When technology adoption interventions fail: The case of domestic biogas digesters in Senegal

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Abstract: Biogas digesters, which take organic materials and convert them into methane gas for cooking and lighting, are marketed as a renewable energy solution to the energy poverty challenges faced by many developing countries. In 2015, the Senegalese government began installing household biogas digesters with the goals of reducing fuelwood use and increasing employment via a fertilizer supply chain. We evaluate Senegal's biogas program, relying on data from households who received a digester installation between 2015 and 2017 and those who were scheduled to, but had not yet received an installation. We find that the majority of digesters installed were either never operational or had broken down at some point between installation and the date of our survey. Only 15 percent of digesters in our sample were operating at the time of our survey in early-2019. Using linear and logistic regression, we find that having attended trainings and being motivated to install the digester for fertilizer production are both positively associated with digester operation. Not surprisingly, our impact evaluation of the program shows no effect of digester installation on the fuel use, health, agricultural, or employment outcomes that were targeted by the program.

1. Introduction

In 2016, only sixty percent of the global population had access to clean technologies and fuels for cooking (WB& SE4All 2019). The other forty percent, about 3 billion people, are living in energy poverty, of which lack of access to clean cooking is one dimension. Without clean fuels and technologies, households rely on traditional solid fuels like firewood, charcoal, and dung to meet their cooking energy needs. They often use these fuels in open fires or traditional stoves, emitting pollutants like fine particulate matter and black carbon into their cooking spaces, the local environment, and the Earth's atmosphere. At the local level, these pollutants exact a large health toll; breathing smoke from cooking contributes to around 4 million deaths per year, over half of which are women and children (Adair-Rohani et al. 2016). These emissions also contribute to global climate change through emissions of greenhouse gases like carbon dioxide, methane, volatile organic compounds, and other short-lived climate forcers, like black carbon. In sub-Saharan Africa, where access to clean cooking is especially low, emissions from woodfuel combustion are estimated to account for up to eleven percent of total greenhouse gas emissions (Bailis et al. 2015). In addition to harmful emissions, reliance on traditional fuels and stoves levies a large time burden on energy poor households, especially young girls (Krishnapriya et al. 2021). A survey of African countries revealed that, in households that rely on traditional fuels and stoves for cooking, girls spend an average of 18 hours per week collecting fuel and water (Adair-Rohani et al. 2016). This is a significant time burden that can mean girls are shifting time away from other activities like education.

In light of the negative consequences of energy poverty, global attention has increasingly focused on expanding access to clean cooking fuels and technologies. This is captured most directly in Sustainable Development Goal 7, which, within Target 7.1, tasks countries to "ensure access to affordable, reliable, and modern energy for all" by 2030. Indicator 7.1.2 specifically measures the "proportion of population with primary reliance on clean fuels and technologies." This high-level prioritization is mirrored in national governments' focus on expanding energy access. China, for example, has achieved significant growth in energy access through government-led programs that help households switch from solid, traditional fuels to modern fuels like liquid petroleum gas (LPG), natural gas, and electricity (IEA 2017). In sub-Saharan Africa, experts project that 300 million people will gain access to clean cooking before 2030. However, this progress will be outstripped by population growth, and the percentage of the population without access is projected to increase (Oparaocha et al. 2018).

This paper presents an evaluation of a program targeted at reducing energy poverty in Senegal, where 76 percent of households do not have access to clean cooking technologies and fuels (WB & SE4All 2020). In rural areas, this figure is estimated to be as high as 95 percent. Firewood use in Senegal is especially problematic, as it contributes to deforestation and desertification in the Sahel (Brandt et al. 2014). For this reason, as well as those cited above, Senegal is investing considerably in programs aimed at helping households transition away from reliance on solid fuels for cooking.

Because of the popularity of animal husbandry,[1] biogas digesters have been touted as a potential solution to Senegal's energy poverty, especially in rural areas. Organic materials, such as cow dung, are a necessary input into biogas production. The cow dung is placed into the digester, where anaerobic digestion converts it into two outputs. The first is methane gas, which can then be used for cooking and lighting. The second output is a spent digested slurry that is rich in micro- and macro-nutrients and, as compared to direct application of animal dung, penetrates the soil faster and reduces nitrogen losses (Surendra et al. 2014; Weiland 2010). Given these two outputs, biogas technology has the potential to reduce energy poverty, improve health and environmental outcomes, and increase livelihoods through enhanced agriculture productivity and the possible development of a fertilizer supply chain.

But biogas digesters are an expensive technology to install, maintain, and operate, and it is not yet clear whether Senegal's investment in biogas technology, or the *Projet National de Biogaz du Senegal* (PNB-SN), will successfully reduce energy poverty in the country. This paper takes the first steps towards answering that question. Our research relies on data collected from households who have been deemed eligible to receive a biogas digester from PNB-SN. We first consider the households who received an installation in the first phase of the program. We find that the majority of the digesters never produced enough gas for cooking or, if they did, have since fallen into disrepair. We investigate the determinants of digester operation and find that households who receive any training on digester operation, live closer to weekly markets, and are motivated to install biogas for fertilizer production are more likely to maintain their digester. Other household characteristics like education levels, prices of fuel alternatives, and household size fail to explain significant variation in digester operation.

To identify the impact of the program on energy, health, and productivity outcomes, we compare eligible households who have already received biogas installations with those who have yet to receive a digester. We are not able to conclude that digesters are shifting households out of energy poverty. Thus, we find no effects on health or productivity outcomes. This may be because the majority of the digesters are not operating properly. To investigate this, we compare the same outcomes of interest between households with and without operating digesters, controlling for the drivers of operation we identified previously. This analysis is limited by a small sample of operating digesters, but the results suggest that successfully operating a digester for at least half of its usable life is not enough to substitute households away from solid fuels.

The remainder of this paper is organized as follows. We first review the existing literature related to energy access interventions, focusing on sub-Saharan Africa and Senegal. Section 3 discusses the details of Senegal's domestic biogas program; section 4 discusses the data and empirical methods we use for our analysis of digester operation as well as our impact evaluation. Section 5 presents results of these analyses, section 6 discusses program costs, and sections 7 and 8 present the discussion of these results and conclusions.

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[1] There are 3.5 million head of cattle in Senegal, which is an average of 2 per household (FAOSTAT 2020). In Sahelian countries, like Senegal, the livestock sector accounts for 30 percent of agricultural GDP and 60 percent of the total population derives their living from livestock (Molina-Flores et al. 2020).

2. Theoretical framework and relevant literature

The question of successfully transitioning a household or community to clean and/or modern cooking has been studied quite extensively. The literature considers two main areas of research: 1. Adoption of improved fuels and technologies and 2. The impacts of these fuels and technologies on environmental, health, and other development outcomes.

2.1 The adoption question

Theoretical treatment of the adoption question, or the study of why some adopt clean stoves or fuels and while others do not, has mostly considered a household perspective. Most recently it has been modeled in a utility maximization framework (Pattanayak et al. 2018). The adoption of improved stoves and fuels is considered adoption of an averting behavior, in that the technology and/or behavior change helps households avoid the serious health consequences of indoor air pollution. Households choose how much averting behavior to adopt in order to maximize expected utility subject to income, time, and health production constraints. Averting behavior itself is a function of time, knowledge, and materials. All of these inputs are costly. Materials must be bought; learning requires time and, in some cases, money. Time spent on averting behavior means less leisure time or less time earning a wage or engaging in household production. The household solution in this theoretical framework posits that households will engage in averting behavior until the marginal benefit of one additional unit of the behavior, i.e. avoided health costs, is equal to the time, material, and knowledge costs of that unit.

In 2012, Lewis and Pattanayak published a systematic review of the literature considering adoption of improved cookstoves and cleaner cooking fuels in developing countries. Adoption is defined differently, depending on the study. Some studies consider cookstoves, defining adoption as the decision to purchase an improved stove. While others define adoption as actual stove usage. Other analyses look at fuel use, specifically the decision to switch from using a solid fuel like firewood or charcoal towards a cleaner fuel like liquid petroleum gas (LPG). The reviewed studies consider three categories of determinants: demographics like age and household size, socioeconomic characteristics like education and income, and stove and/or fuel prices. The authors conclude that income, education and urban status are positively associated with adoption across the majority, but not all, of the studies. It was less clear how household size, gender composition, and fuel price and availability influence adoption. Importantly, some potentially important adoption drivers like access to credit, strength of the supply chain, and social norms had been largely ignored by the literature (Lewis & Pattanayak 2012). A more recent 2016 study focused on clean cooking fuels, and the authors expanded the scope of their review to include qualitative analyses and case studies (Puzzolo et al. 2016). In total they reviewed 44 studies, including 17 biogas studies. They found that household socioeconomic and demographic characteristics were important for adoption decisions, but also highlighted the role of program and policy characteristics, legislative and standards, technical characteristics of stoves and fuels, and market development (Puzzolo et al. 2016).

A subset of this adoption research specifically considers biogas in sub-Saharan Africa, recognizing the significant challenges in promoting and maintaining biogas stoves. Mwirigi et al.

(2009) study biogas adoption amongst Northern Kenyan dairy farmers. The authors consider the decision of whether or not to maintain an operational digester and define multiple dimensions of functionality, including whether the stove is operating or not, how the digester was fed, and the repair history. The authors find that socioeconomic status is correlated with adoption of digesters, but not with maintenance and operation. In addition, the owners of functioning digesters are more likely to practice zero-grazing livestock management and own more heads of livestock, i.e. it is easier for these households to collect enough organic waste to feed the digester. Walekhwa, Mugisha, and Drake (2009) study Ugandan households' decisions to "produce and use biogas technology." Applying a utility-maximization framework, they find that larger, wealthier households owning more cattle are more likely to adopt biogas, while those located more remotely and with more land are less likely to adopt. Both of these studies consider adoption without the presence of a government promotion program that could help to reduce some of the time, material, and knowledge costs of biogas adoption. Though, even providing free stoves has not always proven to be effective at increasing adoption (Lewis & Pattanayak 2012).

2.2 The impacts question

Adoption is, of course, an important objective of any program aimed at reducing energy poverty. But the majority of these programs are targeted at more than adoption, hoping to reap the "triple benefits" of improving health and time savings for households, preserving local forests and associated ecosystem services, and reducing emissions that contribute to local air pollution and global climate change (Jeuland & Pattanayak 2012). Another segment of the cookstove literature has considered the impacts of improved stove and/or clean fuel adoption.

Two studies in particular speak to the Senegalese context. The first, a randomized evaluation of solar stoves, found that use of such stoves led to a 14 percent decrease in fuelwood consumption, though households remained reliant on traditional stoves to meet capacity needs (Beltramo & Levine 2013). The continued use of solid fuels meant that solar stoves did not have any impact on health outcomes. These findings suggest that a larger, biogas stove, which often has multiple burners, may be better suited to the Senegalese context.[2] Another randomized evaluation of smaller stoves, in this case the Jambaar wood and charcoal stoves, found that improved stoves led to reduced fuelwood and charcoal use and, at least in the case of the fuelwood stove, this reduction was enough to produce improvements in respiratory health (Bensch & Peters 2015, Bensch & Peters 2013).

Other studies have focused specifically on biogas and show that adoption of the stoves can have positive impacts. For example, a 2012 study of Rwanda's household-level program found that digester installation reduced the amount of firewood consumed daily by about 30 percent (Bedi et al. 2015). They estimated that this reduction in firewood consumption was associated with a 3 tonne annual reduction of CO_2 equivalent greenhouse gases.[3] This result shows that

[2] The average Sengalese household size is nine people.
[3] This assumes that all firewood used was non-renewable biomass and that there is no leakage in the biogas digesters (Bedi et al. 2015).

the digesters are indeed helping households shift towards cleaner, modern fuels, even if the technology is not enough to wholly eliminate reliance on fuelwood used for cooking and other purposes. They find no impacts on overall time use, as the time saved on fuel collection is offset by the time needed to operate the digester. In the Kenyan study mentioned above, authors found that households with a functioning digester had only half the expenditures of non-biogas households for electricity, fuelwood, and LPG each month (Mwirigi et al. 2009), though there was no difference in charcoal expenditure.[4] In Tanzania, a small sample study of fixed-dome digesters found that biogas installation and operation led to less fuelwood consumption, less time spent collecting fuel, lower CO_2 emissions, and higher farm incomes (Laramee & Davis 2013).

The studies discussed here do not provide conclusive evidence as to whether or not biogas is an appropriate technology to reduce energy poverty and achieve environmental, economic, and health benefits. While, in some cases, it may be effective at reducing traditional fuel use, it is not clear if this reduction is enough to bring about substantial reductions in energy poverty rates or bring countries closer to the targets outlined in SDG7. Biogas digesters are expensive to install and are likely only affordable to the wealthiest households. For this reason, they may not be effective at addressing energy poverty if they are primarily shifting households away from other clean, but costly, fuels like LPG and electricity.[5] Some biogas programs have failed to achieve their desired impacts because of maintenance challenges and a generally low willingness to adopt the technology (Kammila et al. 2014).

2.3 Theory of change

The theory of change figure presented here outlines a framework for our analysis. We focus on the household perspective, starting from the installation of the biogas digesters and following through to the development outcomes and impacts that PNB-SN targets.

Through our survey we seek to observe activities, outputs, outcomes and impacts along the causal chain. We collect data on both PNB-SN activities and household activities, to understand when installations occurred, if trainings were given, what appliances households adopted and whether or not they were successful at maintaining operation of the digester. If a household is able to successfully operate the digester, the two main outputs are methane gas and the spent bioslurry, which can be applied to soil as a high-quality fertilizer. While we do not directly observe these outputs in our data, we are able to measure how households are using any produced bioslurry, either applying it to their own fields, selling to others, or throwing it away. We also observe household cooking and lighting practices, where we can detect if households have adopted the necessary appliances, i.e. a biogas stove or lamp, and if they are using these appliances with the methane gas to meet their cooking and/or lighting needs.

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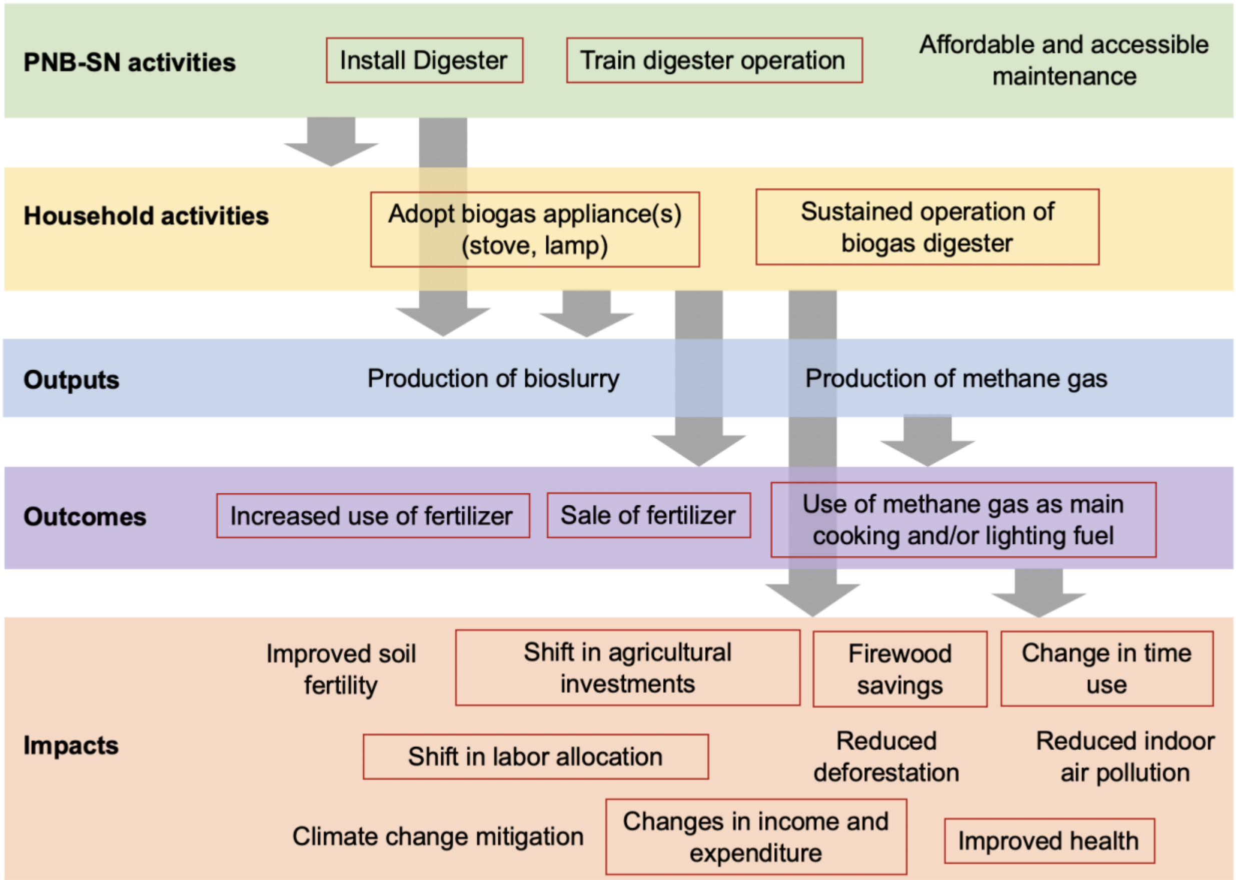
[4] This study only considers fuel expenditure, not collection. In the control group, households without biogas digesters, firewood and charcoal were the most commonly purchased fuels.

