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# Solar Ovens and their Impacts on Health, Fuel Use and Monetary and Time Costs on Fuel- Results from a Randomized Controlled Trial

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# Abstract:

More than 2.5 billion of the world's poor rely on wood and other biomass fuel for household energy, including cooking. Burning biomass fuel is directly linked with indoor air pollution (IAP), or the inhalation of harmful toxins produced by biomass fuel combustion. IAP causes over 1 million deaths a year, primarily of children; and in Senegal Lower Respiratory Infection (an illness closely linked to IAP) is the leading cause of death responsible for 16% of total mortality.[2] Women in our sample are at high relative risk of health problems from breathing in harmful smoke from cookfires as they are exposed to more than 140% of the daily exposure to CO deemed safe by the WHO.[3] In addition to increased exposure to carbon monoxide by women and children who are close to the fire when cooking, women and girls face large time costs in collecting fuel. Due to large family sizes (12 persons on average) and low fuel efficiency of traditional stoves, cooking for one's family is equivalent to a full-time job. Our sample reports an average 6-7 hours per day spent cooking and an average 1 hour per day to collect fuel. The responsibilities associated with cooking and collecting biomass fuel disproportionately falls on women and girls, and limits other economic activities for women outside the home. Burning wood and other biomass fuel also harms the local environment through deforestation and desertification. The wider sub-Saharan region is classified as one of two of the world's most vulnerable zones for climate change. Given Senegal is part of the sub-Saharan existing dryland, the increasing desertification due in part to deforestation has local and global implications for climate change.[4]

We study the impact of the introduction of solar ovens on the costs and usage of fuel, time spent collecting fuel, carbon monoxide exposure and respiratory illness symptoms using a randomized evaluation. We compare outcomes for households randomly allocated to receive the solar ovens early (treatment) and those set to receive the solar oven six months later (control). The majority of our households report using the solar oven to prepare part or all of the dinner meal (40%) and of the treatment households observed cooking with their solar oven at the time of the six month follow-up survey (n=242) 61% report they are cooking dinner. In the sixth month of owning the stove, women in the treatment group used their oven about 19% of the time, a 100% increase from the one month mark, indicating anecdotally that intensive training on how to use the solar oven provided by the local NGO partner is correlated with increased women's usage of the solar oven over time.

At the six month follow-up, the top complaints households had about their solar oven are-1). Cooking takes too long (50%); 2. The solar oven is too small to fit the needs of their large family (25%); 3). The reflector of the solar oven is not durable (21%). The solar oven can feed six persons, however household size averages 12 persons. Critically, 80% of households report cooking for more than 6 persons. Thus, the hypothesis that the solar oven proves to be too small to meet the cooking needs of our households seems to be well-supported. When we account for the adult age equivalent of number of people women cook for we find that the mean (median) size of households is 5.8 (5.2)- below the 6 person cutoff. From the adult age equivalent measure of consumption behavior we learn that 42% of our sample has an adult age equivalent greater than 6. Thus, it is clear there is a size mismatch between size of households and size of the solar oven.

For medium households containing 7-12 persons, the introduction of a solar oven reduces daily fuel consumption between 11-13% for the entire treatment group and 16-20% for treatment households with more than one solar oven in the compound. For treatment households with more than one solar oven in a compound and a household size of 7-12 persons there is a 25% decline in time spent next to the cook fire. However, for treatment households of all sizes with only one solar oven per compound, there is no statistically significant effect on time spent next to the cook fire. In addition,


[2] Total mortality represents all ages mortality, see WHO (2006).
[3] WHO cites 25 ppm as the average limit for any 8 hour exposure, see WHO (2010).
[4] See United Nations Convention to Combat Desertification (2010)

the average time the household spends collecting fuel declines only marginally (1%). There is no evidence of a treatment effect in exposure to carbon monoxide or in symptoms associated with Acute Respiratory Illness. We conclude that because the solar oven was too small to replace completely traditional stoves, even for the preparation of one daily meal, for a significant portion of our households, women continue to use traditional stoves alongside solar ovens. Thus partially due to the size mismatch the impacts of the solar oven on our outcome indicators is diminished.

Our study concludes that the population is well identified as a population which can benefit from an improved stove. However the solar oven is underutilized. This can be partially explained by because it's size is too small for at least a quarter of the population. Additional, hypotheses for the technology non-adoption puzzle are explored in the third paper of this dissertation "Peer Effects and Usage of the Solar Oven- Evidence from Rural Senegal." The authors consider this randomized controlled trial a success because as a result of this impact evaluation, the proposed nationwide rollout of the Hotpot to all regions of Senegal will not take place. Evidence suggests that the behavior change associated with solar cooking is not insurmountable, demonstrated by small but growing usage of the solar oven over time. Yet, a viable sustainable solar oven is missing from the local market and in its absence other improved stoves should continue to be explored.

# 1. Introduction

Over 3 billion people worldwide burn wood and other biomass fuel for cooking, boiling water, lighting, and heating (Rehfuess et al., 2006)[5]. Burning biomass fuel for household energy and industry has lead to an enhanced greenhouse effect caused by an increase in the quantity of carbon dioxide in the Earth's atmosphere.[6] According to NASA's Goddard Institute for Space Studies, at a global level, average temperatures have climbed 1.4 degrees Fahrenheit (0.8 degree Celsius) around the world since 1880, much of this in recent decades. Burning biomass fuels for cooking contributes to deforestation which then contributes to the enhanced greenhouse effect or global warming. Sub-Saharan Africa has the highest rate of biomass fuel use of any world region, with over 80% of the population (over 590,000,000 people) that report use of biomass fuels as the primary energy source of the household.[7] Careful estimates suggest that under current trends, household energy use in Africa will produce 6.7 billion tons of carbon by 2050.[8]

Costs of fuel can be a large percentage of household expenditure in developing countries. Since 2004, crude oil prices have repeatedly surged to all-time highs. Accordingly, prices for transport, cooking and heating have increased in many countries. In Senegal, gas prices soared (doubled in Dakar) as a result of a shortage in late January 2009 due to Government delays on subsidy payments to importers. During this shortage, charcoal vendors took advantage of the gas shortage to raise their prices, sometimes to almost double the usual amount and charcoal become difficult to find.[9] Cooking with gas is largely an urban phenomenon in Senegal and the practice enhanced as a result of the government's butanisation campaign that began in the 1970s to combat deforestation through encouraging Senegalese to use natural gas instead of charcoal or wood. In the rural areas, 60% of households in our sample report using gas once a day to reheat food. Thus, even for our rural households, who use wood as the primary fuel to cook with, they are also affected by rising gas and charcoal prices and are increasingly desperate for alternatives.

The burden of time required to collect biomass fuel is great and often falls on women. Women are forced to tradeoff activities with potentially higher returns- including education and economic opportunities- in order to collect fuel for cooking. Thus, by reducing the time spent collecting wood and cooking, improved stoves can potentially give women and girls the opportunity to pursue other activities including education and employment outside the home. The effects on additional time for education and employment could in turn positively affect intra-household bargaining and effectively increase women's decision power in the household. An increase in intra-household bargaining power for women could lead to more gender equality in society. And, as some research suggests, when women make decisions a higher percentage of the household income is spent on the children[10].

In addition, to efficiency in the use of women's time, improved stoves can improve women's health. Biomass fuels have very low combustion efficiency and they emit large quantities of

[5]See also Mehta, S.et al. (2006)
[6] The greenhouse effect is a naturally occurring process. The enhanced greenhouse effect is the added effect to the environment's natural greenhouse effect caused by the gases present in the atmosphere due to human activities such as the burning of fossil fuels and deforestation. See Sir John Houghton, (2004)
[7] See WHO 2007)
[8]See Bailis, R. et al (2005)
[9]See Look, A. (2009)
[10]See Handa, S.et al. (2006)

health-damaging air pollutants, including Carbon Monoxide gas (CO). As women often cook indoors in open fires or with poorly functioning stoves, the result is a high level of exposure to toxins associated with burning biomass fuel referred to in the literature as Indoor Air Pollution (henceforth referred to as IAP). IAP from burning biomass fuel causes 1.6 million premature deaths every year and afflicts nearly half of the world's population, predominantly the rural poor. Negative health effects associated with IAP include respiratory illness and pneumonia, lung cancer, bronchitis and emphysema, weakened immune system, and reduced lung function. The WHO reports that IAP is responsible for 3.6% of the global burden of disease.[11] Further, a review of the literature from many epidemiological studies concerning IAP finds significant health effects associated with high levels of exposure to CO including child acute respiratory infections (ARI) and adult chronic obstructive pulmonary disease (COPD), with growing evidence of low birth weight, cataracts, lung cancer, otitis media, and tuberculosis.[12] A recent WHO publication concerning a meta-review of global studies on IAP find that when aggregating results of the top scientists' global studies, the risk of pneumonia in young children increases by a factor of 1.8 due to exposure of CO from unprocessed solid fuels.[13] Alarmingly, the trend in global biomass fuel use over the past 25 years has remained stable and even increased in parts of the developing world. Unless households in developing countries switch to improved stoves, or stoves which are more fuel efficient and emit less carbon monoxide gas, practitioners predict IAP will remain a substantial health problem worldwide for the global poor, particularly women and children, for years to come.[14]

Improved stoves in the developing world have the potential to reduce all of these problems. Low-emission fuel efficient stoves have had mixed success in different development settings. Since the 1940s, efforts have been made to increase the efficiency of biomass cook stoves by a range of development actors including governments, international development organizations, and NGOs.[15] Despite these efforts, improved biomass cook stoves have not yet been successfully scaled up to reach the world's rural poor. The limits to adoption highlight the importance of designing both a stove which is culturally and locally appropriate to the development settings and a distribution mechanism which facilitates the change from the traditional stove. Few programs dedicated to the distribution of improved stoves have included rigorous evaluation of the impacts. Authors of the few existing rigorous evaluations of the impacts of improved stoves cite the wide agreement in the scientific community that additional rigorous evaluations are needed to accurately evaluate the impacts of improved stoves, particularly on health.[16]

The solar oven used in this experiment, the Hotpot, was selected for the following three reasons. First engineers at UC Berkeley verified that the Hotpot was a well designed stove and its' aluminum reflector and glass bowl would not break easily.[17] Second, one of our NGO partners, Solar Household Energy (SHE), did a small pilot study in Méckhé, Senegal and found the stove fit well with the communities' needs and was widely adopted by the

[11] See WHO (2010)
[12] See Clark, M.et al. (2007)
[13] See Dherani, M et al. (2008)
[14] See Diaz, E. et al. (2007)
[15] See Household Energy Network (2010)
[16] See Smith, K, et al. (2000)
[17] The original stove reflector made in aluminum was replaced with a cardboard reflector due to prohibitive costs of importation. This decision was made solely by the NGO partner SHE and CEGA learned of the decision on arrival in the field after the product had been shipped.

population. Third, the Government of Senegal, particularly President Abdoulaye Wade, has made the usage of renewable energy, and particularly solar energy, a national priority in response to the glut of demand Senegal faces for biomass fuel to serve household energy needs.[18] One indication of how important renewable energy is for President Wade's administration is his recent creation of the Ministry of Biofuels and Renewable Energies. The establishment of such a dedicated ministry is unique in Africa and given the large commitment of the government to renewable energy, particularly solar, the Hotpot was a seemingly good fit with local needs and national priorities.

Using a randomized evaluation approach, in which the solar ovens are phased in for each village over time, we estimate the solar oven's impacts on costs and usage of fuel, time spent collecting fuel, and health. We contribute to the development economics literature through the micro-economic analysis of the effects of improved stoves on costs and time associated with cooking. Our contributions to the health economics literature include our review of linkages between cooking, particularly improved stoves, and health. And this work contributes to the energy economics of household fuel use literature through our research on household energy use and cooking practices in West Africa.

From our study, we find the majority of our households used the solar oven to prepare part or all of the dinner meal (40%). The solar oven can feed six persons, however at the baseline our households report an average of 13 persons for whom they cook and 11 persons at the six month follow-up. Thus we have an average of 12 persons per household over both survey waves and the solar oven proves to be too small to meet the cooking needs of our households. In the sixth month of owning the solar oven, women in the treatment group used the stove about 19% of the time, a 100% increase from the one month mark, indicating the continued intensive training model on how to use the solar oven may have had positive effects on usage.

For medium households containing 7-12 persons, the solar oven reduces daily wood consumption between 11-13% for the entire treatment group and 16-20% for treatment households with more than one solar oven in the compound. For treatment households with more than one solar oven in a compound of size 7-12 persons there is a 25% decline in time spent next to the cook fire. However for treatment households of all sizes with only one solar oven per compound, there is no statistically significant effect of time spent next to the cook fire. In addition, the average time the treatment household spends collecting fuel declines very marginally (1%) in the first difference and disappears in the subsequent regression analysis. Finally, there is no evidence of a treatment effect in exposure to carbon monoxide or in symptoms associated with Acute Respiratory Illness and other symptoms associated with cooking.

While we find no treatment effect on CO exposure, our results for CO show women cooks' consume more than 140% of the recommended daily exposure to CO deemed safe by the WHO. A medical study measuring CO ppm of smokers versus non-smokers quantify that non-smokers had a mean CO ppm level of 1.9 while smokers had a mean level of 11.6 CO ppm.[19] Of the smokers, the mean number of cigarettes smoked in the past 24 hours was 11.5. Thus, for a simple proxy to understand the relationship between the amount of CO

[18] See Associated Press, (Sept. 19, 2006)
[19] See Meddleton et al (2000)

ppm/hour women were observed to inhale and the illustrative equivalent of number of cigarettes smoke, we can estimate the following. If we make the assumption that the level of CO ppm inhaled is linear to the number of cigarettes smoked, which is a simplified assumption for illustrative purposes, we find that every cigarette smoked has the equivalent effect of 1 CO ppm additional inhaled.[20] Given on average women in our sample breath in 7.51 CO ppm/hour, this is the equivalent of smoking about 8 cigarettes per day. While the example is illustrative, it is revealing and serves to indicate the large health risks associated with cooking. Women, in our sample, suffer respiratory illness symptoms disproportionately to their husband, who on average are 11-23% less likely to report any of the seven symptoms associated with respiratory illness than their wives. Given women have the social responsibility to cook, the 11-23% more respiratory symptoms reported by women serve as an indicator that women, and often their young children who accompany them, face larger risks for respiratory illness than their husbands who share the same household. One likely place women are uniquely exposed to respiratory illness is over the cook fire, through concentrated exposure to CO.

We conclude that because the solar oven was too small to replace traditional stoves for at least 42% of our households[21], even for preparation of one daily meal, most households continue to use traditional stoves alongside their solar ovens. Treatment households show a small and statistically significant reduction in wood use (11-13%). However, the lack of treatment effect for time spent collecting fuel, carbon monoxide inhalation levels, self reported respiratory symptoms can be partially explained by the inability of most households to completely replace at least one daily meal with the solar oven. Behavioral economics aspects of the technology adoption decision are explored in the third paper of this dissertation (see Beltramo (2010)).

Our population is well identified as a population which can benefit from an improved stove, however the solar oven, the Hotpot, is not the right size for the population. A relevant question is why we did not identify this in a needs assessment survey prior to our randomized controlled trial. As development needs greatly outnumber development financing we decided not to replicate the needs assessment our NGO partner SHE conducted in Méckhé, While this proved to be a mistake, our reasoning was sound. Our study concludes that the Hotpot is not the right stove for the proposed nationwide rollout for wider Senegal. Antidotal evidence suggests that the behavior change associated with solar cooking should be accompanied by intensive training to encourage adoption. A viable solar product is missing from the local market in Senegal and in its absence other improved stoves should continue to be explored.

## 2. Related literature and theory review

Costs of fuel can be a large percentage of household expenditure in developing countries. Demand for traditional fuel also places significant pressure on local forests and woodlands, contributing to deforestation, soil erosion and desertification. However important the introduction of improved cook stoves is for household expenditure and the local environment, a core reason for studying improved cook stoves is the linkages to health. Biomass smoke contains a large number of pollutants including irritant gases such as

[20] This is derived from the Meddleton et al. (2000) study by setting the average observed level of CO ppm of smokers of 11.6 CO ppm= No. of average cigarettes smokers reported- 11.5.

