IEA "Africa Case" scenario that targets universal access to electricity for sub-Saharan Africa in 2040. In both scenarios, we assumed an education expansion that follows the past national trends. We built the education expansion scenario using a logistic growth function to allow for the average schooling years to increase relatively faster at lower values, and to saturate when reaching higher values. The logistic function has two parameters, the maximal growth rate and the carrying capacity. In this scenario we took the past percentage increase in educational attainment in the country as the maximum growth rate and the educational attainment in OECD countries reached in 2018 (17 years) as the carrying capacity.

We complemented the first two scenarios with a third "Universal Access + Education" scenario, which aims at reaching both improved education and universal access to electricity until 2040. In this scenario, we assumed logistic growth in education expansion, with the maximum growth rate corresponding to the average past percentage increase in educational attainment in sub-Saharan Africa, increased by one and a half standard deviation. The methodology is explained in detail in Supplementary Method 7.

Limitations

There are limitations of our modelling approach that should be kept in mind when interpreting our results. The aggregation of individual data to sub-national level was necessary to create a consistent panel data set encompassing 44 countries, 403 regions and 26 years. The focus on multiple countries and regions allowed us to study heterogeneous contexts over time. The trade-off is that using such a large data set and aggregating individual data to sub-regions limits the possibilities to empirically assess mechanisms at more granular level by which access to modern energy could affect fertility.

For our empirical models, we used longitudinal data and controlled for a range of additional time-varying covariates as well as temporal and region fixed effects, allowing to remove time-variant unobserved heterogeneity. We also re-ran our models with different variations in measurement and modelling strategies (Supplementary Tables 14-27), including with lagged-explanatory variables which allows to address potential simultaneity biases (Supplementary Table 14). To account for potential confounding factors related to developments in other sectors co-occurring with the expansion of energy access, we re-ran our models using two additional development indicators (Supplementary Tables 26 and 27). At the same time, population dynamics other than fertility changes, such as migration or mortality, could be affected by changes in energy access and could alter the composition of the observed populations in the regions. To address the latter, we included changes in the urbanization rate as a proxy to control for human mobility in the regions. Despite this rigorous approach, endogeneity threats remain that could affect the estimation of our effects. In terms of generalizability, our estimates are mainly based on observations of regional increases in energy access over time and might hence be less informative for cases, where energy access declined, e.g., due to a conflict or economic recession.

Other limitations are inherent in the DHS data. The DHS contain no data on household or regional income and we therefore had to use average national GDP per capita as proxy for economic development. Also the energy indicators in the surveys only capture whether a household has access to or uses modern energy, but not to what extent and whether the access is reliable. Finally, relevant information on the cooking stoves used by the households or on potential off-grid solar devices used is missing in the data.

Despite these limitations, we have high confidence in our obtained model estimates, which have shown to be robust to various measurement and modelling variations (Supplementary Section D) and whose effect size are comparable to those observed in previous studies (Supplementary Section E). Our approach allows for the theory-guided testing of our hypothesis on the energy-fertility relation providing evidence on a global scale. It thus effectively complements related studies that used other identification approaches, such as instrumental variable estimation, to derive an unbiased estimate of the effect of access to modern energy on fertility[14, 15, 12].

Data Availability

The DHS data used to produce the main panel data is publicly available and free of charge, but access to the data requires a permission from the DHS Program. The country-level data were downloaded from the World Bank Open Data repository and are publicly available and free of charge. The conflict data from the Uppsala Conflict Data Program are publicly available and free of charge.

Code Availability

The pre-processing and the analysis were carried out in R and Rmarkdown and are fully reproducible. All the code is available on the git repository of this article: https://gitlab.pik-potsdam.de/belmin/fertility-transition-powered-by-womens-access-to-electricity-and-modern-cooking-fuels. The following R packages were central to the analysis: tidyverse[63], plm[5], knitr[67], wbstats[45], rdhs[61] and DHS.rates[10].

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Author Contributions

HW conceived the project, CB and RH designed methods, CB performed data preprocessing, CB performed statistical analyses, CB, RH, PPP, HW discussed methods and interpreted results, CB wrote the initial manuscript, CB, RH, PPP, HW wrote the final manuscript. PPP and CB prepared figures.

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Conflicts of Interest

The authors declare no conflict of interest.

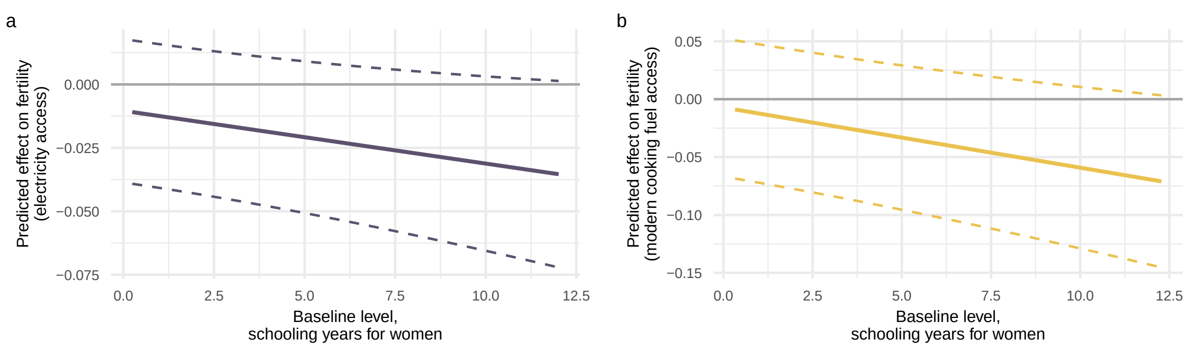

Figure 6: Extended Data Figure 1: Marginal effects of access to modern energy on fertility by average number of schooling years. Panel (a) and (b) represent the effect on fertility of a one unit change in, respectively, access to electricity and access to modern cooking fuels depending on the region's baseline level of schooling year in the first year available in our data. The solid line corresponds to the marginal effect and the dotted lines delimitate the 95% confidence intervals. Panel a) and b) correspond to model M8 and M9 (Supplementary Table 7)

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