[5] These fuels are considered clean at the point of use, because they do emit the local air pollution associated with, for example, fuelwood or charcoal. But, depending on how the electricity is generated, a switch from electricity and/or LPG to biogas is likely to have positive climate effects.

If households are successfully operating a biogas digester and producing both bioslurry and methane gas, we expect to observe a number of outcomes. Related to the bioslurry, we expect that households may shift their agricultural practices in response to this new input. They may begin to grow different crops. Even if they do not shift which crops they grow, they may be able to increase production. They also may reallocate labor towards or away from the farm, depending on how agricultural practices have changed. If they reallocate labor towards farming, household members may move from wage or self-employment to farm employment. Causality could also go the other direction, with an increase in fertilizer availability leading to reduced farm labor demand. If the household sells the bioslurry to other farmers, they can increase household income and/or consumption.

Figure 1: Biogas theory of change



Note: Red boxes indicate dimensions that we measure via the household survey.

Through the production of methane gas, households can shift towards cleaner and more efficient cooking and away from polluting fuels like firewood. Households may save time if they do not need to collect firewood for cooking. They may use this saved time to engage in wage labor or self-employment. But it could also be that overall time use increases because of the time required to operate the digester. Households may also save on overall fuel expenditure if they reduce the purchase of fuels like charcoal or LPG. Again, expenditure may increase if the digester requires large investments for operation and maintenance. Finally, by shifting away from fuels like firewood and charcoal for cooking or kerosene for lighting, households, and especially cooks, can reduce their exposure to indoor air pollution and improve their health outcomes. This switch can also result in a net reduction of greenhouse gas pollutants, as much of fuelwood collection is from non-renewable sources (Drigo et al. 2014) and biogas captures methane gas that would have been released into the atmosphere without the digester. Finally, reducing firewood use helps to avoid local deforestation and desertification.

3. Senegal's domestic biogas program

3.1 Program goals

Senegal's domestic biogas program is operated out of the Ministry of Energy and is one of three programs aimed at increasing access to improved cooking technologies. The other two are Foyers Amelioré au Senegal (FASEN), which disseminates improved charcoal and firewood cookstoves, primarily in urban areas, and Projet de Gestion Durable d'Energie (PROGEDE), which also promotes the use of low-cost biomass stoves.

The domestic biogas program, PNB-SN, is the most recent of the government's improved cooking programs, and targets rural households in regions where cattle rearing is common. The program promotes the development of a national, commercially viable biogas sector (Programme National De Biogaz Domestique Du Sénégal). This approach is designed to develop both the supply and demand side of a biogas market. On the demand side PNB-SN works with local implementing partners to promote awareness of biogas technology and identify households that could benefit from digesters. They have also designed financing mechanisms like specialized credit facilities and subsidy offers to increase affordability of biogas technology. On the supply side they partner with local masons, who carry out the installations instead of PNB-SN doing the installations themselves. They recruit local companies and train their masons in digester construction and maintenance.

A pilot phase of the program was carried out from 2009 to 2013, installing 600 digesters across twelve regions. PNB-SN reports from 2013 and 2014 note the weak results of the pilot phase, notably that they did not meet the goal of installing 8,000 digesters by 2013, despite using three-quarters of the budget, and that many of the digesters did not function properly. They attribute the shortfall in installations to the high cost of the digesters, i.e. affordability constraints. In addition, the loans available to recipient households have high interest rates (as high as 24 percent in some cases) and short repayment periods (less than one year), resulting in high monthly payments (Programme National De Biogaz Domestique Du Sénégal). They note other, non-financial issues that led to the high failure rate, including:

- Lack of knowledge and experience among those responsible for installation and maintenance,
- Failure of monitoring systems and a thin maintenance network, (Most households reported not knowing who to contact in case of a digester breakdown.)
- The low number of installation companies engaged, which led to constrained supply and non-diverse product offerings, (Five installations companies were engaged in the pilot phase.)

- And low digester feedstock availability, including cattle moving away from the digesters, especially during the rainy season, and insufficient access to water (Programme National De Biogaz Domestique Du Sénégal).

These challenges are similar to those faced in other biogas programs. An evaluation of the African National Biogas Partnership activities in Kenya, Tanzania, and Uganda found that high upfront costs, lack of access to affordable credit, and poor after-installation maintenance all led to low uptake and a 27 percent failure rate (Clemens et al. 2018). Based on these lessons, PNB-SN adapted the program before the rollout of the first full-scale phase in 2015. They aimed to increase the number of construction companies trained and improve access to credit. They designed a line of credit with a lower interest rate, 10 percent, and longer payback period, 24 months. They aimed to negotiate with local financial institutions to offer these credit terms to biogas applicants and to raise additional funds to offer a substantial installation subsidy.

The primary objective of the full-scale program was to construct 10,000 digesters by 2019 and to achieve a 90 percent operation rate, bringing clean, renewable energy and a source of fertilizer to Senegalese households. PNB-SN planned to do this by developing a fully functioning national market for the manufacture, distribution, installation, and maintenance of biogas digesters. The larger, development goals of the program are as follows:

- Improve access to modern energy services and, subsequently, reduce national firewood consumption.
- Improve soil fertility through the use of organic fertilizers.
- Improve herd and manure management systems through support for stabling and fodder production.
- Reduce extreme poverty by improving living conditions, decreasing the incidence of respiratory health problems, and improving gender equity.

By 2019 PNB-SN had installed 2,652 digesters. They installed 2,611 at households; the remaining 41 were installed at schools. As of 2019, 967 of these installations were reported to be operational.

3.2 Implementation details

PNB-SN partnered with regional implementing partners, often local NGOs, and installation companies to promote digesters to local farmers, carry out the installations, and provide maintenance services. External funders provided financial support for the program that allowed subsidization of installation costs. With this support PNB-SN subsidized fifty percent of the cost to households. The other fifty percent was to be paid by households via in-kind contributions to construction, i.e. sand, concrete, etc., and through cash contributions that may be financed via a loan.

The national program has outlined the following process for selecting villages and households who are eligible to receive biogas installations. First, PNB-SN defined criteria that each household must meet in order to be deemed eligible for the program. These criteria are meant to ensure that the households who receive a digester are able to maintain digester operation, i.e. have access to sufficient animal waste and water to feed the digester, can afford their share of the installation costs, and will not be put in danger from installation, i.e. have a brick kitchen to prevent fires from combusting methane gas indoors. The specific criteria outlined by PNB-SN are as follows:

- The household owns at least 10 cows,
- The household has access to water,
- The household has a brick kitchen,
- The household has sufficient space to install the digester in the compound, and
- The household is able to make an in-kind contribution (water, sand, and iron) for the construction of the biogas.

The following criteria were shared with the construction companies contracted by PNB-SN to carry out the digester installations. The companies are in charge of identifying households who meet the above criteria. They primarily target villages where cattle production and management are common; in Senegal, cattle rearing is mainly practiced in rural areas. The companies compile a list of households who meet the eligibility criteria and submit the lists to PNB-SN for validation.

After PNB-SN has confirmed that the households on the eligibility lists meet the necessary criteria, the companies receive a payment making up half of their installation costs. This allows the companies to start carrying out installations. According to the PNB-SN regional coordinators, the companies are free to choose the order in which households from the eligibility lists will receive installations. Their decision is based on many factors, including the number of digesters to be installed in each village, the availability of in-kind contributions for construction, and the availability of masons and construction equipment. After the installations are complete, PNB-SN pays out the remaining fifty percent of the construction companies' installation costs.

Each year the PNB-SN provides a suite of training courses. Some are targeted at partner organizations, training implementing partners in promotion, communication, and marketing techniques to increase digester take-up and training masons and technicians in digesters installation and maintenance techniques. Others are targeted at households. Some directly apply to the digester, training techniques for using and maintaining a functioning digester. Others relate to livestock, i.e. feeding livestock to ensure a steady supply of dung for the digester, and agricultural practices, i.e. composting techniques or cultivation using bioslurry as fertilizer. Unfortunately, we do not have detailed information about which trainings were offered when and who received each training.

According to lists provided by PNB-SN, 1,247 installations were initiated between 2015 and 2017 by 48 different installation firms.[6] We have detailed data on the installation process from the 97 households we interviewed.[7] The majority of recipient households benefiting from the

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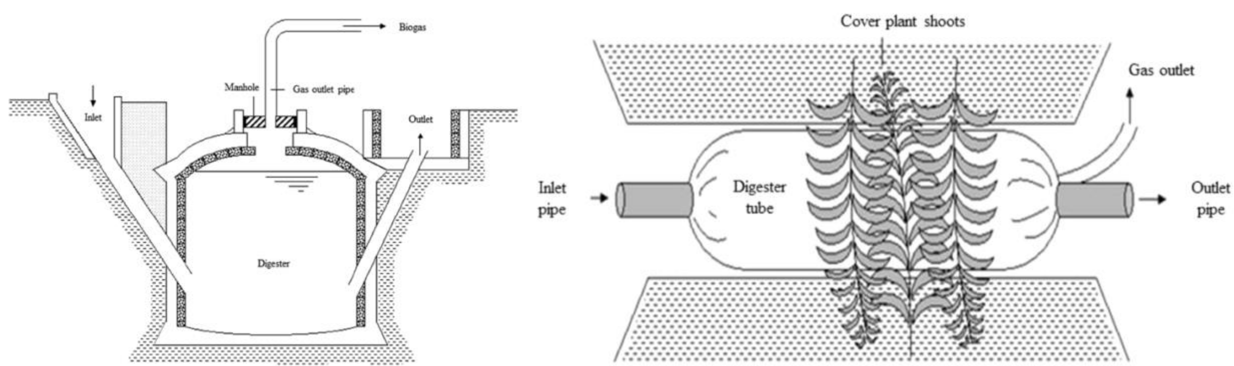
[6] As of 2019, 75 installation firms had been engaged by PNB-SN, of which 40 were actively carrying out installations.

[7] This evaluation was carried out after the intervention was implemented, so there was no intervention monitoring done by our team. During our survey, we did ask a number of questions to households that received the digesters to understand their experience with the domestic biogas program. These data and associated analyses are presented in section 3.2 and 5.1.

program have received fixed dome digesters (Figure 2, Panel A), while a few plastic tubular digesters (Figure 2, Panel B) have been installed in Tambacounda region. According to PNB-SN documents, the exact size of digester that a household receives is determined by household size and the number of cows that the household manages. The majority of households in our sample report installing an 18 cubic meter digester and, on average, the digesters took a little over a month to install.[8] Anywhere between one and 15 masons were involved in the installation processes, with a median of four amongst our sample of 97 households who received installations. Eight of the installations were completed in 2015, 33 in 2016, 37 in 2017, and 19 in 2018.

Figure 2: Types of digesters installed by PNB-SN program (from Surendra et al. 2014)

Panel A: Fixed dome digester Panel B: Plastic tubular digester



As state above, PNB-SN originally planned to subsidize 50 percent of the digester installation costs. According to program documents, an 18 cubic meter digester would cost 728,300 CFA (1,200 USD) to install (Programme National De Biogaz Domestique Du Sénégal). Half of this, 364,150 CFA, is supposed to be paid by PNB-SN directly to the construction companies in charge of installation, while the remaining is paid by the household as an in-kind contribution of construction materials or through cash contributions, which can also be financed via credit.

4. Evaluation questions, design, methods, sampling and data collection

4.1 Primary and secondary evaluation questions

Our research questions fall into two categories. The first group of questions relates specifically to PNB-SN participants. Here we seek to investigate individual’s perceptions of the domestic biogas program, how households operated the digesters after installation, and whether or not program impacts depend on the operation of digesters. Specifically, we ask:

- How were the digesters maintained after installation and are they still operating?
- How did households feel about the program and the installed digesters?

[8] Only 52 out of 100 households who had biogas installations could report the size of the installation.

- What factors are related to how a household operates and maintains their digester?
- What are the impacts of having a functioning digester on fuel, health and productivity outcomes?

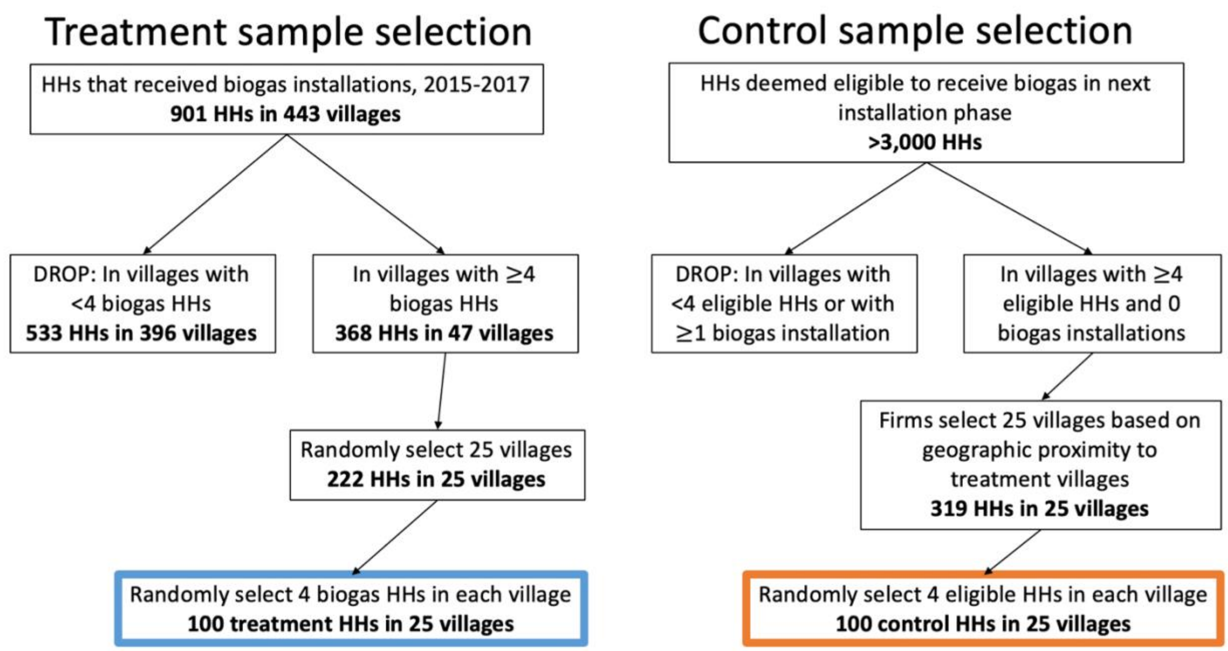
The second relates to the impact of the domestic biogas program on its targeted development outcomes. Specifically, we estimate the impact of an installed biogas digester on:

- Household energy use, including the use of solid fuels like firewood and charcoal, fuel collection time, fuel expenditure, and time spent cooking;
- The respiratory health of children and household members responsible for cooking; and
- Household agricultural productivity and employment outcomes.

4.2 Sampling and data collection

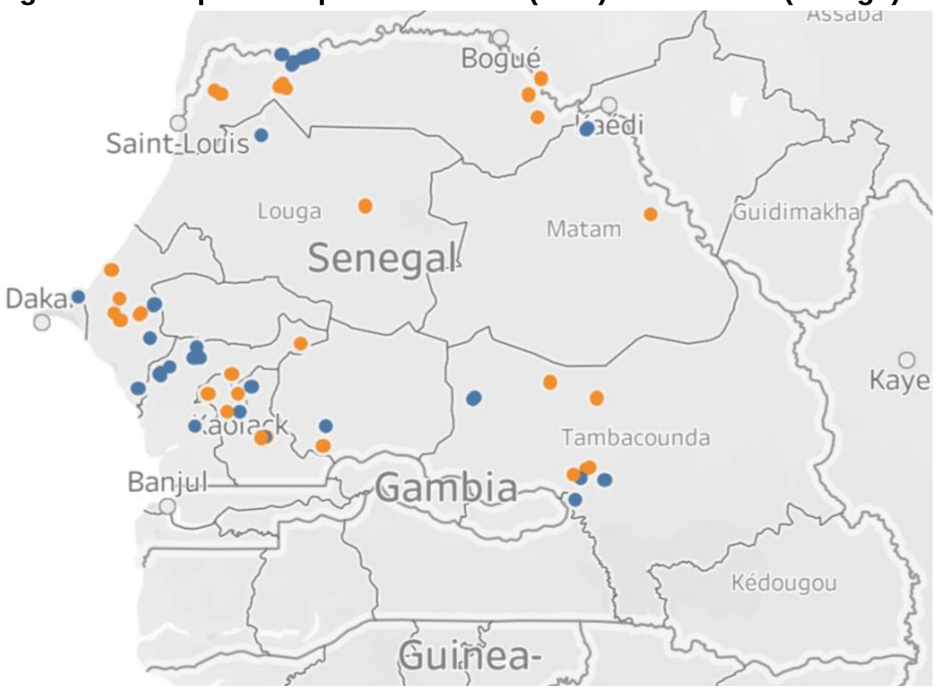
Our focus of this study is the first half of the Large-Scale Dissemination Phase of PNB-SN. This phase followed the pilot phase (which we did not evaluate) and was planned for 2015-2019. Our study planning began in late-2017 and data collection occurred in early 2019, so we focus on installations that were initiated between 2015 and 2017. Specifically, we are interested in two groups of households, one treated by the program, and the second acting as controls, who were planned to receive the intervention but had not received it at the time of data collection. The methodology that we used to select our sample is explained below and shown in Figure 3.