[21] This is derived from the adult age equivalent measure while about 80% of the number of people women report cooking for at baseline is more than six persons.

particulate matter, carbon monoxide, nitrogen dioxide, sulphur dioxide (mainly from coal), formaldehyde, and carcinogens including benzo(a)pyrene and benzene.[22] Evidence has been growing for the link between IAP and Acute Lower Respiratory Illness (ALRI), Chronic Obstructive Pulmonary disease and lung cancer and tentative evidence for association of IAP with asthma, cataracts, adverse pregnancy outcomes and tuberculosis.[23] One influential study, the RESPIRE study in Guatemala, is frequently cited as evidence for the linkage between the reduction of indoor air pollution and improved stoves. This study is the most comprehensive on the impact of IAP on health to date. The RESPIRE study in Guatemala outlined in Smith-Silvertsen, et al (2004) and Diaz, et al (2007) which began in October 2002, is the first randomized controlled trial testing the effects of improved stoves on indoor air pollution for women and their children. The study randomly selected women who either had a child less than four months old or were pregnant at the time the study began. The household was followed for three years, until the infants reached 18 months of age. The study, which took place in the rural area of San Marcos in Guatemala, in the largely Mayan speaking populations, involved weekly visits to each household by field workers trained in identifying Acute Lower Respiratory Illness (ALRI) among children. All children assessed with ALRI were referred to the local physician stationed in the community, and further assessed and treated there. In addition, to the weekly assessments of children for ALRI, researchers examined women’s health using lung functioning tests and semi-annual health assessments. To measure exposure to smoke from the stoves, women were tested using CO breath analyzers and 48-hour CO personal monitoring tubes. The follow-up health assessments conducted bi-annually included respiratory symptoms and other health symptoms associated with cooking including- eye irritation, headaches, throat irritation, and back ache. The RESPIRE study found that CO levels and the reported health symptoms were reduced among women who received the improved stove. There was a statistically significant drop in the other symptoms women reported associated with cooking. Further, the study is the first randomized controlled trial (RCT) to show a statistically significant drop in the incidence of childhood pneumonia for households with improved stoves and hence cement the linkage between improved stoves, indoor air pollution and ARI.[24] The RESPIRE study and conversations with the team at UC Berkeley associated with RESPIRE informed the methodology of this study.

In Senegal, the leading cause of death is Lower Respiratory Infection (LRI) which claims 16% of total mortality.[25] To put this in context, the second highest cause of death in Senegal is malaria which claims 13%. LRI is driven primarily by the relatively high incidence of mortality for children under four due to respiratory infections. One of the causes of respiratory infections is exposure to inefficient cook stoves. Public health specialists note that pregnant women are at higher risk for adverse birth outcomes such as lower birth weight due to higher levels of exposure to CO and carbon particulate matter.[26] For our sub-sample the women who wore the CO tube over the lunch meal, 17% carried a child on their back while cooking. From the sixth month CO survey, women cooks are on average age 26 (median is 24) and are of prime childbearing age. Thus, high levels of CO are particularly deleterious for the health of women who cook and their children who accompany them.

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[22]See von Schirnding et al (2000).

[23] Recent and ongoing research includes work by Esther Duflo, Michael Greenstone from MIT with Rena Hanna from Harvard, Mushfiq Mobarak, Professor at Yale University and Darby Jack, Professor, School of Public Health, Columbia University.

[24] See Smith et al. (2006)

[25] See WHO (2006)

[26] See Wong, E. et al. (2004)

The quantitative and scientific design of the RESPIRE study is unique because as Duflo et al. (2008) point out, much of the evidence on the relationship between air pollution and health 'presents serious shortcomings, as they are largely based on observational studies and may confuse the causal effect of IAP with the determinants to its exposure.' Ezzati and Kammen (2001) cite in many epidemiological studies to date researchers have used indirect measures of personal exposure, such as fuel or housing type to proxy for CO exposure. However, there are large variations in emissions from individual stove types and in exposure profiles within individual households, thus reducing the ability to predict exposure based on indirect measures.[27]It is precisely this dearth of scientific studies on the effects of improved stoves that motivats this randomized controlled trial of a solar oven in rural Senegal.

Additional research on the relationship between IAP and improved stoves which is often cited includes McCracken and Smith (1988), Ezzati and Kammen (2002), Ezzati, Saleh, and Kammen (2000), Ezzati, Mbinda, and Kammen (2000), and Albalek et al. (2001). These studies all show that improved stoves reduce toxic pollutants when they replace traditional stoves for cooking. Importantly Duflo et al (2008) point out that despite this growing literature there is still a deficit on information on the impacts of IAP on health and even less evidence on the impacts on the economic well-being of the family given improved health associated with reduction of IAP with improved stoves. In particular, if improved stoves reduce ARI and improve health for women and children who are most exposed to the cook fire, the economic and schooling downstream effects need to be further researched. Duflo and Hanna (2006) show the absence rate of children from school in rural India- 60%- is in a large part due to poor health. Miguel and Kremer (2004) in their innovative approach to measuring the effects of de-worming initiatives in schools in Kenya, found a reduction of absenteeism by a quarter and a 7.5 percentage point gain in attendance due to the de-worming initiative. Thus, the effects of introducing an improved stove may have significant impacts on schooling attendance outcomes.

The burden of time required to collect biomass fuel is great and often falls on women. Women are forced to tradeoff activities with potentially higher returns- including education and economic opportunities- in order to collect fuel for cooking. A study in rural Malawi found that women spent between 4 to 15 hours per week collecting fuel, depending on the distance from the woodland.[28] In the same Malawi study, children from wood-scarce districts are 10 to 15 percent less likely to attend secondary school than children from less scarce districts. The time-consuming nature of fuel collection may limit other opportunities for these women, such as education and income-generation. Thus, by reducing the time spent collecting wood, improved stoves can potentially give women and girls the opportunity to pursue other activities including education and employment outside the home. The effects on additional time for education and employment may positively affect intra-household bargaining and effectively increase women's decision power in household decisions. The knock-on effects for increasing women's intra-household bargaining power have potentially large implications for overall development.

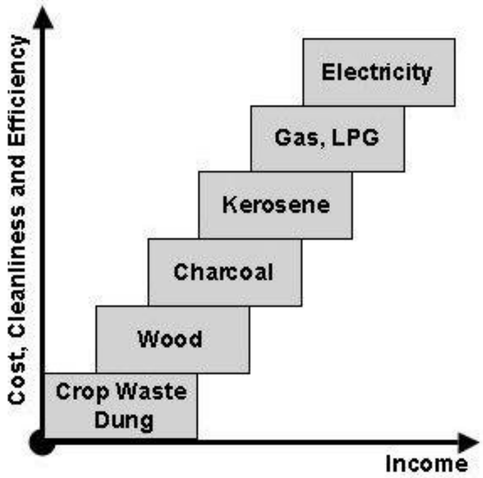
Improved stoves programs are not new and have been widely adopted. China has notably installed over 35 million improved stoves. The government of India in a national program

[27] See Ezzati et al (2000); Ballard-Tremer et al. (1996); Boleij et al. (1989),and Saksena et al. (1992).
28 See Nigel Bruce et al (2006).

has subsidized the distribution of some 12 million improved stoves, and in Kenya some 1.5 million jiko stoves have been distributed. Much valuable experience has been gained from successful and unsuccessful programs in household energy, in particular from the Indian national stove program, the Chinese national stove program and LPG promotion.[29] Key lessons include: 1). The importance of involving users through pilot studies with improved stoves; 2). Sustainable adoption through the promotion of greater availability of appropriately priced interventions through local commercial outlets; 3). Support of targeted subsidies or micro-credit facilities or both to overcome barriers to adoption; and 4). Training through accredited local actors (NGOs/government) is critical for the successful adoption of stoves. These four lessons figured heavily into the design of our program. Our study was designed to pilot the solar stove, the Hotpot, in 20 village communities in 1000 households to test the effectiveness of the core study impacts and assess whether this stove was the appropriate stove to bring to national scale. In addition, the program was highly subsidized, the stove cost consumers $5 equivalent and consumers paid in time payments to address potential liquidity constraints among our households. The program was a joint program with the local NGO Tostan who has been working in Senegal since 1991. Tostan is a highly respected NGO with a dynamic Community Empowerment Program which works with villages for 3 years to train the local population in organizing development initiatives and community empowerment.

The energy ladder (Holdren and Smith, 2000), illustrated in Figure 1A below describes the trajectory in fuel use for different levels of economic development. Disproportionately the world's poor, some 3 billion people, cook on the lowest rungs of the ladder with biomass fuels including animal dung, crop waste, and wood and coal. The efficiency of the three-stone fire used in rural Senegal and in many developing countries is only about 10-15% efficient and thus most of the energy content of the fuel is wasted.

Figure 1A: The Energy Ladder[30]




Smith and Mehta (2000) estimate the burden of disease from the use of solid fuels in developing countries and find sub-Saharan Africa has 5.2% of total death attributable

[29] See Bruce, N.et al. (2006)
[30] See Smith and Mehta (2000)

directly to solid fuel use and attribute 4.9% of total disability adjusted life years (DALYs)[31] in Sub-Saharan Africa to the use of solid fuel use (Appendix 5,Table 5.1). Evidence of the large scale problem and burden of disease due to indoor air pollution in sub-Saharan Africa merits solutions. Improved stoves have the potential to address these problems and Bruce et al (2006) show that interventions can be cost-effective (see Appendix 5, Table 5.2).

## 2.3 Role and design of Randomized Controlled Trials

A randomized controlled trial offers reliable estimates of the impacts of improved stoves which are key for effective policy design. In particular, by understanding the diversity of cooking patterns, including the types of kitchens used and the different stoves, as well as the type of fuel used, and how improved stoves affect these patterns; policymakers can design effective policy and offer sustainable solutions to fit the local communities needs. These estimates can also provide critical evidence for stove manufactures or distributers to attain sustainable financing for improved stoves projects via the voluntary carbon credit market. The Kyoto Protocol creates markets for carbon trading via the Clean Development Mechanism. It is possible that these subsidies available on the voluntary market for improved stoves could accelerate the development and adoption of improved stoves. This opportunity should not be understated as many large donors have made significant resources available in order to scale up rigorously evaluated pilot projects. [32]

Like any impact evaluation the goal of this research is to answer the counterfactual question- How did individuals who did not benefit from the solar oven fare in the absence of the program? The critical objective of an evaluation is to establish a credible comparison group. A controlled randomized trial is the first best solution to avoid selection bias, as by design a randomized evaluation eliminates selection bias[33]. In this case, on average, we can be assured that those who are exposed to the program are no different than those who are not, and that a statistically significant difference between the two groups for the outcome indicators can be confidently attributed to the program.[34]

To see this, take the outcome indicator for households of wood used to cook meals daily. We want to measure the difference between the treatment and control group's use of wood. We write this analytically in 1a below, using the abbreviation ind. to signify individual. The outcome indicators is represented by Y, treatment by T, control by C, E represents the Expectation, and i=ind. Household. The difference can be written:

$$D = E[Y_i^T | Ind\ has\ HotPot] - E\left[Y_i^C | Ind\ has\ no\ HotPot\right] = E[Y_i^T | T] - E\left[Y_i^C | C\right] \quad \text{(1a)}$$

Then as is common, we subtract and add $E\left[Y_i^C | T\right]$ or the expected outcome for an individual in the treatment group had she not been treated. This quantity cannot be observed but is well defined logically and thus we obtain identity 1b:

$$D = E\left[Y_i^T - Y_i^C | T\right] + E\left[Y_i^C | T\right] - E\left[Y_i^C | C\right] \quad \text{(1b)}$$

[31] DALY (disability-adjusted life year) is a composite measure that combines the number of years lived with a disability and the number of years lost to premature death.

[32] The World Bank Group currently manages about one billion dollars to purchase credits for greenhouse gas emissions reductions.

33 Selection bias: "arises when individuals or groups are selected for treatment based on characteristics that may also affect their outcomes and makes it difficult to disentangle the impact of the treatment from the factors that drove selection." (see Duflo et al. (2006).

34 See Duflo, E.et al (2006)

The first term is the treatment effect that we are searching to identify, while the second term $E\left[Y_i^C|T\right] - E\left[Y_i^C|C\right]$ is the selection bias. Selection bias captures the difference in potential untreated outcomes between the treatment and the control households. An example of selection bias could be that households selected to receive stoves were households that showed more than average concern for the effects of breathing in smoke over the cook fire and were more likely to cook outdoors and with improved stoves. In this case $E\left[Y_i^C|T\right]$ would be larger than $E\left[Y_i^C|C\right]$. Thus, an essential objective of most empirical work is to identify situations where we can assume that the selection bias does not exist or find ways to correct for it. In randomization the problem reduces to 1c:

$$\widehat{D}=\widehat{E}[Y_i^T|T] - \widehat{E}[Y_i^C|\text{C}] \quad (1c)$$

Here Ehat denotes the sample average. As the sample size increases, this difference converges to $D = E[Y_i^T|T] - E[Y_i^C|C\ ]$. Since the treatment has been randomly assigned, individuals assigned to the treatment and control groups differ in expectation only through their exposure to the treatment. Had neither received the treatment, the outcomes would have been in expectation the same. This implies that the selection bias, $D = E\left[Y_i^C|T\right] - E[Y_i^C|C\ ]$, is equal to zero. The regression counterpart to obtain $\widehat{D}$ is:

$$Y_i = \alpha + \beta T + \epsilon_i \quad (2)$$

Here T is a dummy for assignment to the treatment group. Equation (2) can be estimated with ordinary least squares, and it can easily be shown that:

$$\widehat{B}_{OLS} = \widehat{E}(Y_i|T) - \widehat{E}(Y_i|C) \quad (3)$$

This result tells us that when a randomized evaluation is correctly designed and implemented, it provides an unbiased estimate of the impact of the program in the sample under study.

## 3. Solar Oven Project overview and data

This section describes the intervention, randomization into treatment groups, and data collection.

### 3.1 Traditional cooking practices in western Senegal, why a solar oven, and qualitative feedback on usage of the solar oven

The Thies region in Senegal is located in the Western area of the country and consists of 1,541 communities which are predominantly Wolof speaking[35]. The region is part of the Western Sahel, is semi-desert, and outside the rainy season from late June through August is tropical and sunny. The villages in our study are rural and relatively poor- the daily average wage women earn is $1.55/day and their husband's give them between $2.87/day for household expenditures. All 20 villages in our sample are of varying size and distance to the region's largest city, Thies.[36] In each village a total of 50 households were allowed to enroll in the program, due to a limited supply of solar ovens available. Of the projected 1000 households in our sample, the project distributed 960 stoves overall at a total cost to

[35] Source the Government of Senegal census year (2002)

[36] See Figure 2: Solar stoves project study region and sample villages

consumers of $5/stove.[37] At baseline, less than 25% of our sample own an improved stove, and most households cook on several types of stoves- mainly charcoal, gas, and a wood traditional three stone fire. The household's choice of stove depends on the meal, season, and size of household. Despite the variety of cook stoves used daily, households in the study zone used wood as the predominant fuel for their cooking needs. Households were observed to have four main types of cooking structures or kitchens: 1). Enclosed kitchen with no windows (23%); 2). Semi-Enclosed kitchen with at least one window (44%); 3). Hut, or open air kitchen with thatch roof but no walls (23%); or 4). An open air kitchen with no structure (11%) of the time.[38] The multiplicity of kitchen types and stoves used by individual households reflects the economic rationale of the village agents and their search for price optimization among a variety of different fuels associated with different stoves. Price differences in wood and charcoal can be attributed mainly to seasonal effects and abundance of wood directly after the rainy season and the dearth of wood at the end of the dry season. Further, in Senegal, the government regulates the number of charcoal producers and this may affect price and availability as well. For gas local prices are dependent on international prices as well as local supply subsidized by the government.