Figure 3: Sampling of treatment and control households



Our treatment group is made up of 100 households who received biogas installations from the PNB-SN. To draw this sample, we used a list of the 901 households that had received installations between 2015 and 2017. Because the main cost of data collection comes from traveling to remote villages, we aimed to interview four households per village. Thus, we dropped recipient households that were in villages where 2 or fewer other households had received an installation. While this restriction does affect the generalizability of our findings, we do not think it is a problem, from a policy perspective. If the government continues to scale up the biogas program, there will likely be numerous installations per village. The 368 remaining households were distributed across 47 villages. From these villages we randomly selected 25, and, within each village, randomly selected four households. This gives us a sample of 100 treatment households. If one of our sampled households was not available to be interviewed, we randomly selected another recipient household from that village as a replacement. In the end, we have a sample of 97 treatment households, as replacement households for unavailable respondents were not available in three of the villages we visited. The locations of these 97 households are displayed in blue in Figure 4.

Figure 4: A map of sampled treatment (blue) and control (orange) households



Similar to the sampling methodology used by Bedi et al. (2015), our control group is made up of households who had been selected to receive biogas installations following the same selection process as the treatment group, but who, because of budgetary reasons, had yet to receive these installations as of December 2018. From PNB-SN we received a list of more than 3,000 households who had been identified as eligible and scheduled to receive installations in this phase of the program. Again, we consider only villages where four or more households appear on the list of eligible households. Instead of randomly selecting villages, we asked the PNB regional coordinators and installation companies, who are responsible for selecting the households that will receive installations, to identify 25 villages that were similar to our treatment villages. While this method is less systematic than, for example, statistical matching on observable characteristics, we believe it more closely mirrors the process through which treatment villages were selected. We additionally asked the regional coordinators to select villages where four or more households appeared on the list of those who were deemed eligible but who had not yet received an installation and where no biogas digesters had yet been installed. In each of these 25 control villages, we again randomly selected four households and, when necessary due to lack of their availability, selected replacement households. In the end, we have a sample of 99 control households, as replacement households were not available in one of the villages we visited. The locations of these 99 households are displayed in orange in Figure 4.

As explained above, we selected treatment and control households from different villages. While there are households in treatment villages that do not have a biogas digester, we believe that these households are likely very different than those, from the same village, who adopted a digester when PNB-SN came to their community. Therefore, as control, we selected households whose villages had not yet received installations from PNB-SN but who were selected to participate in the program once it reached their community. In addition to supporting the internal validity of our results, this design also reduces concern about spillovers between treatment and control households. There are a number of channels through which functioning biogas digesters could affect non-recipient households. It is possible that, if installations reduce the amount of fuelwood demanded by recipient households, fuelwood becomes less scarce for non-recipient households and they may increase their use. If recipient households sell their bioslurry as fertilizer, non-recipient households may shift their agricultural investments in response to this change in input availability.

Data collection occurred in February 2019, with 8 interviewers. Each interviewer spent one day in a village, interviewing all four households in that village. In one village, one household refused to be interviewed and there were no replacement households available, thus only 3 interviews were conducted. In another, two households refused to be interviewed and no replacements were available, so only 2 interviews took place. In a third village, one sampled household was traveling, and no replacements were available. We were limited in the availability of replacements in some villages because we only interviewed households whose names appeared on the PNB-SN lists of households who had received digesters or who had had their eligibility confirmed.

Of the originally sampled 200 households, 65 were not available or refused, 61 of these were successfully replaced with other households from PNB-SN's lists, for a final sample of 196 households across 50 villages. Sampled households were not available for interview and had to be replaced for a few reasons. Fifty-five percent of the households who were replaced were simply not available on the day our team was in the village. Either they had moved or were traveling. For budget reasons, we were only able to spend one day in each village, so we were not able to return to look for these households on another day. Thirteen percent refused to be interviewed because they were upset with the biogas program. Four percent were replaced because the name listed belonged to another household that had already been interviewed, i.e. the household had been listed twice in PNB-SN's lists. Twenty-eight percent were control group households that we discovered did not meet the eligibility criteria to receive biogas, despite their names being listed by PNB-SN on the demand lists. We do not have demographic data on the replaced households to test for potential sources of bias from the high refusal rate. We believe we are likely overestimating impacts and operation rates with our final sample, as households who moved away can no longer use the biogas and those who are upset with the program likely have non-functioning digesters.

Given our final sample size, we used control group observations to calculate the minimum detectable effect size for our key outcome variables. We accounted for intra-village correlation in outcomes in these calculations. As shown in Appendix Table B1, the study is only powered to detect large effects in most outcomes, most notably health effects. While the study does have power limitations, we do not believe this is an economically significant limitation of the study for three reasons. First, biogas installations are expensive, so the benefits would have to be very large to justify the investment, even if they are also largely motivated on redistributive or poverty alleviation grounds (there are many other more cost-effective ways of reducing poverty, for instance). Second, the goal of biogas is to enable households to transition fully away from polluting fuels (and their cost effectiveness relies on at least this and also some agricultural savings or income from selling spent manure), and that is something we can assess, even if the effect sizes must be large. Third, the failure of the vast majority of these systems would obviously seem to compromise the theory of change, regardless of statistical power. While we are limited in the claims we can make about functioning digesters, we believe we are well-positioned to draw conclusions about the effectiveness of installations carried out through PNB-SN.

To develop the survey tool, our team of researchers worked together with the data firm contracted to carry out the interviews and with PNB-SN officials. Within our own research team, including researchers involved in evaluating other components of Senegal's energy access programs like FASEN and PROGEDE, we have over a decade of field experience related to energy poverty and energy transitions in developing countries. The Senegalese data firm is staffed by academics and researchers with extensive experience collecting household-level data across a wide array of topics. Survey modules drew from past surveys carried out by our own team and researchers at the data firm. For some modules, like questions about agricultural and livestock practices and health outcomes, we drew from established surveys like the Living Standards Measurement Surveys and the Demographic and Health Surveys. In addition, we sought input from PNB-SN officials, as they are most familiar with program objectives and details of implementation. The final survey included modules related to household members education, health, and employment; daily time use data for the main cook and oldest female child; energy use, including stoves, for cooking and lighting; agricultural and livestock practices; household demographics and socioeconomic characteristics; biogas installation and operation (administered only to treatment households), and knowledge and perception of PNB-SN and biogas digesters.

The Dakar-based data firm was responsible for coding the questionnaire into the computer assisted interviewing software. They also carried out two pilots of the survey. The first occurred in mid-2018, interviewing households that had received biogas in the pilot phase of the program and nearby households that had not yet received biogas but met the eligibility criteria. In December 2018, we met with PNB-SN to get their input regarding details of the questionnaire. Finally, in January 2019 we conducted a final pilot before the rollout of data collection.

To ensure data quality, the data firm set up a system of frequent communication between the data collection teams in the field and the team of controllers based at the Dakar headquarters. Each field team was headed by a supervisor, who was responsible for coordination between his or her team of interviewers and the controllers in Dakar. At the end of each day of data collection, the supervisor checked and validated each questionnaire completed by her team. The controllers in Dakar checked for outliers or suspicious responses and asked interviewers or supervisors to follow-up with respondents to confirm any unclear or questionable data points.[9]

4.3 Evaluation design and methods

4.3.1 Determinants of digester operation

As a first step, we explore the operation of the digesters that were installed by PNB-SN. Specifically, we investigate what determines the varying levels of digester operability that we observe in our survey data. For this analysis we use only the households in the treatment sample. We first divide the sample according to three binary variables that define important thresholds in digester operation. We test for determinants of reaching these three thresholds using both logistic and linear probability models. First, we divide the sample into households whose digesters had ever operated since installation and those whose never operated. Second, we divide the households based on whether or not their digester had been operating for at least half of its life, i.e. the time since installation was complete. Third, we split the sample based on whether or not the household's digester was operating on the day of the survey. Finally, we use linear regression to test for determinants of operation using a continuous outcome variable that measures the share of time since installation that a household's digester had been at least partially operational. For this outcome variable a value of, for example, 0.6 indicates that the digester had been usable for 60 percent of its life to date and totally broken down for 40 percent.

With respect to our covariates of interest, we rely on the rich literature studying the determinants of household energy choices. Specifically, we draw from reviews of the literature to identify factors that we expect to influence digester operability (Puzzolo et al. 2016, Muller & Yan 2018, Lewis & Pattanayak 2012). The covariates we test fall into five categories. The first includes digester and program characteristics, including the type of digester installed, the age of the

[9] We obtained ethical approval for this study from Duke University's Institutional Review Board. All participants gave verbal, informed consent prior to conducting the survey. Participants were free to refuse to answer any questions and to end the interview at any time. Participants were informed about the aims of the research, the data to be collected, and were assured that data would be stored securely and they would remain anonymous in all reports. They received a local telephone number to use in case of any questions or concerns regarding the survey questions or research project. The survey did not involve any medical treatments nor did we ask any sensitive or potentially upsetting questions. We collected a minimum amount of personally identifying information. We gave each respondent a small gift at the end of the survey to compensate for the time we used for the interview.

digester, i.e. how much time has passed since installation was completed, whether or not the household has connected a toilet to the digester, and whether or not the household received any trainings regarding digester operation and maintenance. For many of these variables it is not ex-ante clear what direction we should expect its relationship with operability to be. For example, older digesters may be more likely to break down. But households who have had digesters longer may also be more experienced and successful in their operation. It's also not clear whether the fixed dome or floating balloon digester has a better operating history in the Senegalese context. We do expect that trainings are positively related to operation, as households without trainings are less likely to have information about how to operate the digester. We also expect households with a toilet connected to have a more consistent feed stock going into the digester, which means better operation.

The second category includes prices of alternative fuels. The higher the price of fuels like charcoal, the more likely households are to maintain an operating digester for the methane gas. We test for the cost of firewood and charcoal. Unfortunately, we were not able to collect sufficient data to test for the relationship between LPG price and digester operation. If wealthy households are both more likely to adopt biogas and LPG, we could expect that, in the absence of biogas, many treatment households would have used LPG for cooking.

The third category of covariates includes household demographic and socioeconomic characteristics. Specifically, we test for the role of household size and the share that is female. It may be that larger households have more labor available to successfully maintain the digester. Households with more females may have more labor available to both maintain the digester and to collect firewood, a task often done by women (Adair-Rohani et al. 2016), so it is not ex ante clear whether they will be more or less likely to maintain an operating digester. With respect to employed adults in the household, it may be that the more members who are employed the less likely operation because of labor constraints at home. But it also could be that households with more employed individuals can better afford any digester maintenance that is required. We also test whether the age of the household head is associated with operation, hypothesizing that older heads are less willing to change their behavior, so less likely to invest in maintaining a new technology. We test for the role of relative wealth and liquidity, using an asset index and binary variable equal to one if a household can access at least 250,000 CFA in emergency funds. (See Appendix C for information about how we construct the asset index.) We expect wealthier and less liquidity constrained households to be more likely to maintain their digester. We also include a measure of credit access, equal to one if a household could access a loan to get emergency funds. This variable may be positively correlated with operation, as households who can get access to funds via credit are more likely to invest in maintenance. It also may be that households who can access emergency funds through their own income or savings are less likely to report accessing a loan, are wealthier, and therefore more likely to maintain the digester. Finally, we test for the role of market access, as we expect households who are more connected to markets are also more likely to have access to digester appliances, replacement parts, and maintenance services.

Fourth, we test for the role of household perceptions, including covariates that indicate the motivation for installing a digester, e.g. to reduce energy expenses, improve health, or produce fertilizer. These variables are coded based on an open-ended question asking households to report their motivation for installing the digester. They do not capture the intensity of motivation. We expect all motivations to be positively related with operation, but it is not clear ex-ante which motivation should have the strongest relationship.

Finally, as cow manure is the primary digester input, we test for the role of livestock ownership and rearing patterns, including stabling and pasturing practices and the collection and use of cow manure. We expect that households with more cows are more likely to maintain the digester, as they are more likely to have sufficient feedstock. We also predict that households who stable their livestock are more likely to operate the digester, as they do not need to collect dung from the fields and bring it back to the digester. We also test for other uses of livestock dung, such as applying it directly as fertilizer or using it as cooking fuel. If households use the dung for other purposes, they may be less willing to put it into the digester and less likely to maintain an operable digester.

4.3.2 Impact evaluation methodology

Unbiased identification of the impacts of biogas installations requires that treatment and control households are similar across both observed and unobserved baseline characteristics. Our sampling strategy, described above, ensures that treatment and control households have gone through the same selection process, i.e. being included in PNB-SN's lists of eligible households and then being selected by the regional coordinators for installation. This helps to balance the two groups on both the observed and unobserved characteristics that drive the selection process. There are some drivers of selection that we cannot observe, such as what drives households to approach PNB-SN and be included on the eligibility lists or what determines where the regional coordinators decide to implement the program. We assume that, by ensuring that all households have been listed on the eligibility lists and gone through the regional coordinator selection process, we have reduced differences that arise from these relatively opaque selection processes. We expect that, in the future, all of the control households will have also received the biogas program.

The remaining threat to identification comes from the fact that treatment villages were selected to receive installations *before* control villages. As discussed above this may be because they are located in a larger village with more biogas eligible households. It may be because they are wealthier, so able to more quickly buy the in-kind inputs or make the necessary payments. Or it may be because these villages are the easiest to access, such that installation costs, including transport of labor and material, are lower. These factors, like wealth and accessibility, may not only affect timing of biogas installation but could also affect household access to host of other goods and services, which in turn could drive differences in our outcomes of interest between treatment and control groups.

We account for this timing selection in our impact analysis by controlling for covariates that may drive the order in which villages and households received installations. We first test whether these variables are balanced between the treatment and control groups and then control for them in our impact estimation. For the treatment households, we are not able to observe the levels of these characteristics from before they received the installation, but we believe, because so many digesters were not operating, that they have likely not been affected by the program. They are therefore the best approximation we have of pre-installation factors that drove the treatment households' earlier selection into the program.

To measure the impact of the biogas installations, we estimate the following equation:

$$Y_{ij} = \alpha + \beta B_{ij} + \gamma X_{ij} + \delta Z_{ij} + \theta V_j + \varepsilon_{ij} \quad (1)$$

where Y_i is our outcome of interest,[10] B_{ij} is a dummy variable equal to one if household *i* in village *j* received a biogas installation from PNB-SN. X_{ij} is a vector of observable demographic controls, including household size, age, gender, education, religion, and ethnicity. Z_{ij} and V_j are vectors of household and village characteristics, respectively, that may drive the order in which the installations are delivered, including village *j*'s accessibility and household *i*'s relative wealth and liquidity, and ε_i is an error term. We cluster standard errors at the village level to account for intra-village correlation. Thus, to identify our parameter of interest, β, we rely on the assumption that, conditional on the set of controls, X_{ij}, Z_{ij}, and V_j, treatment status, B_{ij}, is independent of the error term.

Because we are not able to observe every factor that influenced whether or not an eligible household received an installation initiated between 2015 and 2017, there may still be selection bias in the estimates from equation 1. Because villages that were targeted first are likely larger, more connected, and possibly wealthier, as they could make the required in-kind contribution of construction materials quickly, any unobserved selection would likely result in a positive bias. Therefore, if we estimate positive impacts, it may be that the true impact is lower than our estimates, or even zero. Given that we find null impacts of the installations, we do not believe that this potential source of bias threatens our overall policy conclusions. While other methods like instrumental variable estimation may help to further reduce the bias, we do not believe these methods would fundamentally change our results given the already low power of the study and the facts that most digesters had broken down by the time of our survey and half of the installations were never operational.

The estimates from equation 1 are estimates of the local average treatment effect of receiving a digester *installation* from PNB-SN. It is a local effect because we only consider the population of Senegalese households who are eligible to receive the digester according to the eligibility criteria discussed previously. It also can be interpreted as an intent to treat (ITT) estimate, as it considers all installed digesters, not just those that were successfully operated. There were many households who received an installation, but whose digesters never produced enough gas for cooking (see section 5.1).

We then estimate the impact of having an operational digester on the same set of outcomes, Y_{ij}. For this analysis we use only the sample of recipient, or treatment households. This estimate

[10] We describe how we construct our outcomes of interest in detail in Appendix D.

can be interpreted as the effect of treatment on the treated (ToT) households. The challenge here is that digester operation is highly endogenous, as discussed in section 4.3.1. For example, we predict that wealthier households are more likely to have an operational digester, but wealth also affects our outcomes of interest, like cooking fuel choice, through channels other than the biogas digester. To account for this endogeneity we predict each household's likelihood of having a functioning digester using the observable characteristics and models described in section 4.3.1. We then regress our outcome of interest on a binary variable equal to 1 if a household's digester adheres to our definition of operation, the predicted likelihood of a household having a digester that fits this definition of operation, and the X_{ij}, Z_{ij}, and V_j control vectors from equation 1. The coefficient on the binary variable of operation will then constitute the effect of an operational digester on Y_{ij}. This identification is based on the assumption that conditional on the predict probability of operation which is a function of observables, the average *likelihood* of having an operating digester is equal between those households with and without operating digesters.