As mentioned in the introduction, the solar oven was chosen for the following reasons. First, engineers from the University of California at Berkeley verified the Hotpot to be well designed and likely to hold up well in rural Senegal, and particularly not to break easily. Second, solar cooking is a national priority of the Government. Third, SHE, our NGO partner, conducted a needs-assessment study indicating the Hotpot was an appropriate fit with the local communities. Solar cooking is also attractive because of its' efficiency gains in time and money spent on fuel. Food can be placed in a solar cooker and left to cook, unattended for an hour at a time while women and girls pursue other activities. As solar ovens require no fuel other than the sun's energy, women and girls who bear the responsibility for cooking and gathering fuel, have more income and time to spend on other lucrative enterprises including education or small business activities. The fuel savings can have downstream effects on the environment by lessening the demand for wood and charcoal used for cooking. In addition, solar cookers do not emit any harmful carbon monoxide gas from cooking and the Hotpot has the potential to reduce significantly women's exposure to CO while cooking. In addition, pots used for solar cooking are easy to clean and make cleaning of meals easier. Finally due to the slow cooking process, solar cooking has been noted to help preserve nutrients in food and thus improve health. The solar oven distributed- the HotPot- was designed and engineered by Solar Household Energy and is produced and imported from Mexico.[39] Under a tropical sun it can cook rice in under an hour, a chicken in about two hours, and beans in four hours. On a sunny day in Senegal the oven can be put out as early as 8 or 9 am and can cook as long as 4 to 5pm, and thus ostensibly be used twice daily.

Because the solar oven can be used only during daylight hours, we anticipated the villagers would use the solar oven to cook the lunch meal, which is served between 2-3pm. The lunch meal in Senegal is traditionally the largest meal of the day and would provide the best

[37] The stoves were highly subsidized upwards of 90%. Costs of importing the stove proved much higher than the NGO partner SHE had imagined due to high import duties applied at the port of entry in Senegal Each stove cost about $75.00 to deliver to the villages. This price is clearly not sustainable, though price was secondary to understanding whether a well-made solar oven is appropriate for the rural communities in Senegal.
[38] See Figure 4
[39] See Appendix 2

opportunity to reduce fuel consumption and harmful CO inhalation among cooks.[40] The most common dish prepared for lunch is ceebu jën, or a combination of rice and sauce with fish or meat. The traditional preparation of the meal requires a several step process consisting of sautéing and stewing which cannot be exactly replicated with the slow cooking process of the solar oven.[41] Solar stove trainers and households report making Ceebu jën with the solar oven, however, because the Hotpot skips the frying step, the dish is less crunchy. The meal requires preparing the sauce and the rice apart, and thus is a two pan dish, and can be prepared using solely the Hotpot with similar but not equal taste outcomes. Due to the size constraints, in our final survey, only 8% of our sample used the HotPot to prepare part, or all, of the lunch meal. And at the six month follow-up survey, only 2% of households report preparing ceebu jën with the solar oven. In fact, the main complaint of households about the solar oven was the size was too small (50%).[42] Despite the constraints of the HotPot, our households proved innovative and instead of using the oven to cook lunch, the majority of households used the oven to prepare the relatively smaller dinner meal (40%), snack (28%), and separate meals for children or diabetics (13%).[43] In addition, at the six month follow-up survey, we observed 61% of all households in the treatment group were preparing dinner with the solar oven. As it is a common practice of households to pre-prepare meals and then reheat them at meal time, the pre-preparation of the dinner meal concurrently with the lunch meal proved convenient and consistent with traditional cooking methods for the women in our sample.

### 3.2: The Study Design and Assignment to Treatment

Villages for this study were selected by the non-governmental development organization (NGO) Tostan Senegal[44]. The NGO selected the twenty villages from the universe of more than 245 villages which have completed Tostan's three year Community Empowerment Program (CEP) in the Thies region.[45] Criteria for selection in the program include villages which primarily cook with wood and have graduated from Tostan's CEP at least five years earlier. The reason for the second criteria is that graduated villages are experienced in organizing different development initiatives in their communities, and hence more apt to successfully adopt the program. Tostan's role, as the local NGO partner, is to facilitate the rollout of the project to the 20 villages through their existing village level development network and in particular to aid in organizing the community meetings and training of the

[40] At the six month follow-up, the lunch meal consumed 58% of total daily wood consumption and hence quantifies as the biggest meal of the day in rural Senegal.

[41] Ceebu jën preparation can be broken down into four major steps:1). Fry the fish in oil, take it out and set it aside. 2). Add water, tomato paste, and seasoning to the hot oil, let it boil. 3). Add vegetables in order of their cook time (i.e. carrots & yucca root before cabbage because they take longer to cook). Simmer, then strain out vegetables when they are done. 4). Bring sauce to a boil again, steam rice over the pot with a lid for about 10 minutes. 5). Drop the rice into the sauce to finish cooking. Source (CEGA Research Team Senegal)

[42] The top three complaints of solar oven owners were as follows (percentage of total complaints): 1). Too small (50%); 2). Shorten the time the solar oven requires to cook (35%); Make reflector more durable (11%).

[43] Data is from the six month follow-up survey. The dinner meal, which is often porridge is well suited for solar cooking with the Hotpot. Most porridges consist of a grain base (rice, millet, pasta) water, evaporated milk in a can (lait caillé- or essentially vanilla flavored yogurt), and sugar. The grain is cooked in boiling water and after it cools the other ingredients are added. Common porridges prepared by Wolof speakers include: Sombi = rice porridge; Thiakry = millet porridge; Lax = a second type of millet porridge; Muhamsa = pasta porridge; and Gari = corn pasta. (Source CEGA Research team Senegal).

[44] Tostan Senegal has been working with rural communities in Senegal since the 1970s and has a unique three year community empowerment program to prepare communities to build development locally. Over 2,028 villages have benefited from the CEP since 1991 and 3,791 communities have participated in public declarations (CEP villages and Villages reached by Organized Diffusion) communities in Senegal have benefited from Tostan's program. Source: Tostan Senegal

[45] "The goal of Tostan's Community Empowerment Program (CEP) is to provide African communities with the skills and knowledge to improve their living conditions in a sustainable way." Source: Tostan Senegal

villagers on how to use the Hotpot.

In addition to Tostan Senegal, a second NGO Solar Household Energy, Inc. (SHE)[46] participated in the design and implementation of the impact evaluation. The choice of the solar oven, the Hotpot, was directly based on a needs assessment conducted by our NGO partner SHE in Méckhé, Senegal in 2007. SHE also trained Tostan staff and assisted in trainings and marketing demonstrations in the 20 villages on how to cook with the Hotpot from Jan-March 2008. Together, with Tostan and SHE, our research team from the University of California at Berkeley's Center for Evaluation of Global Action (CEGA) designed this randomized controlled trial which took place from April to October 2008. In particular, CEGA designed and translated the three household surveys into the local language, hired and trained enumerators, field tested and fielded the surveys, oversaw data entry, trained in and completed a full Human Subjects Office Review[47], and the prepared analysis of results of this randomized controlled trial.

Due to shipping constraints of the HotPot from Mexico to Senegal only half the population could receive the stoves at one time, and thus the phased intervention fit well with the program needs. For each village, 50 solar ovens were made available and the study randomly selected 25 households in each village to receive the solar oven at the time of the baseline survey (April 2008) and 25 to receive the oven at the six month follow-up survey (October 2008). All households were asked to participate in the three survey waves:

- Baseline: (April 2008)- Treatment households receive stove
- One-month follow-up: (May 2008) One month after Treatment receive stove.
- Six month follow-up: (October 2008) 6 months after Treatment receive their stove and at the end of the village visit the Control Households receive their stoves.

### 3.3 Data collection procedures

We collect household level data at the baseline, one month and six month follow-up surveys pertaining to household weekly fuel use, time by entire household spent collecting fuel, cooking practices, self reported respiratory and other health related symptoms for women and their children to cooking, as well as statistics on wealth, education, marital status, and family size. [48] In addition to the baseline and six month follow-up surveys a subset of our sample was selected at both the baseline and the six month follow-up to measure the carbon monoxide exposure for women cooking the lunch meal. An accompanying CO survey went along with the measurement of the CO exposure levels for women cooking. This CO survey included information on the type of cooking structure, time spent cooking lunch and types of fuel actually being used.

Our surveys at the six month follow-up benefitted from knowledge gained from the field team in the baseline and one month follow-up survey and were refined in a variety of ways to better record the outcome variables to be more consistent with the local practices. In

[46] Solar Household Energy (SHE), an NGO founded in 1998 has significant experience in the distribution and marketing of the solar oven- the Hotpot. SHE has distributed over 5000 HotPots in Africa and Latin America.

[47] We submitted a formal application and were approved by the Committee for Protection of Human Subjects at the University of California at Berkeley. The CPHS number for this project is: 2007-12-50.

[48] A one month survey measuring the above outcomes was also fielded however we do not include data from the one-month follow-up in our core results because only 9% use the solar ovens during the first month. We reason this rate is very low to detect any changes in wood use and thus we focus our analysis on the difference between the baseline and the six month follow-up where usage is up to 19% of the time.

particular, one such refinement included the discovery that a significant portion of our participant households have more than one study participant in their compound.[49] In certain villages this criteria had been violated and 28% of our sample (209 households) were part of a compound with another treatment or control. The result is that 38% of treatment households and 25% of control households have another treatment or control household in the compound. We use this overlap of study participants per compound to our advantage and test whether our results change when we account for compounds with more than one study participant (i.e. more than one solar oven per compound). Overall for treatment households with more than one treatment participant per compound (and thus at least 2 solar ovens) these households show larger effects of the solar oven on the core outcome variables.

**Stove Utilization** The solar stove usage is measured with an ibutton, a computer micro-chip enclosed in a 16mm thick stainless steel case, which was installed on the lid of all the stoves by the CEGA team.[50] The decision to use the ibutton to measure the solar oven's usage follows directly from recommendations by Kirk Smith and team who first used the ibutton to monitor their improved stove project in Guatemala. Like their team, we adopt the term Stove Usage Monitor (SUM) instead of ibutton.[51] We programmed the SUM's to take 48 temperature readings per day- once every 30 minutes. The SUMs provide clear spikes when the solar oven is used and we use the threshold level of 110 degrees or more as an indication of usage of the solar oven[52]. The daily temperature readings in the sun during afternoons in 9 of our 20 villages visited in April were on average 90 degrees Fahrenheit (32 degrees Celsius) a stark difference from the 110 degrees Fahrenheit (43 degrees Celsius) used as a threshold indicator for stove usage. The SUMs provide a unique observable estimate of daily stove usage per household. There are two month-long periods which are measured- the first month- April-May and the sixth month- October-November. This objective data is contrasted by self-reported usage rates at the one month and six month follow-up survey and with the observed usage rates on six month follow-up village household level visits. We find that stated usage is two times that of actual usage of the solar ovens, while observed usage at the six month follow-up is three times the actual usage. This reinforces the role of SUM's in future research for accurate measures of stove usage.[53]

**Fuel Consumption and Costs** Households were asked on all three surveys to report the amount of each type of fuel- charcoal, gas, animal dung, farm waste, and wood- they used last week. In addition to this qualitative self-report, all households were asked to draw from a pile of wood centrally located in the village to estimate the amount of wood they used to cook lunch with yesterday as well as the number of people they cooked for. On the six month follow-up survey households were asked to draw from their own wood pile and to estimate not only the amount of wood they used to cook lunch yesterday but the amount of wood they used to cook for all the day's meals yesterday. The wood measurements were adapted to include a measure of the total amount of wood used daily because at the one month follow-up survey we found that the majority of households were using their solar

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[49] Multi-household compounds in this setting are typically due to polygamy, although sometimes contain multiple brothers or other relatives.

[50] The ibutton is a product sold by Maxim.

[51] The use of ibuttons to measure stove usage was first piloted by Kirk Smith and his team in their RESPIRE study in Guatemala. We have greatly benefited from this team's pioneering work and advice on the SUM's for this study.

[52] See Appendix 3

[53] See Figure 3

oven to prepare dinner. Hence the measure of the wood used to cook the lunch meal would not be sufficient to capture any reduction in daily wood used by households for cooking.

**Monetary and Time Costs Related to Biomass Fuel Usage** On all three survey waves households were asked to report how much time and money their households spent last week collecting and purchasing fuel. We discovered that in addition to collecting fuel on a daily or weekly basis a significant portion of our households (25%) collected wood in bulk or in a stock. After learning that at least one quarter of our sample collected fuel in bulk we were able to update our survey to capture this phenomenon by adapting our survey tools to best record the method and time spent collecting fuel by the local populations. We believe the six month follow-up survey is thus a better measure of how our population actually collects wood as we specifically include questions on collecting wood in bulk. In the sections below we adapt our analysis to include the possibility that the baseline survey includes some measurement error. Finally, we find significant seasonal variation on the time frequency households report collecting wood.

**CO Inhalation Measures** To measure exposure to carbon monoxide (CO) while cooking lunch, on a subset of our population, enumerators distributed Drager Color Diffusion Tubes (from here forward referred to as CO tubes) in the morning upon arrival in each of our 20 villages (between 8:30-10:00am) and collected them about 5 hours later (2:00-3:30 p.m.) after lunch. These tubes are attached to the cook's attire and households were selected randomly to receive the tube with the help of the local village Tostan representative. The only criteria in the distribution of the CO tube (other than the household's permission) are that the household is cooking with wood on the day of the team's visit to the village. Any household found cooking with gas is skipped. Using the principles of gas diffusion and colorimetric reaction, the Diffusion Tubes allow the reader to reliably measure the Time Weighted Average (TWA) concentrations of CO resulting in CO ppm/hour measure for the lunch meal. The team measured CO tubes on all three surveys in the village on a subset of households. However, because of the structure of the visit, the six month follow-up measurement provides the most precise measure. This is attributed to the fact our enumerators went house to house instead of holding a central village meeting as in the first two surveys. Going house to house allowed the team to deliver the CO tube much earlier and catch 74% of households before they had started the fire while on the baseline and one month follow-up surveys only 20% of households tested received the CO tube before their fire for lunch was started. Given the late distribution for the baseline and the one month follow-up of the CO tubes, we concentrate on the analysis of data reported at the six month follow-up, as it is considered much more accurate and unbiased.

**Respiratory Health** In addition to the quantitative CO measures, on each of the survey days women are asked to respond to several health questions which correlate with respiratory infection for themselves and their sick children. These questions have been constructed to take account of the phenomenon of recency, or that people tend to remember more recent events, and ask study participant's to report on their health and those of their children's health over the last week. Women were asked on both the baseline and six month follow-up to self report respiratory illness symptoms which have been identified by public health professionals as the most common symptoms indicating respiratory illness.[54] At the six

[54] The Respiratory Illness symptoms on our survey are a result of several conversations between Kirk Smith's RESPIRE team and the authors. We appreciate advice from their team of public health specialists in designing these questions.

month follow-up we asked women to report the same seven respiratory symptoms for their husband. The husband's symptoms act as a placebo since men do not cook for the household. The self reported symptoms of respiratory illness include: 1) Fever; 2). Sore throat; 3. Runny/stuffy nose; 4). Cough; 5). Wheezing or trouble breathing; 6). Woke up with chest heaviness at night; and 7). Coughed up mucus. Because women on average have five children we shortened the number of respiratory questions from seven to four for children and women were asked to respond if their children experienced any of the four symptoms including: 1). cough or difficulty breathing; 2). cold and coughed up mucus; 3). runny or stuffy nose; 4). wheezing.

In addition to respiratory illness symptoms, inspired by Kirk Smith team's RESPIRE study in Guatemala, we asked questions on the prevalence of eye discomfort, headache, irritated throat, and back pain during cooking. In Smith et al. (2007) they found a high prevalence of eye discomfort, headache and backache. They found the odds of having sore eyes and headache are significantly reduced in the treatment group versus the control group. These results correspond to a significant drop in the median CO in breath among women in the treatment group which receive the improved stove vs. the control group which do not. Like our colleagues in the RESPIRE study in Guatemala we find a very high incidence of prevalence of eye discomfort, throat irritation, back pain, and/or headache while cooking at the baseline survey. On the baseline the treatment group reports a statistically significantly higher count of 10% more of the four symptoms on average than the controls. We return to this discussion below.