5. Findings

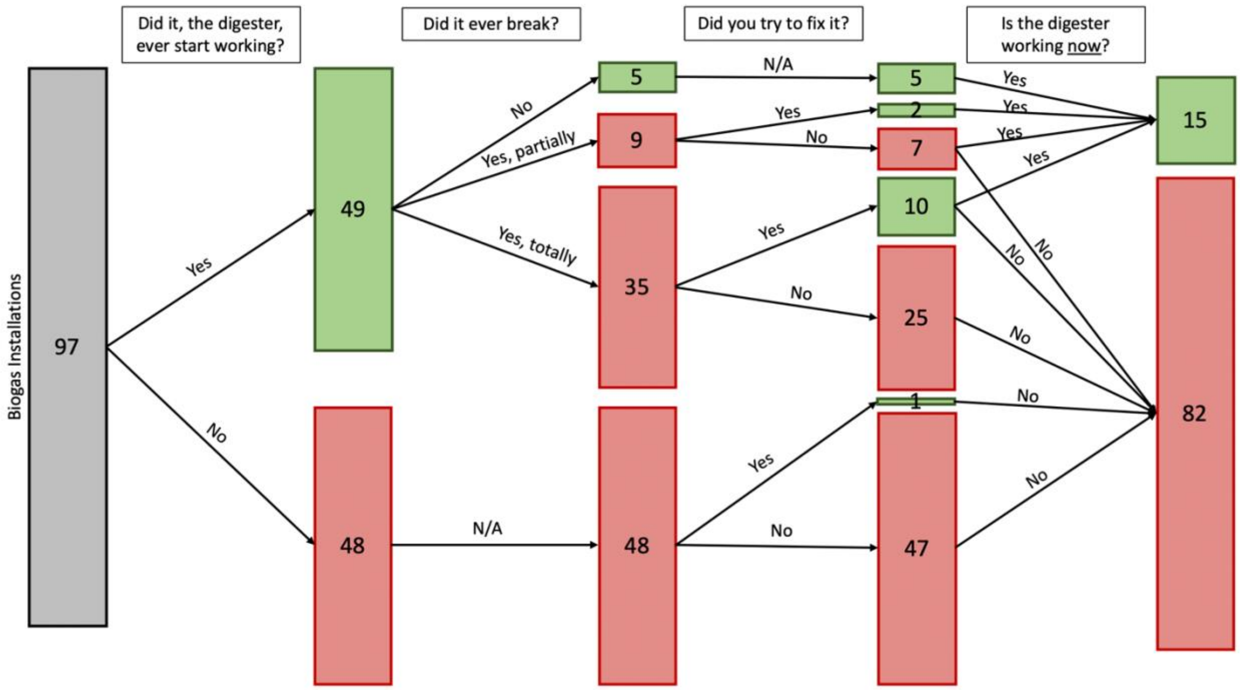
5.1 Digester installation and operation

5.1.1 Digester operation since installation

In total, we surveyed 97 households that had received biogas installations from PNB-SN. As discussed previously, these installations were completed between 2015 and 2018. At the time of our data collection in February 2019, digesters in our sample were on average 2 years old, i.e. it had been 2 years since installation was complete. The newest digester was 7 months old; the oldest was almost four years old. In our sample, the average household reported to have only contributed 70,000 CFA in cash towards installation cost, however, and only two households reported taking a loan to finance the digester. This would imply that households were making large in-kind contributions and/or the actual installation costs ended up being lower than predicted.

Two-thirds of the households we sampled received some sort of training or trainings on how to operate and maintain the digester. The median household had one training session. Most attended a training given by a government official, while others received information from the installation company itself or from friends and neighbors. Of the 63 households who participated in any training, only seven had received written materials regarding digester operation and maintenance and only four were able to show the interviewer the materials. Still, the vast majority of households who attended a training reported that they were satisfied or very satisfied with the biogas training(s) they had received.

Figure 5: Digester operation and repair from installation to interview



Note: The numbers indicate the number of households that fall into each response category. The colors indicate good "green" vs. bad "red" outcomes. For example, 48 of the digesters never started working, which we consider a bad outcome.

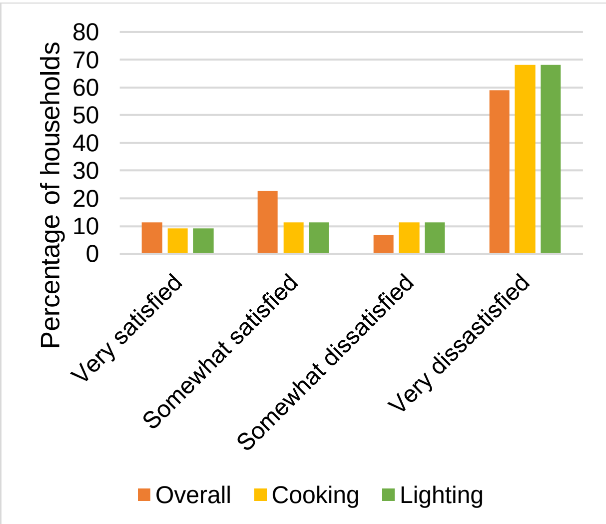
Figure 5 illustrates how the operation of the 97 digesters evolved since installation. Of the 97 digesters installed, 48 of them never operated sufficiently well to produce gas to cook, i.e. these digesters never worked. Of the 49 that did at some point produce enough gas to cook, 44 of them broke at least once. Nine of them broke only partially, i.e. the digester was not functioning optimally but could still be used. The other 35 completely broke down at least once, so badly that they could not be used at all. Thirteen households attempted to repair their digester at least once. Of these 13, only four were successful in all repair attempts. These are the households who sought to repair their digesters and whose digesters were functioning on the day of our interview. In the end, 15 digesters were operating on the day of our visit. Five of these were those that had never broken; four had broken but were successfully repaired; six had partially broken and had not been repaired but were still operating. The remaining 82 digesters were not operating at the time of our survey. They had been broken for at most three years, at the shortest, two weeks. Forty-eight of these were the digesters that had never functioned. Though, one household did try to repair their never-functioning digester, but they were not successful. Twenty-six of the 82 had been operational at some point, but they had broken and were never repaired. The remaining eight digesters had broken at least once, the household had tried to repair them, and may even have been successful at some point, but the last repair was not successful as the digester was not operating on the day of our visit.

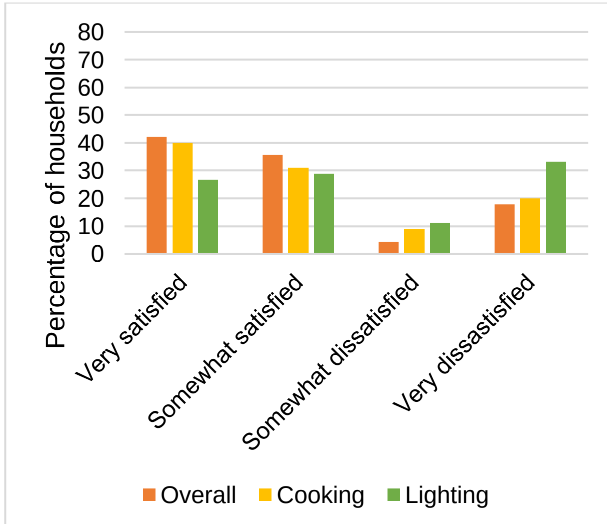
On average, the digesters had been broken so badly as to be totally inoperable for 70 percent of the time since installation; 15 percent of the time they had been partially broken, i.e. they were not working to their full capacity. This means that, on average, digesters had only operated well for 15 percent of their usable life to date. Despite this high breakage rate, 90 percent of households whose digesters were not operating on the day of the survey reported that they had never sought to repair their digester. Of the 13 households who reported doing repairs, they report spending between 0 and 40,000 CFA on all repairs, with an average total cost of 8,000 CFA across these 13 households.

Figure 6: Household satisfaction with biogas digesters

Panel A: Never functioning digester

Panel B: Ever functioning digesters





Of the 15 digesters that were operating on the day of our visit, only eleven households reported using the digester to cook at some point in the 7 days preceding the survey date. Five households report that their main cooking stove is the biogas stove. Two of these households owned digesters that had operated fully since installation, one had a digester that broke but was successfully repaired, and two use digesters that had partially broken, never been repaired, but were still usable. Interestingly, of the five households who digesters had functioned optimally since installation, two report using biogas as their main stove, one reports using LPG, and two report that a traditional, three-stone stove is their main cooking stove. Only six households report using biogas as a lighting source.

Despite these high breakdown rates, fifty-six percent of recipient households said they were overall somewhat or very satisfied with their biogas digester (Figure 6). When specifically asked about cooking and lighting, households were more likely to report being dissatisfied, with fifty percent of households reporting that they were very dissatisfied with the digester's performance with respect to lighting.

There was a large number of households who reported that they were dissatisfied with the biogas digester. When asked what they specifically liked and disliked about the digester, about one-third of households reported that there was nothing that they liked. Of these who reported liking nothing, most reported being dissatisfied with the digester, but about one-quarter reported that they were overall satisfied with the digester. This inconsistency indicates that the satisfaction measures reported in Figure 6 may be subject to a degree of yea saying bias, or a tendency to respond positively to questions that are presented. This could help to explain the seemingly high satisfaction rate, especially as compared to the digesters' low operation rate. It also may be that households are hesitant to criticize a government program or service. The most common response to "What do you dislike about the digester?" was "Nothing." But, among those who stated they had no dislikes, almost half reported being dissatisfied with the digester. This inconsistency indicates that some households are hesitant to discuss negative aspects of a program and may lead some households to overstate their satisfaction with the digesters.

5.1.2 Determinants of digester operation

The preceding section reveals that households manage their digesters differently. Some are able to maintain an operating digester, while other digesters fall into disrepair. To understand this variation, we present the results of linear probability models (Table 1, columns 1-3) and ordinary least squares regression (Table 1, column 4), testing for the relationship between program and household characteristics that may determine how households choose or are able to operate their biogas digester. The results from estimating Table 1, columns 1-3 using logistic regression are presented in Appendix Table A1.

The most stringent definition of operation that we consider in this section is whether a digester is working on the day of our survey visit. The results in Table 1, column 1 constitute a comparison between households who had a working digester on the day of our survey visit (N=15) and those who did not (N=78). Column 2 compares households with digesters that had operated for at least half of their life to date (N=28) with those that had operated for less than half (N=65). Column 3 compares households with digesters that had ever operated even if just for a short time (N=48), with households whose digesters had never operated enough to cook (N=45). Finally, column 4 considers a continuous measure of operation, the share of time since installation that the household's digester was operating at least partially (median = 0, mean = 0.31).

With respect to digester characteristics, having a flexible balloon digester is positively associated with all measures of operation. The coefficients indicates that, compared to having a fixed dome digester, having a flexible balloon digester is associated with between a 13 and 16 percentage point increase in the likelihood that the digester was operating on the day of the survey visit, operated at least half the time, or ever operated. Flexible balloon digesters are associated with a 10 percentage point increase in the share of time that a digester was operating since installation, though none of these coefficients are statistically significant at the ten percent level. It should be noted that most of the flexible-balloon digesters were installed in one region, so there may be other characteristics of program operation in that region that are driving this relationship. Receiving a training is strongly, positively related to most outcomes, associated with a 47 percentage point increase in the likelihood of a digester ever operating. From these results, it could be that the trainings are helpful at getting a digester to start operating, but not as strong of a contributor to maintaining operation (per smaller and non-significant results in column 1). Having a toilet connected to the digester is a strong and significant predictor of ever-functioning digesters, but does not seem to play a role in whether the digester was operating on the day of the visit.

Table 1: Determinants of digester operation

	Currently operating	Operated at least half the time	Ever operated	Share of time working
	(1)	(2)	(3)	(4)
Digester characteristics				
Digester type (=0 if fixed dome, =1 if flexible balloon)	0.16	0.13	0.13	0.097
	(0.11)	(0.14)	(0.18)	(0.12)
Training (=1 if household received a training)	0.13	0.38**	0.47***	0.31**
	(0.15)	(0.15)	(0.10)	(0.13)
Months since completion of installation	0.003	0.004	0.011*	0.004
	(0.007)	(0.007)	(0.006)	(0.006)
Toilet (=1 if toilet connected to digester)	-0.018	0.25	0.80***	0.20
	(0.099)	(0.27)	(0.100)	(0.15)
Prices				
Price of firewood, avg CFA/kg in village	-0.001	0.00002	0.0002	-0.000
	(0.001)	(0.001)	(0.002)	(0.001)
Price of charcoal, avg CFA/kg in village	0.001	0.001	0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)
Household characteristics				
Log household size	-0.14	-0.19*	-0.15	-0.17*
	(0.097)	(0.10)	(0.11)	(0.093)
Share of household who is female	-0.65**	-0.38	-0.68*	-0.38
	(0.30)	(0.39)	(0.38)	(0.30)
Education (=1 if household head has any school above koranic school)	-0.015	-0.059	-0.047	-0.072
	(0.12)	(0.13)	(0.10)	(0.10)
Log number of employed adults in household	0.040	0.056	-0.093	0.028
	(0.075)	(0.083)	(0.064)	(0.068)
Cubic-root distance to market, $km^{1/3}$	-0.011	-0.11*	-0.15*	-0.084*
	(0.030)	(0.062)	(0.080)	(0.045)
Asset index	0.036	0.025	0.062**	0.032
	(0.028)	(0.033)	(0.028)	(0.030)
Access to a loan (=1 if can access emergency funds via loan)	-0.13	-0.11	-0.34***	-0.24***
	(0.100)	(0.11)	(0.099)	(0.082)

Table 1, continued: Determinants of digester operation

	Currently operating (1)	Operated at least half the time (2)	Ever operated (3)	Share of time working (4)
Liquidity (=1 if can access 250,000 CFA in emergency funds)	-0.10	-0.030	0.19**	0.040
	(0.081)	(0.12)	(0.090)	(0.087)
Perceptions				
=1 if energy savings is reason for installation	0.011	0.016	-0.044	-0.010
	(0.10)	(0.12)	(0.11)	(0.10)
=1 if fertilizer production is reason for installation	0.20***	0.20**	0.18*	0.18**
	(0.044)	(0.084)	(0.095)	(0.066)
=1 if health is reason for installation	0.026	-0.015	-0.046	-0.067
	(0.090)	(0.12)	(0.079)	(0.10)
Livestock				
Log number of cows household looks after	0.008	0.034	0.050	0.002
	(0.044)	(0.040)	(0.040)	(0.033)
Minimal pasturing (=1 if cows out to pasture <8 hrs/day)	-0.048	-0.15	-0.087	-0.14
	(0.082)	(0.12)	(0.11)	(0.092)
Manure as fertilizer (=1 if household applies manure directly to fields)	0.020	-0.087	-0.068	0.021
	(0.090)	(0.11)	(0.092)	(0.084)
Manure for cooking (=1 if household uses manure directly for cooking)	0.46	0.18	0.14	0.29
	(0.34)	(0.28)	(0.29)	(0.24)
Constant	0.62	0.62	0.75	0.83**
	(0.43)	(0.47)	(0.53)	(0.39)
Observations	93	93	93	93
R-squared	0.233	0.322	0.513	0.364

Notes: Dependent variables are equal to 1 if digester operated on the day of survey (column 1), at least half the time since installation (column 2), or if it ever operated (column 3); Dependent variable in column 4 is a continuous measure of the share of time since installation that the digester was working fully or partially, equal to 1 if it was never fully broken; Standard errors are clustered at the village level (24 clusters); Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

The price of alternative fuels like firewood and charcoal also have a small, non-significant relationship with all definitions of operation. This is likely driven by the fact that most households rely on firewood for cooking and collect the fuel, as opposed to purchasing it in the market (see Table 3).

Household size and the share of household members who are female are both found to be negatively associated with digester operation across all models of operability. This may be because, the less labor constrained the household, the lower the opportunity cost of sending members to collect firewood. This effect would then be stronger for women, as they are most often responsible for fuelwood collection. Education is, puzzlingly, negative associated with operation. This finding is the opposite of most previous studies, which find that more educated households are more likely to adopt and use improved cooking technologies and fuels. The effect size is small and not statistically significant for most specifications. The number of employed adults is negatively associated with a digester ever operating, which may indicate that having members available at home to work with the digester is important for getting it running. Employed adults is positively associated with all other measures of operation, which may indicate that income from employment helps households to afford maintenance for digesters that break down once they are up and running. Again, none of these relationships are statistically significant. Lack of connectivity, as predicated, is negatively associated with operation, with households farther from a market less likely to have an operable digester across all specifications. Connectively is a particularly strong predictor of whether or not a household was ever able to operate their digester. Finally, assets and liquidity tend to be positive predictors of operation. A one unit increase in the asset index is associated with a six percentage point increase in the likelihood of a digester ever operating. The ability to access emergency funds is associated with a 19 percentage point increase. Credit access is negatively associated with operation, which may reflect the fact that this variable may actually be identifying households who need to access a loan for emergency funds, as opposed to getting it from their own income or savings.

Of the variables measuring motivation for digester installation, only the motivation to produce fertilizer is significantly related to operation. The relationship is positive and significant, increasing operation by about 20 percentage points across all specifications. Both health and energy savings motivations are not strong nor consistent predictors of operation. This may indicate that those households who value the bioslurry fertilizer most are most likely to undertake the daily effort to keep their digester functioning at a high level. Of the 15 households who had operating digesters on the date of the survey, 11 reported using more than fifty percent of their produced bioslurry as fertilizer. Very few households report selling any of their bioslurry, which indicates that either the fertilizer is highly valued by the households who produce it, or other households are not willing to buy it. It could be that promoting the economic benefits, as opposed to health or environmental, would be the most effective marketing strategy to increase uptake of digesters. The fact that fertilizer production, and not energy savings or health, predicts operation may also be indicative of the fact that males are responsible for purchasing decisions in most households. Males may be more likely to make decisions that improve household agriculture as opposed to those that improve the household energy system and indoor air pollution, as women are mostly responsible for fuelwood collection and most affected by indoor pollution.

The relationship between number of cattle and operation is as predicted. More cows are associated with an increase in operation, likely because more feedstock is available. The relationship between pasturing and operation is the opposite of what we expected. Minimal pasturing, which is defined as having your cows out to field for less than 8 hours per day, is associated with a lower likelihood of operation, as opposed to those who have the cows out to field for more than 8 hours per day. Most biogas programs simultaneously promote livestock stabling, based on the belief that keeping cows in stables, instead of out in the pasture, makes it easier to collect the manure and feed the digester. While pasturing means that dung is physically further from the digester, it may also mean that cows are better fed and watered, thus producing more dung. In the case of this negative relationship, the nutrition pathway appears to dominate. Still both the number of livestock and pasturing do not have a statistically significant relationship with operation. Finally, we consider whether other uses of manure predict operation. Households who report using manure directly for cooking are more likely to have operational digesters. This may be because they are bringing the manure to the house for feeding the digester, so it is easy to use some of the digester feedstock, for example, for lighting cooking fires.

Looking across all columns in Table 1, a couple consistent predictors stick out. The first is the importance of trainings, and the second is the role of fertilizer production as motivation. Both of these variables, equal to 1 if a household received at least one training or the household reported installing the digester in order to produce fertilizer, have strong positive and significant relationships with all measures of operation. When looking at column 1, which is the most stringent measure of operation, the share of the household who is female was a strong negative predictor of operation.

5.2 Impact analysis

5.2.1 Descriptive statistics and balance tables

Table 1 reports descriptive statistics for our sample and tests for differences between the treatment and control groups. For skewed outcomes, medians and interquartile ranges are reported, instead of the mean and standard deviation. For these skewed variables, tests of differences in means were conducted using a transformed variable to reduce skewness. For all tests, standard errors were clustered at the village level. All of the measures reported here are from our survey data which, for treatment households, was collected after installations were complete. Given that most of the digesters were not operating, we do not believe that the program had an effect on these measures. For example, the main pathway through which PNB-SN would have affected household wealth is through the sale of bioslurry as fertilizer. Given that so few households were producing fertilizer, we believe measures like the asset index are suitable controls.

The households in our sample are located in rural areas, which is consistent with the fact that most Senegalese households engaged in cattle rearing live in rural areas. Almost all households are headed by a man, only about twenty percent of which have completed any schooling outside of Koranic school. The median household is made up of 13 individuals (mean = 15), which is larger than Senegal's average household size, 8.7 (Patierno et al. 2019). The majority of our sampled households are Muslim and are members of the majority ethnic group in their village. Finally, most of the households cook indoors.

Table 2 characterizes households in our sample, as well as differences between the treatment and control groups. As discussed previously, these households were all selected from PNB-SN's biogas eligibility lists. It may be that households who are members of the majority ethnic group or those who have leadership positions in the community are more likely to be selected

Table 2: Difference in key characteristics between treatment and control groups

	Control	Treatment	Difference	N
Rural (=1 if rural)	0.99	1.00	0.01	196
	(0.10)	(0.00)	(0.01)	
Household size⁺	14	13	-1	196
	(10)	(7)		
Household size, male⁺	7	6	-1	196
	(5)	(4)		
Household size, female⁺	7	6	-1	196
	(7)	(5)		
Gender of household head (=1 if male)	0.93	0.96	0.03	196
	(0.26)	(0.20)	(0.04)	
Age of household head	55.06	51.66	-3.40	196
	(13.17)	(13.16)	(2.51)	
Education of HH head (=1 if any schooling above Koranic school)	0.16	0.22	0.05	196
	(0.37)	(0.41)	(0.07)	
Cooking location (=1 if inside, =0 if outside)	0.72	0.68	-0.04	196
	(0.45)	(0.47)	(0.08)	
Islamic (=1 if HH is Islamic)	0.97	0.95	-0.02	196
	(0.17)	(0.22)	(0.03)	
Ethnicity (=1 if ethnicity is the same as village majority)	0.90	0.88	-0.02	196
	(0.30)	(0.33)	(0.06)	
Political leadership (=1 if any HH member has held political position at any time)	0.10	0.07	-0.03	196
	(0.30)	(0.26)	(0.04)	
Religious leadership (=1 if any HH member has held religious position at any time)	0.10	0.13	0.03	196
	(0.30)	(0.34)	(0.05)	
CSO leadership (=1 if any HH member has held CSO position at any time)	0.04	0.06	0.02	196
	(0.20)	(0.24)	(0.03)	
Land owned or leased, hectares⁺	2.75	3	0.25	194
	(5)	(5.58)		
Asset Index	-0.34	0.34	0.69	196
	(2.26)	(2.09)	(0.51)	
Access to a loan (=1 if can access emergency funds via loan)	0.16	0.13	-0.03	196
	(0.37)	(0.34)	(0.06)	
Liquidity (=1 if can access 250,000 CFA in emergency funds)	0.84	0.80	-0.03	196
	(0.37)	(0.40)	(0.06)	
Distance to nearest weekly market, km⁺	10	5	-5	196
	(11)	(7.33)		
Distance to nearest bus stop, km⁺	2	1	-1***	184
	(4.5)	(2)		

Notes: Means and standard deviations (in parentheses) are reported for each variable, for the treatment and control groups; The distributions of variables marked with ⁺ are right-skewed, so the median and interquartile range is reported; In column 3, the difference between treatment and control mean or median is reported; Stars indicate the result of a t-test of the difference in means between treatment and control; For variables marked with ^, the t-test is performed after a log or cubic-root transformation to reduce skewness; *** p<0.01, ** p<0.05, * p<0.10; For all tests, standard errors are clustered at the village level.

for the first biogas installations. Table 2 indicates that the two groups, those who received biogas installations between 2015 and 2017 and those who have yet to receive them are similar across these characteristics, including whether or not they have ever held political, religious, and civil society leadership roles. Households in the treatment group are slightly wealthier than those in the control group, based on the asset index and land ownership, but these differences are not statistically significant. Households in the control group are slightly larger than those in the treatment group which may be indicative of the fact that installation companies chose to go to easily accessible locations first, and households tend to be larger in more remote areas. This is further supported by the fact that the households in the control group report living significantly further from a bus stop than those in the treatment group. Control households are, at the median, 2 kilometers from the nearest bus stand, while treatment households are only 1 kilometer away. The only difference that is statistically significant below the ten percent level is the difference in distance to the nearest bus stop.[11] The results of difference in means tests report in table 2 indicate that, to a certain extent, sampling only from the eligibility lists and using regional coordinators to match treatment and control villages helped to deal with household and community level characteristics that drive biogas installations. There still may be unobserved differences between the two groups, but it is likely that at least some unobserved differences between the two groups were also reduced by our sampling methods.

With respect to cooking patterns, the average household has two different types of stoves. The most common type is the three-stone stove, which about 80 percent of households have in their home. Almost all of these households report that the three-stove stone is their main cooking stove. The second most common stove is LPG, which about 40 percent of households have, but only five percent of households report that this is their main stove. Only 18 percent of households report having a biogas stove, which is indicative of the fact that many of the installed digesters never operated or were broken down by the time of our visit.

With respect to cooking fuels, the median household uses 5 kilograms of firewood per day (mean = 9) and zero kilograms of charcoal per day (mean = 1.6). One third of households report that they use agricultural residue to cook, but, on average, they only report using about one kilogram per week. Of the households who have an LPG stove, about seventy percent report that they use LPG fuel. This indicates that the other thirty percent of the LPG stoves are present in the household but not being used. The average household burns a 6kg cannister of LPG every two months (median = 0), using about half a cannister per month. The only significantly difference in fuel use between treatment and control is firewood use, with control households using significantly more. As shown in Table 3, treatment households spend more money on purchasing fuel, including the cost of travel, while control households spent more time collecting fuel. The median households spends about three person-hours per week collecting fuel. In the average household, the main cook spends about five hours a day cooking, and this is lower in the treatment households. All main cooks in our sample are women.

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[11] We did not conduct village-level surveys, so can primarily report only household characteristics. Distance to markets and the nearest bus stop are both measured at the village level, taking an average of the reported measures across all households in a village.

Table 3: Difference in household-level outcomes between treatment and control

	Control	Treatment	Difference	N
Self reported daily firewood use, kg⁺	7	3	-4**	193
	(9.9)	(9.00)		
Self reported daily charcoal use, kg⁺	0	0	0	196
	(0.14)	(0.36)		
Self reported monthly LPG use, 6kg cannister⁺	0	0	0	196
	(0.5)	(0.5)		
Total minutes spent collecting fuel across all household members, per week⁺	173.75	150	-23.75	196
	(422.75)	(323.75)		
Total amount spent on fuel (including travel cost) per month, CFA⁺	1,200	1,500	300	196
	(6,363)	(12,000)		
Minutes that the main cook spends cooking, per day	328.01	302.92	-25.10	182
	(111.12)	(99.02)	(19.35)	
Number of crops grown	2.89	2.48	-0.40*	196
	(1.46)	(1.26)	(0.23)	
Corn harvested in past 12 months, kg⁺	400	275	-125	64
	(800)	(1,300)		
Peanuts harvested in past 12 months, kg⁺	1,200	1,000	-200	122
	(2,400)	(1,500)		
Millet harvested in past 12 months, kg⁺	1,000	1,000	0	119
	(1,700)	(1,150)		
Revenue from crop sales in past 12 months, CFA⁺	115,000	84,000	-31,000	196
	(575,000)	(350,000)		
=1 if household uses fertilizer other than direct application of animal manure	0.57	0.75	0.19**	196
	(0.50)	(0.43)	(0.08)	

Notes: Means and standard deviations (in parentheses) are reported for each variable, for the treatment and control groups; The distributions of variables marked with ⁺ are right-skewed, so the median and interquartile range is reported; In column 3, the difference between treatment and control mean or median is reported; Stars indicate the result of a t-test of the difference in means between treatment and control; For variables marked with ^, the t-test is performed after a log or cubic-root transformation to reduce skewness; *** p<0.01, ** p<0.05, * p<0.10; For all tests, standard errors are clustered at the village level.

We also consider the health of two different groups. First, we look at children under 12, as they are physiologically more susceptible to health damage from air pollution. About ten percent of the children in our sample were reported to have a cough at some point in the two weeks preceding the survey and four percent reported to have trouble breathing as well. These two indicators together are indicative of an acute lower respiratory infection. Interestingly, rates of both coughs and possible ALRI cases are higher in the treatment group. We also consider eye problems, as these can be associated with exposure to indoor air pollution. Again, children in the treatment group are more likely to experience eye problems, thought none of these differences are significant at the ten percent level or below. The other individuals we consider are those over the age of twelve who are responsible for cooking in the household, including both main and not main cooks. Respiratory problems among these individuals occur at about the same rate as children, and there is no significant difference between treatment and control.

Cooks in the treatment group experience eye problems at about twice the rate of those in the control.

Table 4: Difference in individual-level outcomes between treatment and control

	Control	Treatment	Difference	N
=1 if individual experienced a cough in the past 2 weeks				
Cooks (>12 y.o.)	0.11	0.12	0.01	473
	(0.31)	(0.33)	(0.04)	
Boys (<12 y.o.)	0.09	0.11	0.02	529
	(0.29)	(0.31)	(0.04)	
Girls (<12 y.o.)	0.09	0.16	0.07	520
	(0.28)	(0.36)	(0.04)	
=1 if individual had ALRI symptoms in the past 2 weeks				
Cooks (>12 y.o.)	0.03	0.07	0.04	473
	(0.18)	(0.25)	(0.02)	
Boys (<12 y.o.)	0.04	0.04	0.00	529
	(0.19)	(0.20)	(0.02)	
Girls (<12 y.o.)	0.03	0.07	0.04	518
	(0.16)	(0.25)	(0.03)	
=1 if individual had any eye issue in the past 2 weeks				
Cooks (>12 y.o.)	0.06	0.06	-0.00	471
	(0.25)	(0.24)	(0.02)	
Boys (<12 y.o.)	0.02	0.03	0.00	527
	(0.16)	(0.17)	(0.02)	
Girls (<12 y.o.)	0.01	0.03	0.02	519
	(0.08)	(0.16)	(0.01)	
=1 if the adult (18 y.o. or older) is employed in a personal business or wage-earning activity				
Full Sample	0.27	0.30	0.03	1,453
	(0.45)	(0.46)	(0.04)	
Males	0.42	0.48	0.06	679
	(0.49)	(0.50)	(0.06)	
Females	0.14	0.14	0.00	756
	(0.35)	(0.35)	(0.04)	

Notes: Means and standard deviations (in parentheses) are reported for each variable, for the treatment and control groups; In column 3, the difference between treatment and control means is reported; Stars indicate the result of a t-test of the difference in means between treatment and control; *** p<0.01, ** p<0.05, * p<0.10; For all tests, standard errors are clustered at the village level.

Households in our sample are mainly rural, agricultural households. The three main crops reported to be grown are peanuts (grown by 122 households), millet (grown by 119 households), and corn (grown by 64 households). Other, less commonly grown crops are cowpea, rice, and onion. Across all households the average number of different crops grown is 2.7, with control households slightly more diversified across crops than treatment (Table 3). Control households also tend to harvest more and generate more revenue from crop sales, despite fewer control households using any sort of improved fertilizer, defined as bioslurry or any type of chemical fertilizer. This may indicate that control households are more remote and more reliant on agriculture for their livelihoods.

In our sample, about one-third of adults are employed in a wage-earning activity or personal business (Table 4). Men are much more likely to be employed than woman, but there is no significant difference in employment status between adults in treatment and control households.

5.2.2 Fuel use and cooking impacts

Here we present estimates of the effect of PNB-SN's biogas installations on our outcomes of interest. In our sample, the only households that report having a biogas digester are treatment households, and all digesters were installed through PNB-SN. Table 5 presents estimates of the impact of digester installation on fuel use outcomes. In Table 5 all regressions are estimated using ordinary least squares and standard errors are clustered at the village-level. Our preferred specification controls for both demographic characteristics and factors that we believe determine whether a household gets treated earlier or later in the program, specifically distance to the nearest market and bus stop, land ownership, an asset index, and a measure of liquidity.

Table 5: Impacts of biogas installation on fuel use outcomes

	Log firewood use, ln(kg/day)		Cubic-root charcoal use, kg/day$^{1/3}$		Cubic-root LPG use, 6 kg cannisters/month$^{1/3}$	
	(1)	(2)	(3)	(4)	(5)	(6)
Biogas installation	-0.31*	-0.17	0.063	-0.097	0.060	0.020
	(0.16)	(0.18)	(0.097)	(0.12)	(0.087)	(0.061)
Cubic-root distance to nearest weekly market, km$^{1/3}$		-0.080		0.0038		0.070
		(0.11)		(0.067)		(0.051)
Cubic-root distance to nearest bus stop, km$^{1/3}$		0.21		-0.15**		0.075*
		(0.16)		(0.072)		(0.039)
Log land owned or leased, ln(hectares)		0.22**		-0.00014		0.042
		(0.082)		(0.051)		(0.031)
Asset Index		-0.097**		0.068***		0.12***
		(0.040)		(0.025)		(0.018)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		0.016		0.032		-0.0028
		(0.20)		(0.094)		(0.090)
Constant	1.66***	0.66	0.30***	0.70	0.28***	-0.20
	(0.11)	(0.81)	(0.067)	(0.46)	(0.056)	(0.28)
Demographic controls	Y	Y	Y	Y	Y	Y
Observations	193	179	196	182	196	182
R-squared	0.018	0.133	0.002	0.105	0.004	0.325

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

The magnitude of the estimates indicate that biogas installations led to a 26 percent decrease in the geometric mean of daily firewood use, or about 1.4 kilos. Without controls, the estimated effect is larger and statistically significant. When the controls are added, the estimated effect size decreases, indicating that, without controls, we would likely over-estimate the treatment effect. If any unobserved differences are still upwardly biasing our estimates, the true effect would be even closer to zero.

The coefficients in columns 4 and 6 indicate that installations led to a very small decrease in charcoal use and similarly small increase in LPG use. Additionally, none of these estimates are found to be statistically significant at the ten percent level or lower. We believe we can conclude that, for the treatment households in our sample, the biogas installations carried out by PNB-SN and their partner organizations did not have an economically significant effect on cooking fuel.

Table 6: Impacts of biogas installation on time use and expenditure outcomes

	Cook time, min/day		Fuel collection time, $(\text{min/wk})^{1/3}$		Total fuel expenditure, ln(CFA/month)	
	(1)	(2)	(3)	(4)	(5)	(6)
Biogas installation	-25.1	-14.0	-0.53	-0.24	0.20	-0.44
	(19.3)	(21.6)	(0.60)	(0.52)	(0.83)	(0.69)
Cubic-root distance to nearest weekly market, $\text{km}^{1/3}$		-15.9		0.12		0.73
		(11.0)		(0.51)		(0.48)
Cubic-root distance to nearest bus stop, $\text{km}^{1/3}$		17.2		0.30		0.097
		(11.0)		(0.27)		(0.44)
Log land owned or leased, ln(hectares)		5.14		0.49**		0.21
		(7.40)		(0.23)		(0.28)
Asset Index		-9.85**		-0.52***		0.98***
		(4.14)		(0.12)		(0.17)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		17.7		0.32		-1.29
		(23.0)		(0.73)		(0.80)
Constant	328***	238***	5.76***	9.11***	4.54***	3.69
	(13.0)	(73.4)	(0.47)	(2.27)	(0.55)	(3.06)
Demographic controls	N	Y	N	Y	N	Y
Observations	182	168	196	182	196	182
R-squared	0.014	0.142	0.006	0.217	0.000	0.248

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

The null effects from Table 5 are mirrored in Table 6, where we consider other fuel and cooking outcomes. The coefficients in columns 2 and 6 indicate that biogas reduced cook time by fourteen minutes per day and fuel expenditure by thirty-five percent, or 2,300 CFA/month. The coefficient in column 4 is more difficult to interpret because of the cubic root transformation, but the estimated effect is small and not statistically significant. In columns 2, 4, and 6 we can see that asset index, a relative measure of household wealth, is significantly associated with lower cook times and fuel collection times as well as higher fuel expenditure. Wealthier households are more to likely purchase, rather than collect their fuels and may use more modern stoves that reduce cooking times. Appendix Tables A2 and A3 present estimates after dropping outliers for firewood, charcoal, and LPG use, as well as fuel collection time and fuel expenditure. Results are robust to dropping outliers.