### 3.4 Summary statistics, unit definitions and sample attrition

**Sample Size** In total our sample has 1113 households in our dataset. In addition to our 960 households belonging to the treatment and control groups, the sample includes 40 households which withdrew from the program[55]. There is also a small sub-sample- 113 households- of what we call the comparison group composed of women who expressed interest in the program and came to the village level meeting to learn more about the solar oven. These women were not enrolled officially in the program, but they were surveyed. In the end because of the inherent limitations of the small sample size of the comparison group we use this group only for our CO results.

Households that withdrew from the program are households that were originally inscribed at the time of the baseline survey and subsequently withdrew from the program. Of the 40 households which withdrew, 80% of the households are from the treatment group while 20% are from the control group.[56] The most common reason given for withdrawing from the program by households who could be found after withdrawing was an unexpected financial shock, most often a sickness or injury to the women herself or her child or family member, which required the household to put all disposable income towards curing the illness.

Table 1 shows at baseline there are 960 of the envisioned 1000 households in both the control and treatment groups. Of which, 792 took Survey 1, though only 736 of those households weighed wood. On Survey 3, at the 6 months follow-up, 906 households from the treatment and control groups took the survey, of which 810 also weighed wood. For the baseline we had less recorded wood weighing because the wood weighing was a second

[55] 25 households withdrew at the one month follow-up and 15 withdrew from the program at the six month follow-up.
[56] Of those that withdrew, the 32 women from the treatment group had their stoves repossessed and redistributed.

station separate from the household survey. Thus, a portion of households took the survey but did not continue on to the wood weighing station despite the best efforts in the field to encourage women to complete the wood weighing station.

A compound represents a polygamous household where multiple wives live together, often in a circle of huts, fenced off from the rest of the village. It is common for multiple wives to share cooking responsibilities and in our sample we find 28% of households report a second wife living in the same family compound. It is important to note that it is also feasible for men to have more than one wife in different villages. Though given the outcome indicators for our study we are careful to define household size on our surveys to only account for members of the household who actually live in the same compound.[57] We permit other women from the village (usually from the same compound) to take the survey on behalf of the women inscribed in the program if the inscribed woman is not present. 47% of respondents at the six month follow-up were substitutes. Treatment households were slightly more represented at the six month follow-up with 50% of households (N=224) being represented while 43% of control households are represented (N=206). We had higher recorded substitutes at the six month follow-up in part because the survey occurred during fish smelting season in two of our villages. Because of this high-commerce period many people were absent from these villages at the time of the sixth month survey. In addition, treatment respondents that had already received their solar oven had less incentive to be present in the village to take the six month follow-up survey than the control group, which were waiting for their HotPot. The higher number of women being represented on the six-month survey could also likely be measurement error. This could be because unlike the sixth month follow-up survey, on the baseline survey we did not have a formal question identifying whether a woman was being represented.

As mentioned, the average household size for our sample from both survey waves is 12 persons, of which 53% are female. As is consistent with poor, underdeveloped countries, the largest percentage of the sample population are young, with 60% 24 and under and 76% age 34 and under. Education levels are low, with 94% of those over age 50, and 48% of youth 13-18, reporting zero or missing education (See Appendix 2 for a more detailed overview of education by cohort)[58].

**Summary statistics for Solar Oven Usage** On average in the first month of having the solar stove, the results from the SUMs show that 9% of women in the treatment group use the solar stove on any given day. In the sixth month of having the stove, 19% of women use the stove on any given day. The more than doubling of usage from the first to the sixth month is likely partially a result of intensive ongoing village training during the first six months by stove specialists employed by the local NGO partner Tostan. Stove specialists visit each village on average twice between the 2nd and 6th month. For villages which the team found to have very low usage and/or weak village level facilitators, the stove specialists stayed

[57] Enumerators read aloud the following definition to each woman before asking her to list every member of her household who adhered to the following criteria.

i. The people living in the household/compound are there all the time.
ii. The guests in the household who have passed more than two weeks in the household.
iii. When given polygamy, if the houses/rooms of women are close to one another it is considered one household/compound.
iv. If you have children that do not live with you, please do not give their names.

[58] Missing indicates the woman respondent was unsure of when was the last year of formal school attended by the household member, and makes up a small portion of our results. In addition, formal education excludes religious education such as koranic school.

between 2-4 days in the village to individually visit women at home to provide additional training on how to cook with the solar oven.

This intensive training model seems to be successful at bolstering usage in previously low usage zones, except for the two villages located on the sea. These two villages[59] proved to be the wrong environment for the solar ovens as the regular wind from the sea compromised the mechanics of the panel solar cooker and cooking was impaired. Despite the limitations for cooking in this zone, demand was relatively high as both villages were 40% over-subscribed with requests to buy the oven. One potential reason for this high demand is that this zone is a center for fish smelting and, thus, these villages suffer a tremendous burden of flies. Thus, woman may have liked the stove because its casserole dish sealed and you could store food in it away from the flies. If we drop these two villages, solar oven usage increased to over 20% of days in the remaining 18 villages. Nevertheless, even after doubling to near 20%, actual stove usage remained fairly low, or only one out of every five days was the solar oven used. Finally, it should be noted that apart from the two seaside villages and outside the average two month rainy season, the weather in our villages was generally sunny and hence favorable for usage of the solar oven.

**Household Size, Number of People Women Cook for, and Hotpot is too Small?**

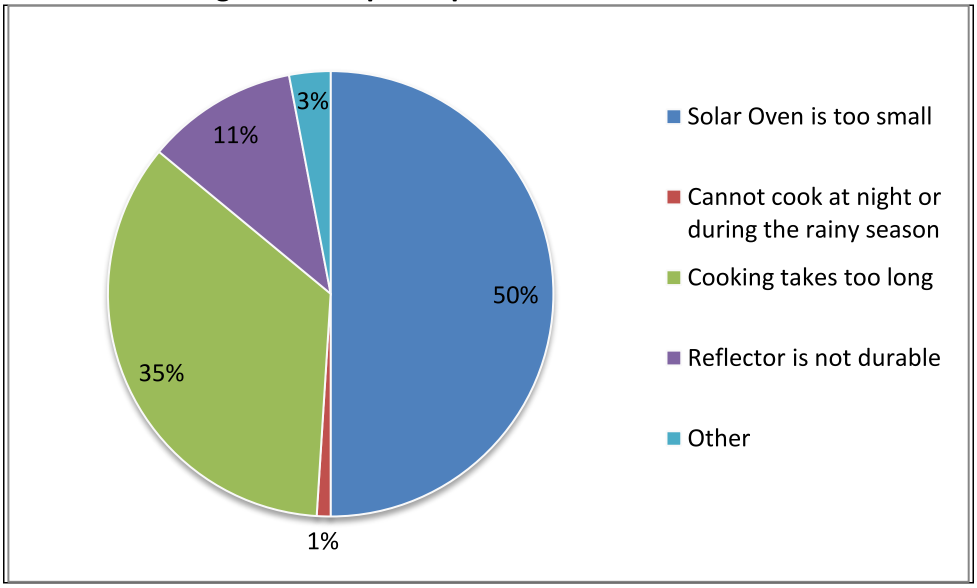
There are several measures we undertake to estimate household size and the number of people the respondent cooks for. In the baseline survey we ask the respondents to list every member currently living in their household/compound[60]. To determine how many people women in our sample cook for, they were asked at the same time they weighed wood, how many people they cooked meals for yesterday. Thus, the self reported number of people women cook for yesterday is how we determine size of household for whom she cooks. At both the baseline survey and the six month follow-up women report how many people they cooked for (see Appendix 4, Table A4.1). When we define wood kilograms per person per household; we use the number of kilograms of wood that women participants report divided by the number of members of their household that they cook for. If women in our sample are part of a compound- or part of a multi-household family- we still determine kg/person the same way, or the number of kilograms she uses to cook divided by the number of people she cooks for.

From Table A4.1, it can be noted that treatment households report cooking for a slightly larger number of people (median 13) than controls (median 12) on the baseline survey, which is statistically significant at the 99% level. At the six month review both treatment and control households report cooking for slightly fewer (median 10) persons than in the baseline, and no statistically significant difference is found. One reason for the variation between number of people women report cooking for in their household may be that there is simply a high level of variance for who women cook for from day to day. Another potential reason for the level change for number of people women cook for could be due to the higher level of representation of women at the six month follow-up, and thus more estimates at the six month follow-up. Or, as we do not ask women to list all their household members at the six month follow-up, perhaps there is more room for estimation and error when asked how many she cooks for daily.

[59] The seaside villages are Darou Salam Joal II and Khelcom Joal. See Figure 3, which reports the number of villagers with solar ovens using their ovens on the day of our sixth month visit. Both villages are well below the sample average- Darou Salam Joal II (Joal II) has only 17% demonstrated usage at the six month follow-up- and Khelcom Joal-26%.

On the sixth month survey, women in the treatment group's top complaint about the solar oven is the solar oven is too small (50%). The second most frequent complaint is the solar oven takes too long to cook (35%), while the third most frequent complaint is the reflector is not durable (11%). The behavior change aspects- such as adapting to the time the solar oven takes to cook- are treated in the third paper of this dissertation.[61] However, the question of whether the solar oven is indeed just too small for households to use can be tested by looking at the number of women people cook for.

**Figure 1B: Top Complaints about Solar Oven**



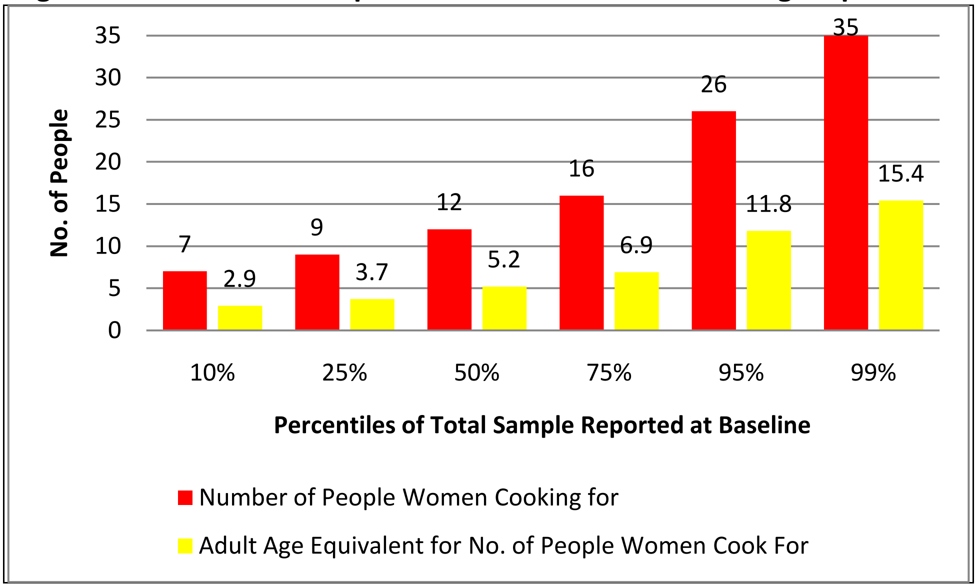

The mean (median) of number of people women report cooking for on the baseline survey is 13.4 (12) with a standard deviation of 6.50 indicating wide tails on the distribution. The majority of our sample, about 80%, consists of households larger than 6 persons. In our regression analysis we control for number of people women cook for by measuring three distinct sizes of household including those of: 6 persons or less (21% of total sample), 7-12 persons (46% of sample), and 13 persons or more (33% of sample). From these measures it seems clear that the solar oven is indeed too small for the households. Thus, women cannot completely replace traditional stoves for even one meal with the solar ovens, and hence the effects of the solar oven on our outcome indicators are significantly diminished.

A second measure we use to test the veracity of the hypothesis of the inherent size mismatch of the stove is the measure of adult age equivalent of number of people women cook for. To do so, in addition to accounting for household size by Small (6 and under), Medium (7-12 persons), and Large households( 13 plus); following Atkinson et al. (1995) we take into account age of each member of the household to measure the adult age equivalent. The central idea is to measure consumption of children in terms of the adult equivalent. A wide range of equivalence scales exist, we use the OECD-modified equivalence scale, also used by the Statistical Office of the European Union (EUROSTAT). This scale, first proposed by Haagenars *et al.* (1994), assigns a value of 1 to the household head, of 0.5 to each additional adult member (18 years of age or more) and of 0.3 to each child (0-17 years of age). To calculate the adult age equivalent of number of people women report cooking

[61] See the third paper of this dissertation, Beltramo (2010) "Peer Effects and Usage of the Solar Oven- Evidence from Rural Senegal", forthcoming.

for, we rely on the household list which includes age of all household members women listed on the baseline survey. For our entire intention to treat sample of 960 households, 772 households in total responded to the number of people they cook for on the baseline survey (See Table A4.1). Of these, 765 completed the household list which includes age, and thus we have 765 comparable observations for the baseline number of persons in the household women report cooking for and the adult age equivalent measure of these individuals. Again, the mean (median) of baseline number of people women report cooking for is 13.4 (12), while in comparison, the adult age equivalent for number of people

**Figure 1C: Number of People Women Cook for vs. Adult Age Equivalent**




women report cooking for is mean (median) 5.8 (5.2).[62] Thus according to the adult age equivalence measure, we find our average household can indeed replace at least one entire meal cooking with the solar oven which cooks for six (see Figure 1C). From the data we know that 58% of our sample have the adult age equivalent equal to 6 persons or less. Thus, it is clear that the size of the stove remains a substantial issue for 42% of our sample who have an adult age of 6.1 persons or more. The adult age equivalent scale provides an important second measure of consumption to measure whether the solar stove is indeed too small for the household to cook with. Unlike the number of people women report for whom they cook that shows about 80% of our households are larger than 6 persons, this secondary measure of consumption in adult age equivalence shows only 42% of our households have a size mismatch between household size and the solar oven. Given this measure, we cannot conclude decisively that the size of the stove was the main obstacle that deterred a solar oven usage/adoption for the entire population. Though, we can conclude that the size of the stove is indeed a significant contributing factor for the low solar stove usage for at least 42% of our households. To ensure the accuracy of our regression analysis we run as robustness checks separate regression analyses that replace our three household size variables with the four different quartiles of household size variables for adult age equivalence. These four quartiles are defined as- Small (bottom 25% equivalent to 1.5-4.2 adult age equivalent); Small-Medium (second quartile equivalent to 4.4-5.7 adult age equivalent); Medium-Large (third quartile equivalent to 5.8-7.3); and Large (top quartile equivalent to 7.4-22.5).

[62] As we expect, on average more than half of our household are made up of youth and children. And the number of people report cooking for is 2.4 times the adult age equivalent scale.

**Summary Statistics for Wood Use and Seasonal Trends in Fuel Consumption** In our sample, 60% of households report they use gas to reheat meals at the baseline survey and 25% report they cook breakfast with gas. At baseline, households use 6.75 kg (15 pounds) of wood to cook the lunch meal for their families. We find large seasonal differences in wood use between our data from the baseline Survey conducted in April (in the end of the dry season) and the 6 month follow-up conducted in October (directly after the rainy season)[63]. Figure 5 shows there is a drop-off in wood purchased (drop of 7%) across the entire sample at the six month follow-up compared to the baseline survey, as well as a 13% drop in charcoal use and a 1% increase in gas use. One hypothesis for this seasonal change is wood is at the baseline survey which takes place at the end of the dry season, wood is scare and thus families substitute purchasing wood for collecting. This hypothesis is supported by Figure 6 which shows an 82% decrease in spending on wood at the six month follow-up when compared to the baseline survey and a corresponding 59% decrease in spending on charcoal. This supports the argument that households are economic agents who maximize efficiently their fuel consumption through varying stove type and fuel used dependent on the relative price to other fuels.[64]

There are also seasonal differences associated with economic activities in a sub-sample of our villages. At the time of the baseline survey (April) many women are involved in the harvesting and selling of mangos both on the roadside and in local markets. In contrast, during the six month follow-up after the rainy season (October), many women in our sample work to harvest their local farms which are often walking distance from their villages. Thus, it is possible that during high economic times (April), when women have increased demands on their time, households substitute purchasing fuel for collecting. In addition, many households collect wood in bulk after the rainy season and hence have a relatively larger supply of collected wood directly after the rainy season (October) vs. at the end of the dry season (April/May).