5.2.3 Health impacts

As discussed previously, we consider health outcomes for two groups of household members, children under 12 and individuals responsible for cooking. To estimate the impact of biogas installations on incidence of a cough and of ALRI, we use logistic regression, controlling for individual's age and gender as well as the household and village characteristics from the previous estimations. We cluster standard errors at the village level.

Appendix Table A5 shows the results for children under 12. Columns 2 and 6 are our preferred specifications, controlling for demographic characteristics as well as variables that drive earlier installations within PNB-SN. The negative coefficient on biogas installation in both of those columns reverses the pattern in Table 4, where children in treatment households were slightly more likely to experience a cough or ALRI symptoms. The odds ratios associated with these coefficients estimate that biogas causes a 5 percent reduction in the likelihood of a child having a cough in the two weeks preceding the survey. The magnitude of the estimated effect is even larger in the case of ALRI symptoms, estimating a 16 percent reduction in likelihood. Still these estimated effect sizes are quite small when we consider that nine percent of children in the control group experienced a cough and 3 percent experienced symptoms consistent with ALRI. In addition, none of these estimated effects are significant at the ten percent level. Heterogenous impact estimates for girls versus boys are displayed in columns 3 and 7. Installation is associated with fewer respiratory health problems in boys and more in girls. For girls, this result is significant in the case of ALRI symptoms, though only at the ten percent level.[12]

The results for cooks ages 12 and above are displayed in Appendix Table A6. Here again, there is no significant effect of biogas installation on respiratory health outcomes, as indicated by the coefficients on biogas installation in columns 2 and 6. Though, the coefficient with respect to coughs is negative and indicates a reduction in likelihood of 16 percent. For ALRI symptoms, the coefficient estimate indicates an increase in likelihood of 12 percent. All individuals responsible for cooking are females, so instead we test for heterogenous impacts by age and find that treatment effects do not significantly vary across ages. We also consider the impact of biogas installations on the incidence of eye problems but find no effects for either children or cooks, as illustrated in Appendix Table A4.

[12] Interestingly, distance to the nearest bus stop and nearest market is negatively and significantly related to respiratory problems across all specifications for children (Appendix Table A5) and cooks (Appendix Table A6), respectively. It may be that more isolated areas experience less ambient air pollution from industry or traffic.

5.2.4 Agricultural and employment impacts

Finally, we turn to agricultural and employment impacts. Impacts on binary outcomes like employment and fertilizer use are estimated using logistic regression. All others are estimated using ordinary least squares.

As shown in Appendix Table A7, we do not estimate biogas to have any significant effects on agricultural patterns. The magnitude of the estimated effect suggests households specialize more after biogas, i.e. reduce the number of crops they grow, but the effect size is small not significant. The coefficient in column 4 is associated with a 75 decrease in crop revenue, or 250,000 CFA. This is a large change, though not statistically significant. It could be that households are shifting away from agriculture to other income generating activities, but this is not supported by the employment results in Appendix Table A9. Biogas digesters may improve agricultural outcomes, most directly through the use of bioslurry as a high-quality fertilizer. Alternatively, the bioslurry could be sold to other farmers and the income used to buy chemical fertilizer or a variety of other productivity increasing expenditures. As shown in Appendix Table A7, column 5, treatment households are more likely to use bioslurry or chemical fertilizers, but this difference is no longer significant after controlling for demographic characteristics and determinants of early treatment.

In Appendix Table A8 we estimate the effects of biogas on harvests, considering the three most commonly grown crops, peanuts, millet, and rice. Again we find no statistically significant effects, thought the magnitude of the estimates are positive. Unfortunately, we did not have data on the acreage cultivated for each crop, so were unable to consider agricultural productivity outcomes.

Digesters could also affect employed outcomes. Time shifted away from cooking or fuel collection could be put into a personal business or a wage-earning activity. Increased agricultural productivity may mean that fewer acres need to be cultivated to feed the family, so some agricultural laborers can switch into wage-earning employment. While biogas installation is associated with higher employment, especially among men, the effect is not significant at the ten percent level (Appendix Table A9). We do not find statistically significant heterogeneous treatment effects across men and women (Appendix Table A9, columns 3 and 4). Across all specifications, women are significantly less likely to be employed than men.

5.2.5 Impacts of operational digesters

The previous sections illustrate that 1. Senegal's domestic biogas program is not yet achieving its desired results and 2. Many digesters never operated or failed to operate for the majority of their usable lives. Could it be then that, the null impact results are being driven by non-functioning digesters and households with functioning digesters are shifting away from solid fuels and experiencing improvements in health and productivity outcomes? Here we compare our same outcomes of interested tested above between households with and without functioning digesters, defined here as digesters that were operational for at least half of their usable life to date.

Table 7: Impacts of operational digesters on fuel-use, cooking and agricultural outcomes

	(1) Log firewood use, ln(kg/day)	(2) Cubic-root charcoal use, $(kg/day)^{1/3}$	(3) Cubic-root LPG use, $(6\ kg\ cannisters/month)^{1/3}$	(4) Cook time, min/day	(5) Fuel collection time, $(min/wk)^{1/3}$	(6) Total fuel expenditure, ln(CFA/month)	(7) Number of crops grown	(8) Revenue from selling crops in the last 12 months, ln(CFA)
Digester operated for at least half of it's usable life (=1 if yes)	-0.0024	0.20	0.074	-21.6	-1.01	0.18	-0.24	0.67
	(0.51)	(0.27)	(0.14)	(29.8)	(1.10)	(1.26)	(0.45)	(2.12)
Predicted probability of digester operating at least half of it's usable life	0.25	0.33	-0.094	-3.48	0.72	1.30	0.85	1.90
	(0.77)	(0.29)	(0.28)	(36.1)	(2.01)	(1.67)	(0.88)	(3.41)
Cubic-root distance to nearest weekly market, km1/3	-0.079	0.0096	0.070	-17.7	-0.20	1.29*	-0.38**	1.11
	(0.18)	(0.097)	(0.070)	(11.3)	(0.71)	(0.69)	(0.18)	(0.71)
Cubic-root distance to nearest bus stop, km1/3	0.23	-0.16	0.12*	3.03	0.079	0.24	0.091	-1.62
	(0.31)	(0.13)	(0.068)	(22.4)	(0.45)	(0.74)	(0.24)	(1.30)
Log land owned or leased, ln(hectares)	0.25	-0.027	0.028	9.62	0.069	0.52	0.28**	0.88
	(0.15)	(0.057)	(0.052)	(11.1)	(0.40)	(0.54)	(0.13)	(0.57)
Asset Index	-0.15**	0.091**	0.15***	-7.94	-0.55***	1.23***	-0.096	-0.87**
	(0.061)	(0.034)	(0.031)	(7.51)	(0.15)	(0.23)	(0.070)	(0.39)
Liquidity (=1 if can access 250,000 CFA in emergency funds)	-0.019	0.0067	-0.11	-20.3	1.45	-1.39	0.14	1.81
	(0.34)	(0.20)	(0.13)	(35.2)	(0.88)	(1.25)	(0.30)	(2.22)
Constant	1.68	-0.11	0.37	295***	11.7***	4.17	1.81*	0.32
	(1.25)	(0.61)	(0.34)	(85.1)	(3.54)	(3.48)	(0.98)	(5.34)
Demographic controls	Y	Y	Y	Y	Y	Y	Y	Y
Observations	83	85	85	78	85	85	85	85
R-squared	0.191	0.154	0.473	0.168	0.292	0.453	0.258	0.197

Notes: Standard errors are clustered at the village level; Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 8: Impacts of operational digesters on individual health and employment outcomes

	(1)	(2)	(3)	(4)	(5)
	Children under 12		Cooks		
	Cough	ALRI symptoms	Cough	ALRI symptoms	Employment status
Digester operated for at least half of it's usable life (=1 if yes)	-0.19	-0.84	0.47	-0.57	0.012
	(0.62)	(1.31)	(0.72)	(0.85)	(0.45)
Predicted probability of digester operating at least half of it's usable life	-0.93	2.38	-0.80	-0.28	1.77**
	(1.45)	(3.13)	(1.25)	(2.13)	(0.69)
Age, in years	-0.13**	-0.075	0.031*	0.039*	0.0032
	(0.057)	(0.11)	(0.017)	(0.022)	(0.0047)
Sex (=1 if female)	0.58*	0.88			-1.82***
	(0.34)	(0.56)			(0.26)
Cubic-root distance to nearest weekly market, km1/3	0.027	0.97*	-0.15	-0.35	0.28
	(0.33)	(0.58)	(0.39)	(0.46)	(0.18)
Cubic-root distance to nearest bus stop, km1/3	-0.81**	-5.59***	-0.30	-1.55	-0.28
	(0.41)	(1.29)	(0.46)	(0.99)	(0.26)
Log land owned or leased, ln(hectares)	-0.45	-2.99**	-0.16	-1.22	-0.051
	(0.36)	(1.46)	(0.28)	(0.80)	(0.14)
Asset Index	-0.050	0.56	-0.22	-0.12	0.093
	(0.15)	(0.36)	(0.15)	(0.16)	(0.076)
Liquidity (=1 if can access 250,000 CFA in emergency funds)	1.26*		1.31	0.77	1.13*
	(0.76)		(0.95)	(0.95)	(0.59)
Constant	-1.35	3.03	-3.44	-0.92	-2.45**
	(2.01)	(2.65)	(2.50)	(3.00)	(1.18)
Demographic controls	Y	Y	Y	Y	Y
Pseudo-R2	0.18	0.46	0.15	0.22	0.19
Observations	412	316	193	193	574

Notes: Models estimated using logistic regression; Standard errors clustered at the household level; Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

As Table 7 shows, a digester that is operational for more than half of its usable life does not seem to be enough to shift households away from solid fuels. The magnitudes of the estimated effect of having an operational digester on fuel use outcomes suggest that households with operating digesters are in fact using less fuelwood than those without and are reducing their fuel collection and cooking time. But these estimates are not statistically significant. Health, agricultural and employment outcomes also show no significant improvement among households with operational digesters, as shown in Tables 7 and 8.

We are extremely limited in this section's analysis by the small sample size. We only found a handful of digesters operating, so it is difficult to use econometric methods to estimate the impacts of these functioning digesters. To attempt to increase the sample of operating digesters, we did this analysis with digesters that had operated for at least half their usable life, instead of only using those that were operating on the day of our survey. So it also may be that digesters have to reach a higher threshold of operation before having impacts on our outcomes of interest. Unfortunately, we only have 5 households who maintained operating digesters for their entire usable life, so we cannot estimate the impacts of high levels of operability.

6. Cost Data

Because our research team did not implement the intervention, the biogas installations, the majority of the information we have regarding costs comes from PNB-SN documents. Program documents report the cost of installing the digester, which varies by size. The cost of the smallest digester, 8 cubic meters, was reported at around 450,000 CFA, or 750 USD (Programme National De Biogaz Domestique Du Sénégal). The largest digester, 18 cubic meters, was reported to cost 728,300 CFA, around 1,200 USD. As discussed previously, installation costs were paid by both the government and the recipient households. Only 52 out of 97 households were able to report the size of their digester, and many of these reports did not match the sizes available from the government documents. Therefore, we do not have reliable data on the size of digesters installed in our sample.

We additionally asked households how much they had spent on associated appliances (like a stove or gas-powered lamps) as well as any repairs since installation. Seventy-nine of the recipient households, around eighty percent, reported that they had not spent any money on appliances or repairs. The average expenditure on appliances and repairs amongst the other twenty percent of households was 37,000 CFA, or 60 USD. We do not have any information regarding appliances or repairs that were paid for by PNB-SN.

If we assume every household received an 8 cubic meter digester and did not spend any money on appliances or repairs, the total cost of the program for all 97 households in our sample was 72,750 USD. Under these same assumptions, the cost for the 901 installations initiated by PNB-SN between 2015 and 2017 would be estimated at 675,750 USD. This is clearly an underestimate as it is very unlikely that repair and appliance costs, whether borne by households or the government, were zero. In addition, we are not considering the value of the time that households spend on operating the digester, which involves collecting biomass and water to feed into the tank.

7. Discussion

7.1 Discussion of findings

Our analysis of PNB-SN has shown that, after two years of full-scale implementation, the program had yet to achieve its desired impacts of transitioning Senegalese households to cleaner and more modern energy sources. This is in contrast to evaluations of other biogas programs, which find that installing digesters can help to substitute at least some of recipient households' fuelwood and charcoal use (e.g. Bedi et al. 2015). In their study of Rwanda's biogas program, Bedi et al. (2015) estimate that, given their observed effects and the installation costs of the digesters, the payback period, or the time in which a household will receive benefits equal to their investment in the digester, is 42 years. With the almost fifty percent subsidy provided by the Rwandan government, the payback period falls to 18 years. In this study, they found that only 10 percent of the installed digesters were failing to produce any gas and, if these digesters were operational, the estimated payback period with the subsidy would fall to 9 years. This is within the estimated 20-year lifespan of the digester, but still constitutes a relatively low rate of return compared to other potential investments. Given that the Senegalese program has not been successful at transitioning households away from polluting fuels and technologies, improvements in other outcomes, such as health and productivity improvements, have also not been realized. This means that, in the case of the PNB-SN installations, the rate of return is likely very low, if not zero. It should be noted that other cooking interventions that have been carried out in Senegal in the past have been successful at reducing reliance on solid fuels, enough so to improve associated outcomes like respiratory health (Bensch & Peters 2015, Bensch & Peters 2013).

Our study also revealed challenges with keeping the digesters operating, contributing to the null impacts discussed above. Half of the installed digesters, amongst the households we surveyed, had not been operational since the time of installation. At the time of our survey visit, only 15 households, of the 97 recipient households interviewed, had operating digesters. Of the 92 digesters that were broken at some time between installation and our survey, only 13 households had attempted to repair the digester. This suggests that support systems are not working. It could be that, like the evaluation of East Africa's African National Biogas Partnership found (Clemens et al. 2018), households do not know who to contact when they need help operating or fixing the digester. This could be caused by a shortage of skilled professionals and/or a lack of information dissemination. It could also be that maintenance services are prohibitively expensive. Households may know who to contact but are not willing or able to pay the price for consultations or repairs.

When considering the drivers of digester maintenance, we find that participation in trainings is positively and significantly associated with functioning digesters. Households in our sample received trainings and information from numerous sources, government officials, installation companies and neighbors. Unfortunately, we do not have enough variation in who offered the trainings nor information about the content or timing of the trainings to test for the role that different types of trainings could play in digester operation.

Households located closer to local markets and relatively wealthier households (as measured via a durable asset index) are also more likely to get their digester operating at least for a short time and, in the case of market access, to keep it operating longer. This suggests that successful digester operation requires both physical access to markets for parts and repairs as well as the ability to make the necessary investments. Additionally, a household's motivation for choosing to install the digester, specifically if they installed for the purpose of producing fertilizer, is important and positively associated with all three dimensions of operation that we study. It may be that emphasizing the fertilizer production potential of biogas would help increase willingness to install and maintain the digesters.

Finally, it is worth noting that the share of females in the household was negatively and significantly associated with both current operation of the digester, i.e. it was operating on the day of our survey visit, and whether the household was every able to successfully operate the digester. We are not able to pinpoint what is driving this relationship, but it is important to note given that investments in clean energy like biogas are likely to disproportionately benefit women and one of the stated goals of PNB-SN is to promote gender equity. If there is something about being a female that is preventing access to biogas, it certainly warrants further investigation.

7.2 Study limitations

It is important to note that our analysis of the drivers of digester operation, is not causal. It is based on operational data, so the relationships discussed, while informative, are correlational.

The primary limitation of this study was its cross-sectional, ex post design. We had initially planned to include households who had yet to receive digesters as of mid-2018, but who would receive them sometime in the next six months. This design would allow us to survey households both before and after installation and use a difference-in-difference design to account for unobserved differences between households who had received the installations earlier versus later in the program. Due to budget constraints, PNB-SN paused installations prior to the roll-out of our study, so we pivoted to carry out a cross-sectional, ex post evaluation of households who had received installations before the pause, between 2015 and 2017. We used our sampling design and survey to attempt to control for differences between early and late recipients, but there may still be differences between our two study groups that could bias our results. It is likely, based on discussions with the construction companies contracted to carry out installations, that households in wealthier communities with better market access received installations first. Therefore, any differences we are not able to account for with our design would upwardly bias our estimates. Given that we find mostly null results, we do not believe this potential source of bias significantly affects the conclusions of our impact evaluation.

The ex post design also limited our ability to capture details of digester operation. The majority of the households in our treatment sample had broken down digesters, and many had been broken for a long period of time before our survey. Therefore, it was difficult to collect accurate data about what practices had led to digesters breaking down. It is possible that some digesters broken down because of improper care and operation on the part of the households. Others may have broken down because of errors in installation or poor-quality inputs and associated appliances. We are not able to disentangle these two causes of breakdown with our data.

With respect to our analysis of the drivers of digester operation, this analysis is based on observational data, and therefore should not be interpreted as casual. This analysis, instead, sheds light on what elements of the biogas program could be updated to, possibly, achieve better rates of digester operation. A more robust test of these elements would randomly allocate households into different designs of the PNB-SN, for example randomizing the number and content of trainings offered, and measure differences in outcomes across these different programmatic designs.

Finally, we consider the external validity of our findings. Our sample consists of households deemed eligible to receive biogas digesters, i.e. they have sufficient livestock, access to capital, and have demonstrated a willingness to receive the digester installation. While this is not representative of the entire Senegalese population, it does reflect the subset of the population that could benefit from biogas. Given our sampling strategy, our sample is additionally made up of households in communities where four or more households were deemed eligible to receive biogas. We expect that, if scaled up, the biogas program will install numerous digesters in each chosen community, so, from a policy perspective this limitation does not serious impact our conclusions.

8. Conclusions and recommendations

The study presented here was designed to evaluate the impact of PNB-SN's biogas digester installations on cooking patterns and associated time use, health and agricultural outcomes in target households. Our analysis has shown that the program, after two years of full-scale implementation, is not achieving its desired impacts of significantly reducing reliance on solid fuels for cooking. Thus, the associated development outcomes of improving respiratory health, reducing the cooking and fuel collection time burden on women, and improving agricultural outcomes through the production of bioslurry are also not being achieved. Through our interviews with households who received installations through PNB-SN, we found that over half of the digesters installed had never produced enough gas for cooking and, on the day of our survey, only 15 percent were operating. In addition, very few households sought to repair broken digesters, which suggests that, similar to the findings of the pilot phase, maintenance services are either not available, households are not informed about where or how to get them, and/or the services are prohibitively expensive.

Given this small sample of operating digesters, we are not able to draw strong conclusions about the potential for *functioning* digesters to bring about the desired impacts. Still, we provide suggestive evidence that digesters that have operated for at least half of their usable life do not seem to be shifting households away from polluting fuels. So it may be that PNB-SN will need to ensure a higher level of operation before they can expect the biogas installations to impact the targeted outcomes.

In addition to our impact evaluation, we assessed the possible drivers of digester operation. The two factors that most strongly predicted digester operation were 1. having attended at least one biogas training and 2. reporting that fertilizer production motivated the household choose to install the digester. This suggests two ways that PNB-SN could potentially improve digester operation rates. First, the program could increase training efforts, ensuring that each recipient household attends at least one training on digester operation and maintenance. Because of data limitations, we are not able to dig deeper into the aspects of trainings that drive digester operation, but future assessments could test for the efficacy of different training content and intensity. The second recommendation to come out of this analysis is for further marketing and targeting of the digester installations, to households that have expressed an interest in fertilizer production and who have the capacity to use it, e.g. they cultivate sufficient acreage. Currently, we do not have any evidence of a market for the bioslurry fertilizer, so targeting could focus on households who plan to use the fertilizer themselves. To reiterate, our analysis of the drivers of operation is not causal, so, before implementing any of these changes, they should be rigorously evaluated to assess their effectiveness.

Finally, it is important to note that biogas installations are costly interventions. The recommendations in the preceding paragraph would likely add to program costs. Therefore, it’s important that any changes to the program are evaluated to ensure that they are producing benefits that are commiserate with the associated costs, especially those borne by recipient households. In the end it may be that, in Senegal’s case, technologies other than biogas digesters are the most effective and efficient solutions to the country’s energy poverty challenge.

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Appendix A: Additional Tables and Figures

Table A1: Determinants of digester operation, logistic regression results (columns 1-3)

	(1) Currently operating	(2) Operated at least half the time	(3) Ever operated	(4) Share of time working
Digester characteristics				
Digester type (=0 if fixed dome, =1 if flexible balloon)	10.2	2.96	3.40	0.097
	(17.1)	(3.57)	(6.05)	(0.12)
Training (=1 if household received a training)	29.5	60.2***	277***	0.31**
	(68.9)	(89.0)	(490)	(0.13)
Months since completion of installation	1.02	1.04	1.09	0.0040
	(0.065)	(0.055)	(0.065)	(0.0063)
Toilet (=1 if toilet connected to digester)	-	9.70**	-	0.20
		(11.1)		(0.15)
Prices				
Price of firewood, avg CFA/kg in village	1.00	1.00	1.00	-0.00027
	(0.011)	(0.0094)	(0.012)	(0.0011)
Price of charcoal, avg CFA/kg in village	1.01	1.01	0.99	-0.00024
	(0.014)	(0.011)	(0.0090)	(0.00092)
Household characteristics				
Log household size	0.49	0.33	0.68	-0.17*
	(0.68)	(0.36)	(0.54)	(0.093)
Share of household who is female	0.00012***	0.019	0.000028*	-0.38
	(0.00029)	(0.071)	(0.00017)	(0.30)
Education (=1 if household head has any school above koranic school)	1.58	0.96	0.49	-0.072
	(1.33)	(0.75)	(0.29)	(0.10)
Log number of employed adults in household	1.03	1.42	0.20*	0.028
	(0.55)	(0.77)	(0.17)	(0.068)
Cubic-root distance to market, km1/3	0.98	0.59	0.095***	-0.084*
	(0.34)	(0.24)	(0.073)	(0.045)
Asset index	1.51	1.26	2.36**	0.032
	(0.53)	(0.34)	(0.89)	(0.030)
Access to a loan (=1 if can access emergency funds via loan)	0.41	0.93	0.042***	-0.24***
	(0.72)	(0.74)	(0.048)	(0.082)
Liquidity (=1 if can access 250,000 CFA in emergency funds)	0.47	0.75	5.08*	0.040
	(0.37)	(0.55)	(4.62)	(0.087)

Table A1, continued: Determinants of digester operation, logistic regression results (columns 1-3)

	(1)	(2)	(3)	(4)
	Currently operating	Operated at least half the time	Ever operated	Share of time working
Perceptions				
=1 if energy savings is reason for installation	2.14	1.60	0.62	-0.010
	(2.78)	(1.23)	(0.62)	(0.10)
=1 if fertilizer production is reason for installation	7.21***	6.40***	4.06	0.18**
	(5.25)	(4.47)	(3.97)	(0.066)
=1 if health is reason for installation	1.60	1.02	1.90	-0.067
	(1.15)	(0.78)	(1.35)	(0.10)
Livestock				
Log number of cows household looks after	0.94	1.19	2.04*	0.0015
	(0.46)	(0.39)	(0.79)	(0.033)
Minimal pasturing (=1 if cows out to pasture <8 hrs/day)	0.51	0.19**	0.31	-0.14
	(0.45)	(0.13)	(0.31)	(0.092)
Manure as fertilizer (=1 if household applies manure directly to fields)	1.74	0.69	0.72	0.021
	(0.92)	(0.38)	(0.46)	(0.084)
Manure for cooking (=1 if household uses manure directly for cooking)	17.1	1.37	3.77	0.29
	(32.7)	(2.08)	(6.48)	(0.24)
Constant	0.23	0.13	167	0.83**
	(1.25)	(0.58)	(700)	(0.39)
Observations	90	93	90	93
Log-likelihood	-28.2	-36.9	-29.6	-
Prob > chi2	0	0	0	-
(Pseudo) R-squared	0.31	0.35	0.53	0.36

Notes: Odds rations from logistic regression estimates and pseudo r-squared are reported in columns 1-3; Dependent variables are equal to 1 if digester operated on the day of survey (column 1), at least half the time since installation (column 2), or if it ever operated (column 3); Dependent variable in column 4 is a continuous measure of the share of time since installation that the digester was working fully or partially, equal to 1 if it was never fully broken; Standard errors are clustered at the village level (24 clusters); Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table A2: Impacts of biogas installation on fuel use outcomes, outliers dropped

	Log firewood use, ln(kg/day)		Cubic-root charcoal use, kg/day1/3		Cubic-root LPG use, 6 kg cannisters/month 1/3	
	(1)	(2)	(3)	(4)	(5)	(6)
Biogas installation	-0.31**	-0.21	0.070	-0.029	0.042	0.0048
	(0.15)	(0.15)	(0.072)	(0.072)	(0.085)	(0.063)
Cubic-root distance to nearest weekly market, km1/3		-0.033		-0.0047		0.066
		(0.099)		(0.066)		(0.052)
Cubic-root distance to nearest bus stop, km1/3		0.079		-0.060		0.066*
		(0.099)		(0.043)		(0.038)
Log land owned or leased, ln(hectares)		0.27***		0.049		0.046
		(0.075)		(0.035)		(0.029)
Asset Index		-0.11***		0.044**		0.11***
		(0.040)		(0.022)		(0.016)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		0.041		-0.012		0.044
		(0.18)		(0.088)		(0.077)
Constant	1.58***	1.29*	0.25***	0.69*	0.28***	-0.12
	(0.098)	(0.69)	(0.052)	(0.39)	(0.056)	(0.30)
Demographic controls	N	Y	N	Y	N	Y
Observations	189	175	194	180	195	181
R-squared	0.021	0.171	0.005	0.117	0.002	0.312

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A3: Impacts of biogas installation on time use and expenditure outcomes, outliers dropped

	Cook time, min/day		Fuel collection time, min/wk		Total fuel expenditure, thousand CFA/month	
	(1)	(2)	(3)	(4)	(5)	(6)
Biogas installation	-25.1	-14.0	-0.50	-0.22	0.12	-0.48
	(19.3)	(21.6)	(0.58)	(0.53)	(0.81)	(0.69)
Cubic-root distance to nearest weekly market, km1/3		-15.9		0.29		0.72
		(11.0)		(0.38)		(0.49)
Cubic-root distance to nearest bus stop, km1/3		17.2		0.34		0.077
		(11.0)		(0.24)		(0.44)
Log land owned or leased, ln(hectares)		5.14		0.62***		0.22
		(7.40)		(0.21)		(0.28)
Asset Index		-9.85**		-0.49***		0.96***
		(4.14)		(0.11)		(0.17)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		17.7		0.55		-1.18
		(23.0)		(0.62)		(0.82)
Constant	328***	238***	5.62***	8.51***	4.54***	3.87
	(13.0)	(73.4)	(0.43)	(1.89)	(0.55)	(3.01)
Demographic controls	N	Y	N	Y	N	Y
Observations	182	168	194	180	195	181
R-squared	0.014	0.142	0.006	0.257	0.000	0.238

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A4: Impacts of biogas installation on eye problems

	Children under 12				Individuals responsible for cooking			
	(1)	(2)	(3)	(4) Odds Ratio	(5)	(6)	(7)	(8) Odds Ratio
Biogas installation	0.55	0.081	-0.43	0.65	-0.081	-0.62	-0.71	0.49
	(0.58)	(0.53)	(0.53)	(0.34)	(0.37)	(0.44)	(1.08)	(0.53)
Age, years	0.00059	0.032	0.032	1.03	0.056***	0.071***	0.070***	1.07***
	(0.045)	(0.054)	(0.055)	(0.057)	(0.012)	(0.016)	(0.023)	(0.025)
Female (=1 if female)	-0.55	-0.61	-1.46*	0.23*				
	(0.40)	(0.44)	(0.88)	(0.20)				
Treatment, female interaction			1.39	4.01				
			(0.94)	(3.76)				
Treatment, age interaction							0.0026	1.00
							(0.026)	(0.026)
Cubic-root distance to nearest weekly market, km1/3		-0.12	-0.097	0.91		0.010	0.0085	1.01
		(0.37)	(0.36)	(0.33)		(0.32)	(0.33)	(0.33)
Cubic-root distance to nearest bus stop, km1/3		-0.76*	-0.78*	0.46*		-0.16	-0.16	0.85
		(0.43)	(0.43)	(0.20)		(0.21)	(0.20)	(0.17)
Log land owned or leased, ln(hectares)		-0.41	-0.44	0.64		-0.23	-0.23	0.80
		(0.27)	(0.28)	(0.18)		(0.21)	(0.21)	(0.16)
Asset Index		0.25	0.27	1.31		0.058	0.058	1.06
		(0.18)	(0.18)	(0.23)		(0.12)	(0.12)	(0.13)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		0.67	0.66	1.94		-0.70	-0.70	0.50
		(0.84)	(0.83)	(1.61)		(0.56)	(0.57)	(0.28)
Constant	-3.90***	-1.83	-1.49	0.22	-4.54***	-1.86	-1.82	0.16
	(0.48)	(2.27)	(2.23)	(0.50)	(0.54)	(2.35)	(2.42)	(0.39)
Demographic controls	N	Y	Y	Y	N	Y	Y	Y
Observations	1,046	762	762	762	471	405	405	405
Pseudo R-squared	0.015	0.12	0.13	0.13	0.049	0.11	0.11	0.11

Notes: Columns 1-3 and 4-7 report logistic regression coefficients; Column 4 (8) reports the odds ratio of the logistic regression shown in column 3 (7); Robust standard errors are in parentheses; standard errors clustered at the household level with 181 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A5: Impacts of biogas installation on respiratory health in children under 12 years of age

	Cough				ALRI symptoms			
	(1)	(2)	(3)	(4) Odds Ratio	(5)	(6)	(7)	(8) Odds Ratio
Biogas installation	1.55	-0.050	-0.38	0.68	1.62	-0.18	-0.86	0.42
	(0.55)	(0.44)	(0.48)	(0.32)	(0.85)	(0.59)	(0.59)	(0.25)
Age, years	0.93**	-0.092***	-0.094***	0.91***	0.98	-0.027	-0.028	0.97
	(0.029)	(0.031)	(0.031)	(0.028)	(0.044)	(0.050)	(0.050)	(0.049)
Female (=1 if female)	1.20	0.24	-0.078	0.92	1.13	0.20	-0.51	0.60
	(0.24)	(0.23)	(0.35)	(0.32)	(0.37)	(0.37)	(0.62)	(0.37)
Treatment, female interaction			0.62	1.87			1.29*	3.62*
			(0.43)	(0.80)			(0.68)	(2.45)
Cubic-root distance to nearest weekly market, $km^{1/3}$		-0.39	-0.39	0.68		-0.039	-0.029	0.97
		(0.39)	(0.38)	(0.26)		(0.35)	(0.34)	(0.33)
Cubic-root distance to nearest bus stop, $km^{1/3}$		-0.44**	-0.44**	0.65**		-0.94***	-0.96***	0.38***
		(0.21)	(0.21)	(0.13)		(0.35)	(0.35)	(0.13)
Log land owned or leased, ln(hectares)		-0.26	-0.27	0.76		-0.30	-0.33	0.72
		(0.19)	(0.19)	(0.15)		(0.27)	(0.27)	(0.19)
Asset Index		0.086	0.090	1.09		0.25	0.27*	1.31*
		(0.093)	(0.092)	(0.10)		(0.16)	(0.15)	(0.20)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		-0.011	0.00063	1.00		-0.19	-0.20	0.82
		(0.50)	(0.50)	(0.50)		(0.79)	(0.76)	(0.62)
Constant	0.13***	0.94	1.11	3.02	0.035***	2.35	2.74	15.5
	(0.038)	(1.82)	(1.77)	(5.35)	(0.016)	(2.37)	(2.29)	(35.4)
Demographic controls	N	Y	Y	Y	N	Y	Y	Y
Observations	1,049	971	971	971	1,047	969	969	969
Pseudo R-squared	0.015	0.094	0.097	0.097	0.0075	0.14	0.15	0.15

Notes: Columns 1-3 and 4-7 report logistic regression coefficients; Columns 4 (8) report the odds ratio of the logitic regression shown in column 3 (7); Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A6: Impacts of biogas installation on respiratory health in cooks

	Cough				ALRI symptoms			
	(1)	(2)	(3)	(4) Odds Ratio	(5)	(6)	(7)	(8) Odds Ratio
Biogas installation	1.12	-0.17	-1.32	0.27	2.15	0.12	-1.82	0.16
	(0.40)	(0.44)	(1.06)	(0.28)	(1.17)	(0.59)	(1.51)	(0.24)
Age, years	1.02*	0.019	-0.00087	1.00	1.03*	0.023	-0.019	0.98
	(0.013)	(0.013)	(0.024)	(0.024)	(0.017)	(0.016)	(0.035)	(0.034)
Treatment, age interaction			0.036	1.04			0.061	1.06
			(0.029)	(0.030)			(0.040)	(0.043)
Cubic-root distance to nearest weekly market, $km^{1/3}$		-0.55**	-0.57*	0.57*		-0.59*	-0.62*	0.54*
		(0.28)	(0.29)	(0.16)		(0.34)	(0.36)	(0.19)
Cubic-root distance to nearest bus stop, $km^{1/3}$		-0.21	-0.17	0.84		-0.69	-0.60	0.55
		(0.20)	(0.21)	(0.18)		(0.47)	(0.49)	(0.27)
Log land owned or leased, ln(hectares)		-0.023	-0.039	0.96		-0.86***	-0.92***	0.40***
		(0.16)	(0.16)	(0.16)		(0.25)	(0.24)	(0.097)
Asset Index		-0.12	-0.11	0.90		0.097	0.11	1.12
		(0.098)	(0.099)	(0.088)		(0.16)	(0.16)	(0.18)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		-0.049	0.019	1.02		-0.70	-0.62	0.54
		(0.50)	(0.51)	(0.52)		(0.72)	(0.72)	(0.39)
Constant	0.059***	-0.048	0.50	1.64	0.014***	1.89	3.12	22.7
	(0.033)	(2.00)	(2.06)	(3.38)	(0.011)	(2.81)	(2.98)	(67.6)
Demographic controls	N	Y	Y	Y	N	Y	Y	Y
Observations	473	427	427	427	473	427	427	427
Pseudo R-squared	0.0093	0.061	0.066	0.066	0.029	0.15	0.16	0.16