**Summary Statistics for Wood Collection** Households report many different techniques for which they gather fuel. At baseline, 45% of women report they collect wood while 51% of women report others in their household collect wood. 15% of households report both the respondent and other family members collect wood. This said, 34% report they primarily buy wood, and 30% both collect and buy wood. From the medians- 50% of women report that the wood they collect lasts 4 days. While at the 75$^{th}$ percent level the wood they collect lasts 30 days. And at the 25$^{th}$ percent level wood they collect lasts 2 days. Thus, we understand that more than 50% of our sample collects wood on a weekly basis, though a smaller subset of the population (25%) stockpiles on a monthly basis. Given the many different approaches to collecting wood, we are tentative to make generalizations. On average women who report that they collect wood, do so an hour/day and report on average an hour/day for other household members (see Table 3a)[65]. Notably, given women spend on average 6-7 hours/day cooking all three meals daily plus the average additional hour/day spent collecting fuel; women spend 7-8 hours a day cooking and collecting

[63] Rainy Season is officially June-September, though due to global warming has significantly shortened and consists of about 2 months of rain total.

[64] Relative pricing of cooking fuels is dependent on the relative scarcity of fuel types interdependent on seasonality and international fuel prices.

[65] We refer to statistics from the six month follow-up because due to the diversity of wood collection practices our six month follow-up survey was adopted to better measure the phenomenon of stockpiling wood.

firewood- equivalent to a full day of work (see table 3a).

**Summary Statistics of Carbon Monoxide Inhalation Rates** We measured carbon monoxide exposure at both baseline and the six-month follow-up. The measures at the six month follow-up are more reliable because at baseline many of the women received their CO tube after they had already lit their fire. At the six month follow-up, 74% of the households that received CO tubes had yet to light their fire. At baseline 80% of the 189 households monitored over the lunch meal with the CO tube had already started their fire upon arrival. Thus, the baseline measurement period is truncated, upward biasing our results. This is explained by the fact the CO PPM/hour measure is determined by taking the total CO PPM number registered on the tube and dividing this number by the total time the tube was exposed to Carbon Monoxide over the lunch meal. While the CO tube will register the total CO in the air near the cook stove, the truncated time the woman have the tube has the potential to upwardly bias our CO PPM/hour reading. Thus we concentrate on the CO ppm/hour results over the lunch meal at the 6 month follow-up survey.

Because of high humidity levels in the region of study we have followed recommendations from the CO tube manufacturer to adjust our sample uniformly for humidity levels. We do so by multiplying the average CO PPM/hour result by humidity constant. Further, the CO PPM/hour data has been top coded, the top 4% has been brought down to the 95% level.[66] For the CO levels we do not disaggregate households by the three sizes. Instead we include only one household size variable- that of households of size 12 or less. This is due to the smaller sample size receiving the CO tubes.

At the six month follow-up the field team also incorporated a separate CO survey and our enumerators noted that 27% of women had irritated or red eyes from the cooking fire upon their visit. Further, 16% of women had children on their back while cooking. Public health specialists note that pregnant women are at higher risk for adverse birth outcomes such as lower birth weight due to higher levels of exposure to CO and carbon particulate matter.[67] The average age of cooks in our CO sample is 26 years of age (median of 24 years). Thus, given women in our baseline survey have a mean age of 23 and on average report having 3 children, we can induce that women who cook are on average of prime childbearing age for the population. Thus, cutting levels of carbon monoxide inhaled due to cooking would only benefit the health of mothers and their children.

As we show in the impacts section, the average CO PPM/hour inhalation rate is 7.51 over the entire 446 households sampled at the six month follow-up (see Table 8).[68] The World Health Organization cites 25 ppm as the average limit for any 8 hours exposure.[69] Multiplying the 7.51 CO/hour average rate in our sample over the lunch meal times the 6-7 hours daily women report cooking we find women in our sample consume 45-53ppm of CO daily. If we only account for the time during meal preparation our sample reports spending

66 We do not bottom code as this seems inappropriate given that zero has much less error than the top outliers. Thisis because of how the tube is designed. The tube has a much wider scaler length between earlier CO levels such as between 0 and 5 then between 100 and 200. Thus, I topcode the six CO Readings for readings above 200 on the six month follow-up study.

67 See Wong, E et al. (2004)

68 Note in Table 3b the CO PPM/hour level at baseline is significantly higher for both groups-24.60. We believe this is due to a truncation of the hours spent cooking variable and an over-estimation due to measurement error from starting late at the baseline survey.

69 See Penney, D. (1998)

directly next to the fire when cooking, an average of 2.5- 4.5 hours next to the fire; women in our sample consume 19-35 CO ppm daily. Using the higher end estimation of time spent next to the cook fire (4.5 hours), women in our sample consume 140% of the daily recommended CO levels by the WHO. While this estimate is the higher estimate of time spent directly next to the cook fire, it is a middle estimate as women report cooking 6-7 hours daily and this is often in the vicinity of the cooking fire.

**Summary Statistics for Self Reported Respiratory and other Health Symptoms** Only 2% of women in our sample report having no children. From the six month follow-up women over the entire sample report that on average they have given birth to 5 children (median). When asked how many of these children are living on average women report 4 children (median) and thus on average every woman in our sample loses one child.[70] From the six month follow-up we calculate the mortality rate of children under five 115 per 1000 live births.[71] This indicates an overall high burden of disease for children under five in our communities.

To better understand the types of respiratory health risks unique to women we asked women to describe the same 7 respiratory illness symptoms for their husbands at the six month follow-up. The results are telling- on average men suffered between 11-23% less respiratory illness symptoms (see Figure 7).[72] The mean of the 7 symptoms for women from both the treatment and control households is 3.96 (equivalent to reporting 4/7 symptoms on average) while the mean for husbands is 2.63 (equivalent to reporting 3/7 symptoms on average). Thus, women disproportionately suffer from respiratory illness supporting the evidence that there is a direct link between indoor air pollution (IAP) caused by cooking and respiratory illness.

For simplification of data analysis, children's symptoms were aggregated at the household level instead of the individual child level.[73] Thus, number of symptoms per child is averaged over total children reporting symptoms in the household to come up with an aggregated average of the total number of symptoms of all children per household. We do this because we suspect some measurement error between our two surveys. At the baseline survey there are 1.31 times the number of children recorded per household with ARI symptoms (or a 30% increase) in comparison with the number of children recorded at the six month follow-up. We believe this to measurement error because on the baseline survey we had the enumerators refer to the household list the women gave of all the children in the family and ask the woman by child to verify if each of her children suffered the symptoms. For the six month follow-up we did not have access to such a household list and thus there was no way to prompt women to respond for all her children. Thus there is an incentive for women to respond to less than the total number of children in the household and to overlook some

70 Of the total children born to women in the sample, of those who subsequently died, 35% of children were "born dead", 49% of children died between 0-4 years of age; and 15% of children died between 5-25 years of age. Further, because our enumerators were not trained professionals this definition is not strictly consistent with the UN definition of live birth which classifies a child as live if it "shows any evidence of life" outside the womb including "beating of the heart, pulsation of the umbilical cord or definite movement of voluntary muscles".

71 The under five mortality rate observed in our sample of 115 per 1000 live births is only slightly higher than UNICEF's 2008 under five national rate for Senegal of 108 per 1000 live births. Source: UNICEF.

72 T-test results show that Treatment households' husbands had a 95% significant lower level of wheezing and trouble breathing than controls' husbands, and a 99% level significant lower percentage of treatments' husbands coughed up mucus than controls' at the 6 months follow-up. This is seen by the double difference results which show that husbands of control households had on average 0.52% less of the seven symptoms than those associated with treatment households.

73 This is partly because the data matching by child is very labor intensive.

of the children. To account for this bias we average the number of symptoms per child at the household level to get a representative child count of symptoms per household.

Finally, as in fuel use and time spent collecting fuel, we find a seasonal difference across the entire sample for respiratory illness. Women on average have 20% less respiratory illness symptoms in April than in October. This is consistent with the results from number of symptoms of children in our households. Children have an increase in the October six month follow-up survey of 0.64 of 1 symptom versus the baseline survey in April. Thus, both women and children across the both groups, show an increase in symptoms of respiratory illness directly after the rainy season at the six month follow-up. In contrast, the four symptoms associated with cooking- eye irritation, headache, throat irritation, and backache decrease for the entire sample in the October six month follow-up survey when compared to the April baseline survey. Thus, as we would expect, cooking symptoms are not dependent on seasonality and show an overall decrease for the sample between the two survey dates (though this result is not statistically significant).

**The Sample is Balanced** Overall, there are no large differences found between the treatment and the control groups for self reported employment and income proxies (See Table 2 for details)[74]. To approximate wealth we use household structure and find both the treatment and control households have on average the same type of household dwellings. Treatment (control) households report 82% (83%) they have roofs made of tin and 76% (71%) have cement floor with carpet in their houses. Households also report similar levels of consumption of rice and flour per week.[75] The majority of both the control and treatment groups report that their husband is the sole decision-maker about major household purchases. On average married women in both groups report the employment status of their husband as employed (68% Treatment and 67% Control). And both groups report the main employment of their husband to be a driver of both a taxi and/or horse driven carriage (29% Treatment and 27% Control). Further, t-tests on the baseline indicators for household size, wood consumed, time spent collecting fuel, and how long the fuel lasts show no significant difference between the treatment and control group. A significant difference between controls and treatments in the number of people they cook for at baseline is found at the 99% level. Treatment (control) households report cooking for a mean of 13.8 persons (12.7 persons).[76] However, when we run a t-test on the number of persons women report cooking for at the six month follow-up we find that the difference is not significant between the treatment and control groups.[77] Thus, while this difference is unexpected, the results from the t test at the six month follow-up confirm that the sample is balanced. After examining the baseline wood collection and consumption as well as the income and employment characteristics we find no significant differences between the control and

[74] Some small reported differences between the treatment group and control exist-treatments reports being slightly more employed (76%) versus the control group (64%). However, the control group reports slightly more self-employment, 5% higher than the treatment. Further, the woman in the treatment group report earning slightly more per week than the control. However, this is balanced by women in the control group who report receiving slightly more income per week from their husbands than those in the treatment group. When we put together the amount women report earning per week and the amount women report receiving from their husbands, overall women in the control group report earning a little less than a dollar more a week than women in the treatment group.

[75] Control households report consuming slightly less of both than treatments (8% less rice and 4% less flour). However, these are relatively small and insignificant differences.

[76] The significant difference in the mean number of people women cook for between the treatment and control group at baseline may be attributed to the lower number of control households present at the baseline survey and thus the low n could statistically bias the number of people women report cooking for downwards.

[77] See A4.1

treatment group at baseline. We are confident the randomization is successful.

## 4. Estimation Strategy

Because the treatment group has been randomly selected, individuals assigned to the treatment and control groups differ in expectation of core results only through their exposure to the treatment. Analysis of our core study outcomes begins with examining the first and second difference of means between our two groups.

$$\widehat{D} = \left[\hat{E}[Y_1^T|T] - \hat{E}[Y_0^T|T]\right] \qquad \text{First Difference (4)}$$

$$\widehat{DD} = \left[\hat{E}[Y_1^T|T] - \hat{E}[Y_0^T|T]\right] - \left[\hat{E}[Y_1^C|C] - \hat{E}[Y_0^C|C]\right] \qquad \text{Second Difference (5)}$$

In order to convert to percent changes, in the impacts section we standardize by baseline levels. Thus in the example of kilograms of wood used over the lunch meal for the treatment households standardized by the baseline treatment group.

$$First\ Difference = \frac{\left[Wood\ Lunch_{Ti}^{6\ mo.} - Wood\ Lunch_{Tj}^{Baseline}\right]}{Wood\ Lunch_{Tj}^{Baseline}} \qquad (6)$$

We also analyze the core impacts of the stove- fuel use, wood collection time, CO inhalation, and self reported health symptoms using OLS regressions controlling for baseline characteristics (results described below in the data section). The basic regression to test our outcome variables, labeled $Y_i$ and indicating wood use, time spent collecting fuel, CO inhalation, or the mean of 7 respiratory symptoms, can be written:

$$Y_i = \alpha + \beta T + \epsilon_i \quad (3)$$

Here T is a dummy for assignment to the treatment group. Equation (3) can be estimated with ordinary least squares, and as shown in Section 2.3 we have an unbiased estimator.

$$\hat{B}_{OLS} = \hat{E}(Y_i|T) - \hat{E}(Y_i|C) \quad (4)$$

**Estimation Strategy for Wood Used**: The regression analysis for daily wood use can be divided into two main parts. The first set of models includes separately a dummy for treatment and the three subsets of household size- 1). Households with 6 members or less; 2). Households with 7-12 members; 3). Households with 13 members or more. Like all parts of the regression analysis, the models starts simple, adding additional variables with each iteration, and ending with what is known in the literature "the entire kitchen sink" regression. To maintain sample size, we include a dummy for when variables were missing, and impute some variables to their mean[78]. For all the models in part one of our analysis, first we use the y variable as the kilograms of wood used daily, then we run again all the

[78] Variables Imputed to the mean include the following baseline variables: the number of people women report cooking for, the number of people women report cooking for centered and squared, wood-use lunch yesterday, the amount of money spent weekly on wood, the amount of money spent weekly on gas, the amount of money spent weekly on charcoal, the amount of kilograms of rice consumed per person per week, the amount of rice consumed per person per week. Further, at the six month follow-up, explanatory variables included in the estimation which are imputed at the mean include the number of people women report cooking for, the number of people women report cooking for centered and squared, and wood-use lunch yesterday.

models substituting the y variable as kilograms of wood used for the lunch meal. Let T=Treatment; hhsize=household size; and 6 mo.=six month follow-up survey.

$$\text{Part 1, Model 1 (P1.M1)}: WoodKg_{6\,mo.} = \alpha + \beta_1 T + \beta_2\, hhsize6 + \beta_3 hhsize7-12 + \beta_4 hhsize13 + \epsilon_{6\,mo.}$$

Model 2 then replaces the isolated x variable of treatment and the dummy variables indicating households size with interaction variables: 1).treatment*households with 6 members or less; 2). Treatment*households with 7-12 members; 3). Treatment*households with 13 members or more.

$$\text{P1.M2}: Woodkg_{6\,mo.} = \alpha + \beta_1 T * hhsize6 + \beta_2 T * hhsize7-12 + \beta_3 T * hhsize13 + \epsilon_{6\,mo.}$$

Model 3 builds off model two by adding village fixed effects[79]. Model 4 builds off model three by adding Household fixed effects from the baseline survey including: the number of people women report cooking for, the number of people women report cooking for centered and squared, wood-use lunch yesterday, the amount of money spent weekly on wood, the amount of money spent weekly on gas, the amount of money spent weekly on charcoal, the amount of kilograms of rice consumed per person per week, the amount of rice consumed per person per week, three dummy variables dividing women's salary into low, medium, and high, and three dummy variables dividing men's salary into low, medium, and high categories. Model 5 starts with model four and adds the endogenous individual and household fixed effects from the six month follow-up including: the number of people women report cooking for, the number of people women report cooking for centered and squared, the amount of money spent weekly on wood, the amount of money spent weekly on gas, and the amount of money spent weekly on charcoal. Fuel costs for wood, charcoal, and gas were bottom and top coded to control for outliers (top and bottom 5% level to 5% and 95% respectively) as is standard practice to avoid outliers driving the mean.

Part II of the core regression analysis of the impacts of the solar oven on wood used for cooking repeats Models 1-5 from Part I, but this time substituting the explanatory treatment variable with a dummy variable indicating compounds with two or more treatment households or compounds with 2 or more solar ovens. Aside from this substitution, the models in Part II are identical to Part I.

Finally, to test whether the number of people women cook for does not change when she receives a solar oven we run an instrumented variable regression instrumenting the number of people women report cooking for at the six month survey with the number they cook at baseline.

**Time costs collecting fuel and time spent next to the fire** The methodology for measuring the time costs of collecting fuel associated with cooking is similar to that of fuel use. The dependent variable is equal to a household's total wood collection time per week, or both the women respondent's time plus the time of other members of the household. We build model 1 beginning with the explanatory variables singularly as the treatment. In model 2 we substitute the interaction variable of treatment times the three household size and in model

[79] Village fixed effects are captured by creating dummies for each of the 20 villages.

3 we build from model 2 and add the village fixed effects. In model 4, we start from model 3 and add controls for non-endogenous household level effects from the baseline survey including: the number of people women report cooking for, the number of people women report cooking for centered and squared, and the kilograms of wood used for lunch. Model 5 builds from model 4 and includes the endogenous controls from the six month follow-up including the number of people women report cooking for and then this variable centered and squared, as well as baseline time next to the fire.

Models 6-10 use the same format as 1-5, just replacing the treatment dummy by compounds with more than one treatment household (or at least 2 solar ovens). As before in wood use, we run an instrumented variable model for the number of people cooked for. When we run robustness checks on the time spent collecting wood we include the same household characteristics we did for the regression analysis in the amount of wood used. We add the amount of money spent on buying wood per week (CFA), a dummy variable if women share cooking responsibilities, and a dummy variable for missing values for each of these variables. Finally, we repeat this analysis substituting the y variable for the separate measures of time women spent collecting fuel and time other household members spent collecting fuel. The results do not differ for individual accounting versus the accounting as a household unit and thus we choose to display results for total household time spent collecting fuel.

To measure the effects of the solar oven on time women spend next to the cook fire, we follow the exact same estimation strategy as that of fuel collection. The y variable is the time (in minutes) that women report spending next to the cook fire to prepare the daily meals at the six month follow-up.

**Carbon Monoxide Inhalation:** The estimation strategy used for measuring the impacts, if any, on amounts of carbon monoxide inhaled by cooks in our sample is slightly different than the specifications to measure wood use and time costs associated with cooking. The estimation strategy builds as before but includes only one household size-12 persons or less. We do this because our CO sample was a sub-sample of our entire population and thus to preserve n we restrict our household size to just one group 12 or less versus the three groups used previously. The dependent variable is Carbon monoxide CO ppm/hour from the six month follow-up and all models include a constant and error term. Model 1 begins by including only the treatment dummy as the sole explanatory variable. Model 2 includes in its' X variables an interaction variable of the dummy for treatment times the dummy for households with 12 persons or less in household. Model 3, builds from 2, and includes village fixed effects and four adds in addition the number of persons households cooked for at baseline and this variable centered and squared, as well as the amount of kilograms used to cook lunch- all from the baseline survey. Model 5, builds from 4, and adds the endogenous control variables from the six month follow-up of number of people women cook for and this variable centered and squared. Model 6, builds from 5, and adds additional control variables from the baseline survey including the number of hours women report next to the fire. Model 7, builds from 6, and adds additional endogenous control variables from the six month CO survey including the kilograms of wood used daily, the number of hours women report next to the fire, and a dummy variable where one indicates that the woman has not yet lit her fire. Model 8, builds from 7, and aims to test if CO levels vary depending on the type of kitchen women use and includes dummy variables for the four types of kitchens: 1). Kitchen is completely enclosed and has no windows; 2). Kitchen is semi-enclosed with at least one window; 3). Kitchen is a hut; 4). Kitchen is open air. Model 9, builds from 8, and aims to test if CO levels are greater for women who spend more hours by cook fires with poor ventilation and we create interaction variables with kitchen types 1 and 2 above times the amount of time women report spending daily next to the cook fire. Model 10, builds from 9, and aims to uncover if women inhale more CO if they cook with relatively more wood than others. To do so we add the interaction variables for kitchen types 1 and 2 interacted with kilograms of wood used daily from the six month follow-up. Model 11 tests whether there is a greater treatment effect for households which have less ventilated kitchens- kitchen type 1 or 2- and own a solar oven. We do this by adding an interaction variable of treatment times kitchen type 1 and 2. Model 11 is very endogenous as the smokiest kitchens even if they use the solar oven, will likely have the most smoke left given the solar ovens do not replace the use of traditional cook stoves. Finally we run a series of instrumented variable regression where we instrument treatment with a dummy variable from the six month follow-up survey where 1 indicates women were using their solar oven on the day of six month follow-up survey, and 0 represents women observed not using their solar oven. None of these regressions yield statistically significant results for the treatment effect on carbon monoxide inhalation.

**Self reported health symptoms for women and children** As in the other analysis for wood used and time spent collecting fuel, the regression analysis for self reported health symptoms begins simple and builds. As before, to maintain sample size, we include a dummy for when variables were missing, and imputed several values at their mean[80]. The y variable is either a mean number of respiratory symptoms the women reports or a mean number of symptoms she reports of eye irritation, headache, sore eyes and back pain while cooking, both at the six month follow-up. The OLS regressions then begin with a specification which includes a y variables and a dummy for treatment households. Model two adds the interaction variable treatment times households with 12 persons or less to the explanatory variables. Next, model 3 adds village fixed effects. The fourth specification add the household level characteristics at baseline including the number of people women report cooking for, this same variable centered and squared and the kilograms of wood used for lunch. Model five adds the endogenous explanatory variables, as before, the number of people women report cooking for at the six month follow-up and this same variable centered and squared. Next to understand whether the respiratory illness symptoms vary for treatment households that have smaller households we introduce two additional interaction explanatory variables- 1).treatment dummy times number of people women cook for at baseline and 2). Treatment times the number of people women cook for at baseline both centered and squared. Model 7 adds the number of hours women report sitting next to the fire for all three daily meals at baseline and a dummy variable for the primary fuel of the household is gas. Model 8 adds the additional control of the number of symptoms for the respondent at the time of the baseline survey. Model 9 includes the number of respiratory symptoms for the husband. To examine if women report less or more symptoms depending on the type of kitchen (kitchen type 1-4 see CO section), Model 10 adds dummy variables for kitchen types. Finally, model 11 adds endogenous explanatory variable of the daily kilograms of wood used at the six month follow-up.

[80] Additional explanatory variables imputed to their mean include include number of symptoms of respiratory illness for both women and children, daily kilograms of wood used (baseline), number of other symptoms associated with cooking including eye irritation, headache, throat irritation, and back ache.

When we run robustness checks on both sets of self reported health symptoms we include the same household level characteristics as we did in the wood weighing and time spent collecting fuel and we add a dummy variable for the four types of cooking structure a woman cooks in, including 1). Cooking hut is enclosed and has no windows; 2). Cooking hut is semi-enclosed and has at least one window; 3). Cooking hut is open air with a thatch roof; and 4). Cooking is done in the open air. We also include a dummy variable to indicate whether the women enrolled in the program is part of a polygamous household, and a dummy variable for whether she is employed or not. Finally, we run the entire set of regression specifications for each of the seven ARI respiratory symptoms and for each of the four symptoms associated with cooking.

## 5. Impacts

### 5.1 Impacts on Wood Usage, Part A. First and Second Difference Results

To see the impact the solar oven has on wood usage by households we start by analyzing the first difference (see equation 4) between the treatment and control groups' means at the six month follow-up. Next we analyze the double difference (see equation 5) between the two groups' means over the baseline and six month follow-up surveys. Further, as previously noted, given 28% of our intention to treat participant households (209 households) are part of multi-household compounds, we segment our sample further by compounds with more than one study participant per compound. The results from the first and second differencing are in Table 4 and summarized below.

Among households cooking for 12 or fewer at the six month follow-up, treatments use a mean of 9.9 (median of 9) kg of wood daily, while controls used a mean of 10.28 (median of 9.52). The first difference equates to a 4% lower mean (5% lower median) wood used by treatments. Dividing by the number of people women report cooking for at the six month follow-up, treatments use a mean of 1.04 (median of 0.84) kg of wood per person, while controls use 1.12 (median of 0.90) kg of wood per person daily. The first difference equates to a 7% (7% lower median) overall drop in wood kg. per person used daily. This 7% drop in fuel used per person daily is significant at the 95% level (See Table 4).

The double difference of kg. of wood consumed for the lunch meal for households 12 or less shows a 6% drop for average treatment households versus controls (significant at the 95% level). This result is magnified when we divide by the number of people in the household women cook for and the double difference result of kilograms per persons over the lunch meal shows a 14% drop in fuel used, significant at the 95% level.

Dividing the treatment group into treatment households with at least one other treatment study participant in the compound for households cooking for 12 or fewer the mean wood kg daily per person is 0.97 (median 0.80) while control households with only 1 study participant in compound report 1.18 kg (median of 0.94) of wood used per person daily. This is an 18% drop in daily wood used and is significant at the 99% level. As noted our sample was correctly randomized and is balanced and thus the statistically significant first, second and single difference results outlined above are not due to pre-existing baseline differences of wood consumption between the treatments (used 6.81 kg of wood for lunch) and the controls (used 6.68 kg of wood for lunch).

**Part B: Regression Results** Table 8 outlines the core regression results. We find across many specifications, the point estimates lead us to believe there was a decline in wood usage among households that received the solar oven, but the estimated decline was small and not always statistically significant. For the 809 households who weighed the amount of wood used yesterday, the mean was 10.04 kilograms (median 9 kg.). As mentioned we divide our households into three distinct sizes: 1). Households with 6 persons or less which represent 21% of total, 2). Households with 7-12 persons which represent 46% of total, and 3). Households with 13 persons or more which represent 33% of total. Households of size 7-12 persons in the treatment group showed a consistent and statistically significant drop in daily wood use of between 11-13% (see table 8). Treatment households with 7-12 persons and more than 1 treatment participant in the compound show a statistically significant (at the 99% level) drop in wood use between 16-20%. It is consistent for women in households which have more than one solar oven to show a larger drop in wood use because with two solar stoves households of 7-12 persons can feed their entire family.[81] Households of 6 persons or less or 13 and more do not show any statistically significant signs of the treatment effect. These results are consistent with the first, second, and single difference results.

Finally because we are concerned that the number of people a woman cooks for may change when she receives a solar oven, we instrument for the number of people women report cooking for at the six month follow-up with the number they report cooking for at baseline. Our results are consistent with the OLS results.

**Part C: Robustness checks for wood use** In order to ensure our results are robust we use as y variables the wood kilograms (kgs.) used all day yesterday, wood kgs. used all day yesterday per capita, wood kgs. used for the lunch meal, and wood kgs. used per capita over the lunch meal. In all cases, results were similar to those in Table 8. Then we interacted treatment status with a dummy for the size category of households including 6 and under, 7-12 members, and 13 members and higher. Again, results were similar to those reported in Table 7.

To test if changing household size into adult age equivalent has an effect on our results, all the above regression specifications are rerun exactly as before but this time regressions M1 and M2 replace household size with the small, small-medium, medium-large, and large household sizes determined by adult age equivalent.

Part 1 Model 1B :

$$(\text{P1. M1B}): WoodKg_{6\,mo.} = \alpha + \beta_1 T + \beta_2\, Small\ hhld + \beta_3 SmallMed\ hhld + \beta_4 MedLarge\ hhld + \beta_5 Large\ hhld + \in_{6\,mo.}$$

As in the original regression analysis Model 2B then replaces the isolated X variable of treatment and the dummy variables indicating households of the four relevant sizes with interaction variables:

Part 2 Model 2B:

[81] Other explanatory variables that are consistently significant in our regression analysis include village fixed effects, baseline lunch kilograms used for the lunch meal, six month follow-up number of people women cooked for, baseline amount of money spent last week on gas, and the constant.

$$\text{P1. M2B}: Woodkg_{6\,mo.} = \alpha + \beta_1 T * Small\ hhld + \beta_2 T * Small - Med\ hhld + \beta_3 T * Med - Large\ hhld + \beta_3 T * Large\ hhld + \epsilon_{6\,mo.}$$

The same regression specifications are run, as before for the compounds which have more than one treatment in the compound (more than one solar stove in the compound). For compounds with more than one solar stove in the compound the treatment variable is replaced for an indicator variable defining the sub-sample of treatments in a mixed compound.

We find, as before, Model 1B, like Model 1 does not yield any significant results for treatments. Regression results for the treatment variable interacted with adult age equivalent size of household are significant for the small household size or the equivalent of 1.5-4.3 adult age equivalents in the household. Small treatment households show a statistically significant drop (95%) in daily wood use of between -0.44 to -0.40 depending on the specification, or a total of about 4% savings of wood daily. This is approximately two-thirds smaller than the drop seen by households with 7-12 persons in the treatment group seen in Table 8 (or a 11-13% drop in daily wood usage). One possibility is adult age equivalence does not accurately capture the consumption patterns of our households. In particular, the assumption that youth and children under 18 years of age are all uniformly equal to 0.5 while each adult counts 1, seems an oversimplification. In fact, one would most likely expect youth 13-17 to have a consumption pattern near that of adults. One could speculate on the reasons why adult equivalent household size shows a smaller drop in wood use, but it would be difficult to ascertain the veracity of these hypotheses. Instead, we focus on what we understand more fully, that the smallest adult age equivalent households in our sample used the solar oven more and realized a statistically significant drop at the 95% level. The other groupings, medium-small, medium-large, and large interacted with the treatment variables showed no statistically significant reduction in daily wood consumption. This confirms that size is indeed a verifiable obstacle to technology adoption. And in particular that smaller adult age equivalent households do indeed use the stove more often.

**5.2 Impacts on time spent collecting fuel and cooking practices**

Just as in fuel use for cooking, the manner for collecting fuel differs widely by household (see Summary Statistics Section above). At the six month follow-up, families which collect wood report both women and other members of the household each spend about 1 hour/day to collect firewood (see Table 3a). Through first differencing we find that treatment households spend ten minutes less a week than control households collecting wood (see Table 5). This result is statistically significant at the 95% level according to the t-test. The result however represents only a 1% drop in time spent gathering wood, as on average our households spend 2 hours a day collecting fuel. This confirms the solar oven is too small to replace traditional cook stoves and hence does not have a large effect on time spent gathering fuel.

The regression results show no treatment effect on the time costs in collecting fuels. From model specifications 2-5, we find that being a part of the treatment households has a consistently negative coefficient of -5 to -13 minutes saved associated with being a member of a treatment household, though this effect is not statistically significant. When I run models 6-10 for treatment households with more than one treatment in the compound, we find that the interaction variable of two treatments or more in a compound* household size

6 and less persons has a consistently negative sign, though is not significant. Given these results are not statistically significant and not consistent for all household sizes we conclude that there is no statistically significant savings found of time spent collecting wood. Perhaps the 1% drop in time spent collecting fuel observed in the first difference results is just too small to be picked up in our regression analysis. We conclude there is a negligible drop in time spent collecting wood associated with the adoption of the solar oven. Thus, again, because the solar ovens are too small, households are compelled to continue to use contemporaneously the traditional stoves. Thus, the mismatch of the size of the oven to size of households is reflected by the minimal drop in time spent collecting fuel.

**Part B: Robustness checks wood collection** As we believe that our six month follow-up wood collection numbers are more precise than our baseline, we try to minimize any potential measurement error by dividing the time per week women and/or other members of the household report collecting fuel by the amount of time that fuel lasts. As in the wood usage regression results we include village characteristics and household characteristics. We vary the dependent variable in regression models 1-10 to just account for total time spent collecting fuel by respondent or just by other members of the household. However, no matter how we vary the specification of this regression we find that the amount of time spent by treatment households- whether just accounting for women, just accounting for other household members, or accounting for all household members together divided by number of days the wood collected lasts, none of the versions of our regressions are significant. Further, when we replace treatment with treatments with more than one treatment in the compound, our results remain insignificant.