Notes: Columns 1-3 and 4-7 report logistic regression coefficients; Column 4 (8) reports the odds ratio of the logistic regression shown in column 3 (7); Robust standard errors in parentheses; standard errors clustered at the household level with 181 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A7: Impacts of biogas installation on agricultural outcomes

	Number of crops grown		Revenue from selling crops in the last 12 months, ln(CFA)		Use of improved fertilizer	
	(1)	(2)	(3)	(4)	(5)	(6)
Biogas installation	-0.40*	-0.35	-0.32	-1.51	0.85**	0.64
	(0.23)	(0.24)	(1.39)	(1.20)	(0.40)	(0.43)
Cubic-root distance to nearest weekly market, $km^{1/3}$		-0.052		0.24		0.30
		(0.16)		(0.74)		(0.27)
Cubic-root distance to nearest bus stop, $km^{1/3}$		0.068		-1.26		-0.057
		(0.13)		(0.80)		(0.21)
Log land owned or leased, ln(hectares)		0.28***		0.83*		-0.032
		(0.088)		(0.45)		(0.15)
Asset Index		-0.054		-0.24		0.16
		(0.052)		(0.30)		(0.12)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		0.049		0.00065		-0.30
		(0.23)		(1.32)		(0.50)
Constant	2.89***	1.70*	8.02***	11.8**	0.26	0.10
	(0.17)	(0.96)	(1.09)	(4.83)	(0.29)	(2.17)
Demographic controls	N	Y	N	Y	N	Y
Observations	196	182	196	182	196	182
(Pseudo) R-squared	0.022	0.153	0.001	0.156	0.031	0.076

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; Columns 5 and 6 report logistic regression coefficients and pseudo r-squared; *** p<0.01, ** p<0.05, * p<0.1

Table A8: Impacts of biogas installation on agricultural outcomes (continued)

	Crops harvest in last 12 months, $kg^{1/3}$					
	Corn		Peanuts		Millet	
	(7)	(8)	(9)	(10)	(11)	(12)
Biogas installation	0.75	0.73	0.22	0.59	-0.64	0.63
	(1.41)	(1.42)	(1.18)	(1.37)	(1.22)	(1.29)
Cubic-root distance to nearest weekly market, $km^{1/3}$		1.97**		1.04		0.87
		(0.93)		(0.87)		(0.75)
Cubic-root distance to nearest bus stop, $km^{1/3}$		0.053		-1.99**		-0.95
		(0.75)		(0.75)		(0.67)
Log land owned or leased, ln(hectares)		-0.48		0.60*		-0.20
		(0.48)		(0.34)		(0.40)
Asset Index		0.43		0.070		-0.26
		(0.34)		(0.29)		(0.28)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		1.95*		-0.25		0.067
		(1.00)		(1.10)		(1.05)
Constant	7.68***	5.39	10.6***	6.00	9.90***	1.72
	(0.40)	(6.49)	(0.95)	(4.25)	(0.85)	(4.45)
Demographic controls	N	Y	N	Y	N	Y
Observations	64	58	122	114	119	114
(Pseudo) R-squared	0.008	0.203	0.001	0.204	0.004	0.155

Notes: Robust standard errors in parentheses; standard errors clustered at the village level with 49 clusters; *** p<0.01, ** p<0.05, * p<0.1

Table A9: Impacts of biogas installation on adult employment

	(1)	(2)	(3)	(4) Odds Ratio
Biogas installation	0.16	-0.23	-0.088	0.92
	(0.23)	(0.23)	(0.26)	(0.24)
Age, years	-0.00011	-0.00079	-0.0010	1.00
	(0.0030)	(0.0033)	(0.0033)	(0.0033)
Female (=1 if female)	-1.59***	-1.59***	-1.41***	0.24***
	(0.17)	(0.18)	(0.25)	(0.062)
Treatment, female interaction			-0.37	0.69
			(0.35)	(0.24)
Cubic-root distance to nearest weekly market, km1/3		0.062	0.065	1.07
		(0.13)	(0.13)	(0.13)
Cubic-root distance to nearest bus stop, km1/3		-0.26*	-0.25*	0.78*
		(0.14)	(0.14)	(0.11)
Log land owned or leased, ln(hectares)		-0.11	-0.11	0.89
		(0.12)	(0.12)	(0.11)
Asset Index		0.11*	0.11*	1.12*
		(0.061)	(0.061)	(0.068)
Liquidity (=1 if can access 250,000 CFA in emergency funds)		0.16	0.16	1.17
		(0.34)	(0.34)	(0.40)
Constant	-0.29	-0.73	-0.82	0.44
	(0.21)	(1.28)	(1.25)	(0.55)
Demographic controls	N	Y	Y	Y
Observations	1,435	1,301	1,301	1,301
Pseudo R-squared	0.098	0.12	0.12	0.12

Notes: Columns 1-3 report logistic regression coefficients; Column 4 reports the odds ratio of the logistic regression shown in column 3; Robust standard errors are in parentheses; standard errors are clustered at the household level with 184 clusters; *** p<0.01, ** p<0.05, * p<0.1

Appendix B: Minimum detectable effect sizes

We conducted power calculations to include in our pre-analysis plan (available upon request). Unfortunately, due to program delays, we were not able to implement our initial difference-in-difference study design. Thus, we took our already fixed budget and maximized the number of households we could survey using our new cross-sectional design. The budget resulted in a sample of 200 households, split evenly between treatment (with biogas installations) and control (without biogas installations). Given this sample size and setting power at 0.80 and alpha at 0.05, we have done similar calculations to those presented in the pre-analysis plan. We have calculated the minimum detectable effect size, accounting for intra-village correlation in outcomes (see Appendix Table B1). We did this using Stata's *power twomeans* and *power twoproportions* commands for continuous and binary outcomes, respectively.

Based on the mean and standard deviation of outcomes observed in our control group, we can see that the study is only powered to detect large differences between treatment and control, most notably on firewood use. Clearly, the study does have power limitations, but we do not believe this constitutes an economically significant limitation of the study. Firstly, these biogas installations are extremely expensive, and so the benefits from biogas would have to be very large to justify the investment, even if they are also largely motivated on redistributive or poverty alleviation grounds (there are many other more cost-effective ways of reducing poverty, for instance). Second, the goal of biogas is to enable households to transition fully away from polluting fuels (and their cost effectiveness relies on at least this and also some agricultural savings or income from selling spent manure), and that is something we can assess, even if the effect sizes must be large. Third, the failure of the vast majority of these systems would obviously seem to compromise the theory of change, regardless of statistical power.

It is true that our small sample size and the low functionality of these installations limits our ability to make claims about the impacts of functioning biogas. Still, we believe our study is still well-positioned to allow conclusions about the effectiveness of Senegal's biogas program and installations that were carried out through PNB-SN.

Table B1: Minimum detectable effect sizes

	Control		Minimum detectable effect	
Outcome	**Mean**	**SD**	**Delta**	**%**
Log firewood use, ln(kg/day)	1.66	1.17	0.47	28%
Cubic-root charcoal use, $(kg/day)^{1/3}$	0.30	0.68	0.28	91%
Cubic-root LPG use, $(6\ kg\ cannisters/month)^{1/3}$	0.28	0.45	0.23	82%
Cooking time, minutes/day	328.01	111.13	56.46	17%
Cubic-root fuel collection time, $(minutes/week)^{1/3}$	5.76	3.46	1.77	31%
Log fuel expenditure, ln(CFA/month)	4.54	4.47	2.27	50%
Incidence of cough among children*	0.09		0.06	67%

Incidence of ALRI symptoms among children*	0.03		n/a	n/a
Incidence of cough among cooks*	0.11		0.08	71%
Incidence of ALRI symptoms among cooks*	0.03		n/a	n/a
Employment status	0.14		0.12	86%
Number of crops grown	2.89	1.46	0.70	24%
Cubic-root corn harvested, $kilos^{1/3}$	7.68	3.27	3.00	39%
Cubic-root peanuts harvested, $kilos^{1/3}$	10.62	5.18	3.68	35%
Cubic-root millet harvested, $kilos^{1/3}$	9.90	5.56	3.64	37%
Improved fertilizer use	0.57		0.25	44%
Log annual crop revenue, ln(CFA)	8.02	6.32	3.92	49%

Notes: *one-sided tests comparing proportion between treatment and control group, testing if treatment group is lower (i.e. healthier); For binary outcomes (those for which SD is not reported), the control group mean is the proportion of the control group for which the variable =1

Appendix C: Construction of the asset index

The asset index was computed using principal component analysis (PCA). Assets were chosen based on those used by the Demographic and Health Surveys to conduct their wealth index for rural Senegal. Table F1 shows the variables that were included, summary statistics and the component score for each. Variables are set equal to 1 if a household reports owning the listed asset. In the case of drinking water and construction materials, each household is coded based on their main water source or construction material. Parallel analysis was used to determine the number of factors to include. As shown by the results in Figure F1, 8 components were included.

Table C1: Indicators included in wealth index principal component analysis

Asset	Mean	Std. Dev.	Analysis N	Missing N	Component 1 Score
Bank account	0.38	0.487	196	0	0.138
Car	0.09	0.282	196	0	0.169
Motorcycle	0.21	0.408	196	0	0.069
Bicycle	0.14	0.346	196	0	-0.059
Refrigerator	0.19	0.396	196	0	0.274
Television	0.41	0.494	196	0	0.320
DVD/CD/VCR Player	0.02	0.142	196	0	0.007
Radio	0.72	0.450	196	0	0.080
Sewing Machine	0.06	0.231	196	0	-0.039
Cassette player	0.01	0.071	196	0	0.052
Iron	0.05	0.210	196	0	0.076
Fan	0.24	0.428	196	0	0.310
Mobile Phone	0.98	0.142	196	0	0.010
Tractor	0.03	0.158	196	0	-0.073
Computer	0.12	0.329	196	0	0.187
Mosquito net	0.95	0.210	196	0	0.053
Private toilet	0.70	0.458	196	0	0.149
Drinking water from:					
Well	0.27	0.445	196	0	-0.249
Drilling	0.09	0.290	196	0	-0.008
Public	0.09	0.290	196	0	-0.079
Private tap	0.49	0.501	196	0	0.267
Shared tap	0.05	0.210	196	0	-0.015
Other tap	0.01	0.101	196	0	0.055
Wall material:					
Mud brick	0.16	0.366	196	0	-0.257
Metal	0.01	0.071	196	0	-0.011
Straw	0.05	0.221	196	0	-0.030

Wood	0.03	0.158	196	0	-0.046
Stone	0.06	0.240	196	0	-0.104
Cement brick	0.69	0.462	196	0	0.292
No wall	0.01	0.071	196	0	-0.019
Floor material:					
Mud	0.11	0.316	196	0	-0.211
Tiles	0.12	0.323	196	0	0.227
Stone	0.19	0.396	196	0	-0.143
Cement	0.48	0.501	196	0	0.077
Sand	0.09	0.290	196	0	0.039
Roof material:					
Metal	0.40	0.492	196	0	0.084
Straw	0.23	0.422	196	0	-0.324
Slate	0.13	0.334	196	0	0.091
Cement	0.12	0.329	196	0	0.190
Zinc	0.12	0.323	196	0	0.007

Notes: Variables are set equal to 1 if a household reports owning the listed asset. In the case of drinking water and construction materials, each household is coded based on their main water source or construction material.

Figure C1: Parallel analysis results

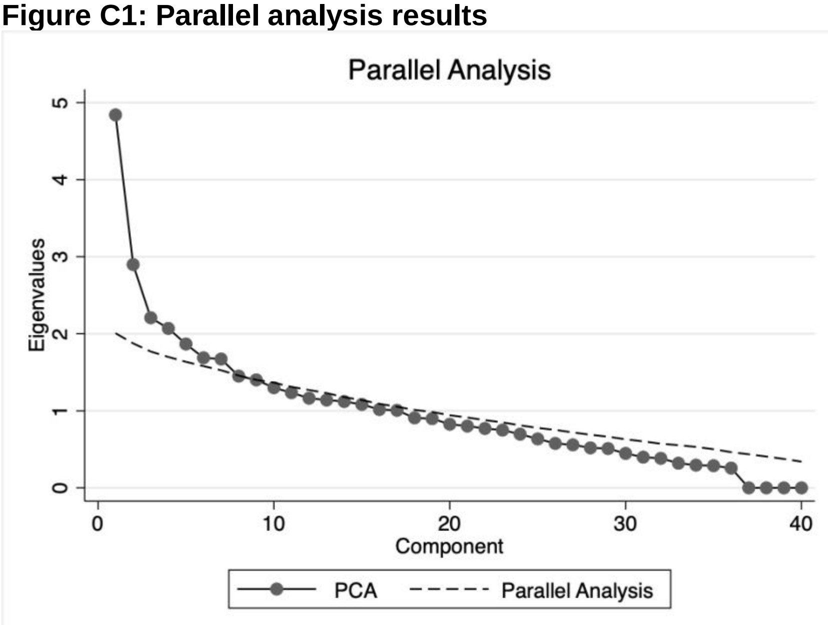
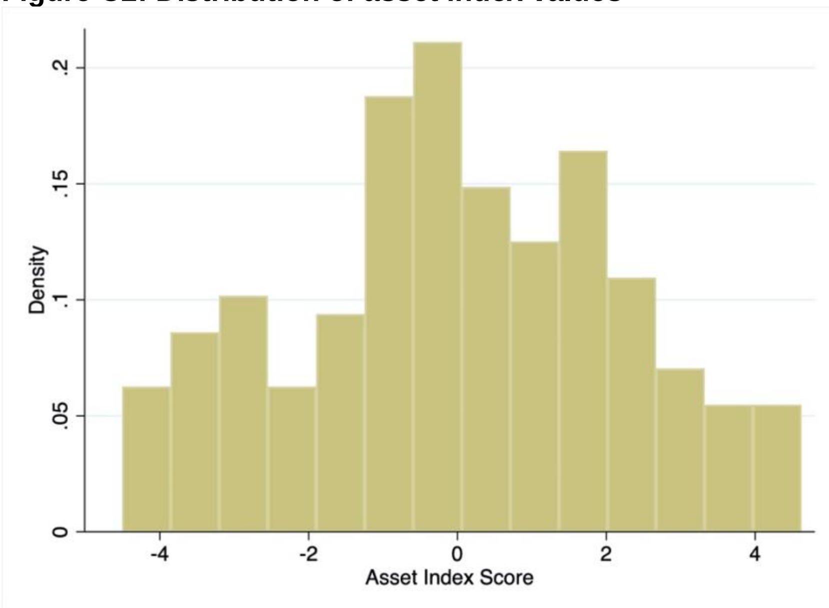


Figure C2: Distribution of asset index values



Appendix D: Construction of outcomes of interest

The outcomes of interest for our impact analyses fall into three categories. The first is household fuel use. We first consider measures of fuel use, including firewood, charcoal, and LPG. For firewood and charcoal, we asked households how much of the fuel they used in a typical day, week or month. Households most commonly reported daily use, so the outcome variables we construct are kilograms of firewood and charcoal used on by the household on a typical day. For LPG, we ask how many 6-kilogram cylinders a household uses in a typical month. These variables are bounded at zero and their distributions positive-skewed. Therefore, in our analysis we take either the natural log, for firewood use, or cubic root, for charcoal and LPG use, of the measures to reduce skewness.

We also consider other household fuel and cooking outcomes. We are first interested in total cooking fuel expenditure, which includes all household expenditure for cooking fuels in a typical month, including any travel costs. Many households do not purchase all of their cooking fuels, but, especially in the case of firewood, collect the fuels. Therefore, we also consider the total time spent each week by all household members to collect cooking fuel. Fuel expenditure and collection time are again bounded at zero and positive-skewed, so we use cubic root and logarithmic transformation, respectively, to reduce skewness. Finally, we consider how much time the main cook spends cooking on a typical day. This data was collected via a 24-hour time diary.

The second outcome category we consider is health. All of our health outcomes are based on self-reported information about household members health in the near past. We are primarily interested in respiratory health, specifically for children, as they are more susceptible to indoor air pollution (Prüss-Ustün et al. 2016, Smith et al. 1999). We consider a child to have had a mild respiratory problem if they reported having a cough. We consider a child to have an acute lower respiratory infection (ALRI) if they report a cough accompanied with short, rapid breaths. This is consistent with the Demographic and Health Survey's methods for estimation ALRI prevalence (Stallings 2004). We also collect data on whether or not a child had any eye problems in the two weeks before the survey, as indoor air pollution can affect eyes as well. In addition to collecting these outcomes for children, we collect them for anyone over 12 years of age in the household who is responsible for cooking, as they are likely heavily exposed to indoor air pollution while cooking.

As our last category, we consider a range of employment and agricultural outcomes. We look at whether adults in the household are currently, at the time of the survey, employed in any personal businesses or wage-earning activities. Because bioslurry, a fertilizer, is a product of biogas digesters, we also look at agricultural practices. We first look at how many crops the household reports growing. This variable was bounded from above at 5 (we only allowed reporting of five main crops), but, despite this upper bound, the distribution of number of crops is normally distributed across households. We then consider fertilizer inputs, defining a binary variable equal to one if a household uses any fertilizers over and above the direct application of manure to their fields, for example any bioslurry or chemical fertilizers. We also consider outputs. We measure the total kilos of crops they harvested in the past 12 months, considering the main three crops grown in our sample, peanuts, millet, and corn. Finally, we look at the total revenue they collected from selling any crops in the past 12 months. These output variables, revenue and harvests, are again positive-skewed, so the same transformations are applied to reduce skewness.