The same robustness checks as outlined above are done on time spent collecting fuel and time spent next to the fire, though no adult age equivalent household size is significant in either of the two models.[82]

**5.3: Time next to the fire** Regression models 1-5 find no statistically significant effect for treatment households and the time women spend next to the cook fire. In models 6-10, compounds with more than one treatment household which have between 7-12 persons do have a consistently statistically significant drop of time spent next to the cook fire that is between 33-42 minutes depending on the regression specification that we run (see Table 8, column 9). This represents about an 18% drop in time spent next to the cook fire for these households.[83] To ensure robustness, we run an additional set of regressions consistent with the estimation strategy of Models 1-10 where we replace the y variable with the first difference of time spent next to the cook fire at the six month follow-up. The results are consistent with our previous results and we find that for compounds with more than one treatment household of the size 7-12 persons, our results are statistically significant at the 99% level. However, for treatment households with only one solar oven in the compound there is no treatment effect. Thus, only households of size 7-12 persons with more than one solar oven in the compound have a statistically significant drop in time spent next to the fire (18%) while the majority of our households with only one solar oven show no treatment effect.

[82] Results are available upon request from author.

[83] 18% is derived by taking the mean of the 2.5-4.5 hours (150-270 minutes) women report spending daily by the cook fire to cook all three meals. Given the mean is 210 using the median from the regression results of 33-42 minutes, or 38 minutes, we find an 18% reduction in average time spent next to the cook fire for women in compounds of 7-12 persons with more than one solar oven.

**5.4: Carbon Monoxide Exposure Part A First Differences** At the six month follow-up survey there is no significant difference in CO exposure over the lunch meal between our treatment and control group (see Table 6). In the six month follow-up survey there are 221 treatment households, 135 control households, and 90 comparison group households who receive the CO tube. The result of the control group plus the comparison group gives us 225 households, while the treatment has 221 households. The mean for the treatment group is 7.92 CO ppm/hour and for the control plus comparison group the mean is 7.11 CO ppm/hour. The 0.80 CO ppm/hour lower exposure of the control group (or 11% difference) is highly insignificant (84% level), (see Table 6). Thus, we conclude that the difference between the two groups is statistically insignificant and there is no treatment effect on the amount of CO ppm inhaled at the six month follow-up.

When we divide our treatment group into households which have at least more than 1 treatment study participant in the compound the mean is CO/ppm of 6.35, much lower than the entire treatment group of 7.92 and the wider control and comparison group average of 7.108. This difference result is borderline significant. Importantly because control households had a high portion of treatment study participants in the compound, the mean for the control households with no other study participants in the compound is 7.58, higher than the total control household average of 6.95. Thus, as we compare treatment households with more than one treatment participant in the household versus control households with only one study participant in the compound, we see the difference between the means of CO/ppm inhaled per hour drops by 16%. However, again here the CO ppm/hour results are not significant. We conclude there is no statistically significant drop in CO inhalation for either of the two groups.

**Part B: Regression Results and Robustness Checks**

For all specifications there is no evidence of a treatment effect on the CO ppm/hour inhaled by women in our sample.[84] To ensure that the results are not biased by including the one category of households of 12 or less, we run Models 1-12 again replacing the interaction variable of treatment times households of 12 persons or less with a second interaction variable- treatment times number of people women report cooking for at baseline. Our results do not change and remain consistently statistically insignificant. Further, we replace the interaction between treatment and households of 12 persons or less with the interaction variable of compounds with two or more treatment households (equivalent to two or more solar ovens) times households of 12 persons or less. We do not find any change in any of the regression specifications 1-12, and our results remain statistically insignificant. We are confident that there is no evidence that treatment households breathe less CO ppm/hour than control households. This result is not surprising given the size mismatch of the solar oven for the households, and women must continue to cook with the traditional stoves while concurrently using the solar oven. Even given our wood usage results indicating that treatment households use 11-13% less wood than treatments, they all light the same numbers of fires and thus because carbon monoxide exposure has a large standard deviation and is interdependent on cooking structure, type of stove used, and how women cook, the reduction in wood usage is too small to observe a treatment effect on CO inhalation among our sample.

[84] The only variables that are at times statistically significantly are some village dummies and the constant.

The same robustness checks as outlined above substituting the adult age equivalence measure of number of people women cook for are carried out on CO inhalation. The same regressions are rerun for the carbon monoxide parts per million per hour replacing the household size variable with the adult age equivalent size of households. As with the daily wood consumption regressions, P1.M1B, similarly the regressions here do not yield any statistically significant results for the treatment group and the adult age equivalent quartiles of household size. However, P2.M2B do show statistically significant results for the X variable treatment households interacted with small adult age equivalent household size at the 95% level between 1.41-1.48 CO PPM/hour. This is a change from the core regression analysis. Given the entire sample has a mean (median) of 7.63 (4.37) of CO PPM/hour consumed the statistically significant increase of 1.41-1.48 for the bottom quartile of adult age equivalent number of people women cook for, represents a 19% increase in CO PPM/hour consumed by treatment households with one solar oven. We rerun the regression results replacing treatment with the sub-sample of treatments with more than one treatment household in the compound (at least two solar stoves in the compound). This result becomes insignificant when we account for households with more than one solar stove in the compound.

The results that small households in the treatment group breathe in statistically more smoke than the other adult age equivalent quartiles is puzzling. One hypothesis is that small households breathe in more CO relative to the other larger age equivalent household size quartiles because they cook for relatively shorter periods. Further, if one believes that a significant portion of the CO inhalation occurs with the lighting of the wood fire (though this is not found in the literature), than the CO ppm/hour variable could likely be biased upwards. Though it is curious why the interaction variable of small age equivalent households in the treatment group in particular would breathe in more CO ppm/hour than those in the control group.

**5.5 Self-Reported Health Impacts Part A: Seasonal Differences**

Seasonal differences between our two surveys account for the 20% increase in respiratory symptoms at the six month follow-up survey versus that of the baseline. This seasonal trend is mirrored in the symptoms among children and thus we conclude that women and children- from both the control and treatment group- are more likely to have symptoms of respiratory illness directly after the rainy season (October) than at the end of the dry season (April/May). This result persists in our regression analysis where consistently the explanatory variable of baseline symptoms has a statistically significant coefficient (at the 99.99% level) of -1, indicating a -1/7 or 14% decline in symptoms at the baseline survey in relation to the six month follow-up. In contrast, the four symptoms associated with cooking- eye irritation, headache, throat irritation, and backache have an overall decrease for the entire sample from the April/May baseline survey to the October six month follow-up survey. Thus, these cooking symptoms which are not dependent on seasonality show an overall decrease for the sample between the two survey dates. This said, the effect is not different for treatments and not statistically significant, leading us to conclude there is no evidence of a treatment effect on non-respiratory four symptoms associated with cooking.

**Part B First Difference Results:** At baseline there is no statistically significant result for the difference in the count of 7 ARI symptoms between the treatment and the control group. However, when we look at the ARI symptoms by symptom we find that treatment households report a statistically significant difference in four of the seven symptoms at baseline. For these four symptoms- throat irritation (17%**), stuffy nose (17%**), wheezing (19%**), and woke up with chest heaviness at night (16%**)- treatment households report a higher incidence of these symptoms than the control households (See Table 7). At the six month follow-up the count of 7 ARI symptoms does not show a statistically significant difference between the two groups. Though, as before when we analyze the first difference between the two groups by individual symptoms, four of the seven symptoms show a statistically significant difference between the two groups at the six month follow-up. For these four symptoms- cough (14%**), wheezing (17%**), chest heaviness (11%*), and coughed up mucus at night (13%*), again treatments have a higher incidence of symptoms than controls. The double difference over the two surveys shows an overall decline in four of the seven symptoms for treatments compared to controls, while two symptoms show increases, and one symptom has neither increased nor declined. This is reflected in Figure 7, which shows the first difference results at the baseline where the treatment group has slightly more respiratory symptoms on average than the control. While at the six month follow-up the control has slightly more respiratory symptoms on average than the treatment. Overall, treatments do not show a statistically significant difference between the count of the 7 ARI symptoms between the baseline and the six month follow-up.

For the four non-respiratory symptoms measured associated with cooking, at baseline, there is a statistically significant difference between the count of the four symptoms for the treatment group than the control- a 10% higher incidence of the four symptoms significant at the 99% level. When we look at the symptoms individually, the treatment group reported consistently small but statistically significant differences for sore eyes-9% greater (99% level); headache while cooking- 5% greater (95% level); irritated throat while cooking- 6% greater (95% level); and back pain while cooking- 8% greater (99%) more than controls. This is consistent with the ARI symptoms at baseline as treatment households report a consistently higher incidence than the controls. However, unlike the ARI symptoms, this difference is statistically significant also at the six month follow-up. At the six month follow-up, treatment households report overall a 6% higher incidence rate of the count of the four symptoms- sore eyes, sore back, headache, and throat irritation- which is statistically significant at the 95% level. The treatments thus show a slight drop from 10% to 6% larger count of non-respiratory symptoms than controls. However, this change is too small to conclude that owning a solar oven had an effect on the four symptoms associated with cooking.

Part B **Regression results** Consistent with the regression analysis for wood kilograms and time spent collecting wood; village dummies were consistently significant at the 95-99% level indicating self reported health varied depending on village level characteristics. When we run the same set of 7 regression results for each of the seven individual symptoms- a total of 49 regressions- only three coefficients are significant. The three symptoms that the coefficients are significant are for the symptoms of cough, wheezing, and coughed up mucus. Consistent with the first difference, these coefficients are all slightly positive for the three regressions which show statistically significant results, indicating treatments had slightly higher levels of incidence of these symptoms than the women in the control group at the six month follow-up. However, because the majority of the regression specifications for the respiratory illness individual symptoms-46 of the 49- are not significant we do not include these results in a table. In particular, neither the count of 7 symptoms between the treatment and control group nor the treatment households with more than 1 solar oven in the compound show a statistically significant difference between the two groups at the six month follow-up. We conclude that owning a solar oven has no effect on the seven ARI symptoms.

Finally in our regression analysis, the explanatory variable the average number of husband's symptoms is consistently positive and statistically significant at the 99.99% level. The coefficient across all the regression specifications is 0.27, indicating that for every 1% increase of average of 7 respiratory symptoms for women there is a little over a quarter of a percent increase for their husbands. This reinforces what we have already seen in the summary statistics that women's husband's have less respiratory symptoms and supports the findings that respiratory illness is linked to cooking.

For the four non-respiratory symptoms associated with cooking, the results of the regression analysis show only one of the seven specifications where the results are statistically significant and positive. However, because the majority of the regression results are insignificant- 6/7 for the treatment households and all 7/7 of the regression specifications with more than one treatment household in the compound- we conclude that like the 7 ARI symptoms- there is no treatment effect of owning a solar oven on the incidence of the four symptoms associated with cooking.

Consistent with the ARI symptom results, the husband's count of respiratory symptoms as an explanatory variable is statistically significant at the 99% level for all the specifications and the coefficient is positive ranging between .09-.1. This indicates that women's combined symptoms of eye irritation, headache, sore eyes, and back ache while cooking are positively correlated with the husband seven respiratory symptoms. Finally, cooking in an open hut with a thatch roof is negative and statistically significant at the 95% level indicating women who cook in an open hut with a thatch roof are statistically less likely to have symptoms of eye irritation, headache, sore eyes and/or back ache. This supports the hypothesis that simply by changing how women cook they may be able to mitigate some symptoms from cooking. These results suggest an education component should be included on the dangers of cooking and simple solutions in future improved stoves projects.

We find no significant differences between the treatment and control group in the odds of having any of the reported symptoms for both respiratory illness or other symptoms associated with cooking. This is not surprising given our colleagues in the RESPIRE study only found a drop in both symptoms of sore eyes and headache when they found a corresponding significant drop in CO levels between the treatment and the control group. Thus, given we the non-respiratory symptoms are correlated with respiratory symptoms, we are not surprised that there are no significant changes with the introduction of our solar oven to households. Further, because of size constraints households continue to use the traditional three stone fire and there is no drop in CO levels.

## Conclusions

The successful randomization of our sample indicates that all the statistically significant results can be attributed to the treatment effect. The more than doubling of usage from the first (9%) to the sixth month (19%) as shown by the SUMs can be attributed at least partially to the result of intensive ongoing village training by stove specialists and highlights the importance of training in facilitating behavior change. Another possible explanation for the increase in usage is that it takes time for households to adapt to using the solar oven regularly.

The SUMs proved critical in measuring objective stove usage. Solar oven users at the six month follow-up report using their solar oven 38%, or double the SUM-measured usage rate of 19%. When we observed stove usage at the six month follow-up, for the 17 of the 20 in villages where the weather was sunny, we found 61% of women were using their solar ovens– or more than 3 times the actual usage rate. There is clearly a role for SUM's in future studies.

For wood use, households of size 7-12 persons in the treatment group showed a consistent and statistically significant drop in daily wood use of between 11-13%. Treatment households with 7-12 persons and more than 1 treatment participant in the compound show a statistically significant (at the 99% level) drop in wood use between 16-20%.

For time spent collecting fuel there is no statistically significant savings found in our OLS regression analysis for treatment households. Though we do find a 1% decrease in the average time the treatment households spend collecting fuel in our first difference results. There is no evidence that treatment households breathe less CO ppm/hour than control households. These results are not surprising given nearly 80% of our households report cooking for 7 persons or more and when we substitute adult age equivalent results 42% of these households have a size greater than 6. A large portion of women continue to cook with the traditional stoves while concurrently using the solar oven. While there is no evidence the solar oven decreases CO ppm inhaled by women in our treatment group, we find our sample breathes in 140% of the daily recommended level of CO ppm. This is roughly equivalent to smoking 8 cigarettes a day.

For respiratory symptoms, overall, treatments do not show a statistically significant difference for the count of the 7 ARI symptoms between the baseline and the six month follow-up. However, for both groups, women's husbands are 11-23% less likely to report any of the seven symptoms associated with respiratory illness. This is an important indicator that women who have the sole responsibility to cook, and their children which accompany them, face larger risks for respiratory illness than their husbands who share the same households. For the other symptoms associated with cooking, treatment households report at the six month follow-up an overall 6% higher incidence rate of the count of the four symptoms- sore eyes, sore back, headache, and throat irritation- which is statistically significant at the 95% level. However, as the treatment had a higher incidence of the four symptoms that were associated with cooking at both the baseline and the follow-up survey we conclude that there is no evidence of a treatment effect.

Finally in our regression analysis, the explanatory variable the average number of husband's symptoms is consistently positive and statistically significant at the 99.99% level. The coefficient across all the regression specifications is 0.27, indicating that for every 1% increase of average of 7 respiratory symptoms for women there is a little over a quarter of a percent increase for their husbands. This reinforces what we have already seen in the summary statistics that women's husband's have less respiratory symptoms and supports the findings that respiratory illness is linked to cooking.

Overall, the statistically significant drop in wood use for treatment households is not mirrored in the other outcome indicators- time spent collecting wood, CO inhalation, or self reported respiratory illness. Because the solar ovens are often too small, most households continue to use contemporaneously the traditional stoves to cook all meals. This dampens the treatment effect significantly on all outcome indicators.

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# Contents for Tables, Figures and Appendices

| Table 1: Sample Size and General Attendance on Survey Day | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Randomized treatment | Randomized control | Total intention to treat | Treatment with at least one other treatment in compound | Control with at least one other treatment in compound | Only one control in compound |
| Number receiving lottery ticket | | 488 | 472 | 960 | 184 | 117 | 355 |
| Baseline survey | Original respondent | 430 | 305 | 735 | 168 | 89 | 257 |
| | Absent, but returned at follow-up | 4 | 104 | 108 | 2 | 22 | 82 |
| | Original respondent absent, but another woman in compound responded for her | 35 | 22 | 57 | 14 | 6 | 16 |
| | Total who completed survey | 465 | 327 | 792 | 182 | 95 | 273 |
| Baseline wood weighing | Yes | 438 | 298 | 736 | 170 | 78 | 220 |
| | No, cook with gas | 19 | 17 | 36 | 1 | 3 | 14 |
| | No, took survey but left before wood weighing | 27 | 29 | 56 | 12 | 17 | 53 |
| Six month follow-up survey | Withdrew from study | 32 | 8 | 40 | 0 | 0 | 0 |
| | Absent at six month follow-up | 8 | 11 | 19 | 0 | 10 | 1 |
| | Original respondent | 246 | 230 | 476 | 72 | 50 | 135 |
| | Original respondent absent but another woman in compound responded for her | 224 | 206 | 430 | 95 | 53 | 153 |
| | Total who Completed Survey | 470 | 436 | 906 | 167 | 103 | 288 |
| Six month follow-up wood weighing | Yes | 419 | 391 | 810 | 167 | 103 | 288 |
| | No, cook with gas | 47 | 47 | 94 | 8 | 8 | 39 |
| Six month follow-up | Sub-sample CO tube | 221 | 136 | 452 | 86 | 32 | 104 |

*= A comparison group of 90 women who were neither treatments or controls also had CO tubes at the 6-month follow-up and are included in the analysis in addition to the 136 randomized control group making 226 non-treatments.

| Table 2: Summary Statistics on Age, Gender, Education, Income and Employment | | | | | | |
|---|---|---|---|---|---|---|
| | Total Sample | | Treatment | | Control | |
| | N | average | n | average | n | average |
| Average Age for All Household Members | 13,080 | 18 * | 6799 | 18* | 4392 | 18* |
| Gender female | 7231 | 53% | 3751 | 54% | 2367 | 53% |
| Portion of sample with no education | 8819 | 65% | 4562 | 65% | 2853 | 63% |
| Portion of women inscribed in program with no education | 835 | 78% | 415 | 76% | 285 | 78% |
| Woman respondent is employed | 953 | 69% | 477 | 76% | 336 | 64% |
| Among women employed occupation is housework | 302 | 84% | 127 | 83% | 117 | 85% |
| Woman's daily salary[1] (US$) | 484 | $1.55 | 279 | $1.75 | 156 | $1.38 |
| Woman respondent is self employed | 797 | 89% | 413 | 87% | 275 | 92% |
| Among women employed who report not being paid for work | 265 | 51% | 137 | 45% | 94 | 53% |
| Husband is employed | 892 | 83% | 448 | 82% | 311 | 86% |
| Among husbands' employed whose occupation is driver, which includes both a taxi and horse drawn carriage | 678 | 28% | 332 | 29% | 240 | 27% |
| Husband who are self-employed | 760 | 68% | 384 | 68% | 265 | 67% |
| Husbands who are employed who report receiving a monthly salary | 371 | 57% | 192 | 59% | 132 | 57% |
| Amount women report their husband's provide for them to purchase household items daily[1] (US$) | 740 | $2.87 | 375 | $2.72 | 260 | $3.17 |
| Average kg/week of flour your family consumes | 945 | 3.13 | 472 | 3.21 | 334 | 2.97 |
| Average kg/week of rice your family consumes | 577 | 3.08 | 294 | 3.07 | 200 | 2.94 |
| Portion of household decision maker designated as husband | 935 | 57% | 466 | 56% | 329 | 61% |
| Material of the roof of the house of the respondent identified as tin | 948 | 82% | 474 | 82% | 277 | 83% |
| Portion of respondent's whose home have a floor other than dirt | 948 | 95% | 474 | 96% | 334 | 95% |
| Portion of respondents who report their home has a cement floor with carpeting | 854 | 74% | 428 | 78% | 310 | 71% |
| * indicates the median; All data for this table is from the baseline survey, collected April 2008. | | | | | | |

[1] The exchange rate in 2008 is fixed at 500 CFA/$1 USD though this is not perfectly accurate as the U.S. Treasury Annual Exchange rate is 436 CFA/$1 USD.

| Table 3a: Summary Statistics Baseline | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Overall | | Treatment | | Control | | Treatment-Control |
| | Mean (s.d) | Obs. | Mean (s.d.) | Obs. | Mean (s.d.) | Obs. | Mean Percent Change (s.e.) |
| Household Characteristics | | | | | | | |
| # in household | 11.74 (7.73) | 930 | 11.94 (7.54) | 486 | 11.53 (7.92) | 444 | 4% (0.51) |
| # cooked for yesterday | 13.40 (6.49) | 772 | 13.80 (6.70) | 459 | 12.77 (6.13) | 313 | 8% (0.46)* |
| #cooked for squared | 42.10 (87.76) | 772 | 45.01 (90.90) | 459 | 37.84 (82.94) | 313 | 19% (6.26) |
| Fuel use | | | | | | | |
| Wood used yesterday at lunch (from wood weighing in kg.) | 6.75 (2.50) | 737 | 6.80 (2.45) | 439 | 6.70 (2.61) | 298 | 1% (0.19) |
| Total time (minutes) preparing 3 meals/day | 294.57 (113.39) | 696 | 297.69 (111.40) | 402 | 290.31 (116.11) | 294 | 3% (8.62) |
| Total time (minutes) next to cook fire in preparing 3 meals/day | 176.7 (120.42) | 839 | 179.16 (121.09) | 484 | 173.37 (119.58) | 355 | 3% (8.04) |
| Time spent (minutes) by woman respondent collecting fuel per collection period (# of days fuel lasts) | 77.19 (53.50) | 363 | 77.85 (53.29) | 210 | 75.28 (53.49) | 153 | 3% (5.60) |
| Time spent (minutes) by other household members collecting fuel per collection period (# of days fuel lasts) | 80.95 (55.81) | 350 | 80.18 (54.69) | 206 | 82.06 (57.55) | 144 | -2% (6.00) |
| Days in average collection period | 3.97 (5.60) | 477 | 3.86 (5.20) | 277 | 4.13 (6.11) | 200 | -7% (0.52) |
| * p<0.05, ** p<0.01, *** p<0.001 | | | | | | | |

## Table 3b. Summary Statistics Baseline

| Self Reported Health for Women and Children and Carbon Monoxide Inhalation over the Lunch Meal | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Overall | | Treatment | | Control | | Treatment- Control |
| | Mean (s.e) | Obs. | Mean (s.e.) | Obs. | Mean (s.e.) | Obs. | Mean Percent Change (s.e.) |
| Count of 4 problems while cooking (sore eyes, sore back, headache, throat irritated) | 3.03 (1.49) | 774 | 3.15 (1.40) | 444 | 2.87 (1.60) | 330 | 10%** (0.11) |
| Count of 7 symptoms for self (Symptoms include: fever; sore throat; runny or stuffy nose; cough; wheezing; woke up with chest heaviness; coughed up mucus | 3.22 (2.73) | 852 | 3.33 (2.71) | 484 | 3.08 (2.76) | 368 | 8.% (0.19) |
| Carbon monoxide CO PPM/hour for subset of cooks | 24.60 (15.04) | 176 | 25.57 (16.16) | 115 | 22.78 (12.60) | 61 | 12.25% (2.17) |
| Count of 4 symptoms for children (Symptoms: include cough; coughed up mucus; runny or stuffy nose; and wheezing | 2.57 (1.06) | 614 | 2.60 (1.03) | 328 | 2.53 (1.10) | 286 | 2.77% (0.09) |
| Percent of women who report their children are present when they cook | 0.74 (0.44) | 719 | 0.73 (0.45) | 372 | 0.76 (0.43) | 347 | -4% (0.03) |
| Percent of women with children on their back when they cook | 0.40 (0.49) | 696 | 0.43 (0.50) | 360 | 0.38 (0.48) | 336 | 13% (0.04) |
| Percent of women who report their children play near fire while they cook | 0.32 (0.47) | 696 | 0.32 (0.47) | 360 | 0.32 (0.47) | 336 | 0% (0.04) |
| Baseline self reported other symptoms associated with cooking | | | | | | | |
| | Overall | | Treatment | | Control | | Treatment- Control |
| | Mean | Obs. | Mean | Obs. | Mean | Obs. | |
| Sore eyes while cooking | 82% | 875 | 87% | 447 | 78% | 428 | 9%** |
| Headache while cooking | 70% | 960 | 72% | 488 | 67% | 472 | 5%* |
| Irritated throat while cooking | 69% | 960 | 72% | 448 | 66% | 472 | 6%* |
| Back pain while cooking | 67% | 960 | 71% | 488 | 63% | 472 | 8%** |
| Baseline Individual ARI Symptoms for Women | | | | | | | |
| Symptom 1: fever | .50 | 960 | .51 | 488 | .48 | 472 | 6% |
| Symptom 2: throat irritated | .35 | 960 | .38 | 488 | .32 | 472 | 17%** |
| Symptom 3: stuffy nose | .48 | 960 | .52 | 488 | .44 | 472 | 17%** |
| Symptom 4: cough | .45 | 960 | .45 | 488 | .45 | 472 | 0% |
| Symptom 5: wheezing | .43 | 960 | .47 | 488 | .39 | 472 | 19%** |
| Symptom 6: woke up with chest heaviness at night | .49 | 960 | .53 | 488 | .45 | 472 | 16%* |
| Symptom 7: coughed up mucus | .42 | 960 | .44 | 488 | .42 | 472 | 5% |

* p<0.05, ** p<0.01, *** p<0.001 (Yes includes both the responses for symptom occurs either sometimes or always while cooking)

| Table 4: First and Double Differences over the Lunch Meal Kilograms of Wood Used[2] | | |
|---|---|---|
| (The six month follow-up-Baseline) / Baseline | Wood used at the lunch meal (kg.) in households and compounds with 12 persons and under (Std. error) | Wood used at the lunch meal (kg/pp) in households and compounds with 12 persons and under |
| Average over all groups (N= 841, Std error 1.6) | -18% | 1% |
| Treatment (N=439, Std error 1.6) | -20% | 0% |
| Control (N=298, Std error 1.6) | -14% | 14% |
| Treatment with at least 1 other treatment study participant in compound (N=170, Std. error 1.6) | -19% | 5% |
| Treatment with only 1 study participant in compound (N=269, Std. error 1.6) | -20% | -2% |
| Control with at least one other treatment study participant in compound (N=78, Std. error 1.5) | -12% | 8% |
| Control with only 1 study participant in compound (N=220, Std. error 1.6) | -14% | 0% |
| **Double Difference Results** | | |
| Treatment minus control | -6% (*) | -14%(*) |
| At least 2 treatment study participants in 1 compound minus control | -5% | -10%(**) |
| At least 2 treatment study participants in 1 compound minus control with only 1 study participant in compound | -5%(*) | 5%(**) |
| Control with at least 1 treatment household in compound minus control | 2% | -6% |
| **Single Difference Daily Wood Usage Six month follow-up** | | |
| (The six month follow-up minus baseline) / baseline | Wood used daily (kg) for households and compounds with 12 persons and less | Wood used daily (kg/pp) for households and compounds with 12 persons and less |
| Treatment (N=418) minus control (N=391) | -4% | -7% (*) |
| At least 2 treatment study participants in 1 compound (N=167) minus control (N=391) | -2% | -13%(**) |
| At least 2 treatment study participants in 1 compound (N=167) minus control with only 1 study participant in compound (N=103) | -2% | -18%(**) |
| Control with at least 1 treatment household in compound(N=103) minus control(N=391) | 5% | -13%(**) |
| ** (*) = statistically significant difference in one-sided t-test at the 1% (5%) level. Note: All data has been top and bottom coded at the 5% level. | | |

[2] Note that the first differences are taken such that the denominator of the first difference equation changes along with the sub-group. I.E. take for example the sub-group of mixed compounds with at least two treatment households. Here the denominator will be Baseline Wood Weighed for the sub-group with two treatments. I choose to vary the denominator along with the sub-group instead of fixing the wider baseline control group to avoid results being biased by differences in baseline wood weighing between the sub-group and the wider control group.

**Table 5: First Differences in Time Spent Collecting Wood**

| | | | Mean | Median | Std. Dev | N | Difference in means |
|---|---|---|---|---|---|---|---|
| | Total Intention to Treat Sample | | minutes | | | | (treat (a) – Control (a)) |
| | | Woman | 159.46 | 150 | 48.53 | 405 | |
| | | Rest of Hhld | 160.36 | 150 | 52.6 | 321 | |
| Treat (a) | Treatment | Woman | 158.91 | 150 | 45.07 | 188 | 0.1 |
| | | Rest of Hhld | 157.07 | 150 | 49.71 | 148 | -9.81(*) |
| Control (a) | Control | Woman | 158.81 | 150 | 49.99 | 171 | |
| | | Rest of Hhld | 166.88 | 150 | 56.03 | 135 | (Treat (b)- Control (c) |
| Treat (b) | Treatment households which are part of compounds with at least 2 treatment study participants | Woman | 155.9 | 150 | 47.91 | 76 | -0.28 |
| | | Rest of Hhld | 155.14 | 150 | 48.6 | 64 | -11.99 |
| Control (c) | Control households which have only 1 study participant in the compound | Woman | 156.18 | 150 | 50.13 | 126 | |
| | | Rest of Hhld | 167.13 | 150 | 59.71 | 150 | |

** (*) = statistically significant difference in one-sided t-test at the 1% (5%) level
All data is from the six month follow-up study which took place in October 2008.

**Table 6: First Difference in CO PPM/hour (top coded)**

| | | Mean | Median | Std. Dev | N | Difference in means |
|---|---|---|---|---|---|---|
| | Overall | 7.512 | 4.075 | 8.854 | 446 | (treat (a) – Control (a)) |
| Treat (a) | Treatment | 7.923 | 4.478 | 9.049 | 221 | 0.969 (+14%) |
| Control (a) | Control | 6.954 | 3.75 | 8.973 | 135 | (treat (a)- Control + Compare Group (b)) |
| Control (b) | Control + Compare Group | 7.108 | 4 | 8.658 | 225 | 0.815 (+11%) |
| Treat (b) | Treatment households which are part of compounds with at least 2 treatment study participants | 6.352 | 3.846 | 7.082 | 85 | (Treat (b)- Control (d) |
| Control (c) | Control households which are part of compounds with at least 1 treatment study participant | 7.374 | 4.298 | 8.344 | 52 | -1.226 (-16%) |
| Control (d) | Control households which have only 1 study participant in the compound | 7.578 | 4.037 | 9.794 | 103 | (Treat (b)- Control + Compare (e)) |
| Control (e) | Control + Compare households which have only 1 study participant in the compound | 7.186 | 4.027 | 8.524 | 169 | -0.834 (-12%) |

Notes: ** (*) = statistically significant at the 1% (5%) level

| Table 7: Respiratory Illness Symptoms in Women and Children and Other Symptoms Women Report while Cooking | | | | | |
|---|---|---|---|---|---|
| Symptom | Treatment | | Control | | Difference (Treatment- Control) |
| | Mean (s.e.) | Obs. | Mean (s.e.) | Obs. | Mean Percent Change |
| # of 4 problems while cooking (sore eyes, sore back, headache, throat irritated) | 2.85<br>1.55 | 488 | 2.69<br>1.65 | 472 | 6%* |
| # of 7 symptoms for self (Symptoms include: fever; sore throat; runny or stuffy nose; cough; wheezing; woke up with chest heaviness; and coughed up mucus | 3.94<br>2.78 | 488 | 3.58<br>2.75 | 472 | 10% |
| # of 4 symptoms for children (Symptoms include cough; Coughed up mucus; Runny or stuffy nose; and Wheezing | 3.24<br>0.39 | 488 | 3.19<br>0.35 | 472 | 2% |
| First Difference in Symptoms Associated with Cooking | | | | | |
| | Mean | Obs. | Mean | Obs. | Percentage Point Change |
| Sore eyes while cooking (%) | 78% | 488 | 74% | 472 | 4%* |
| Headache while cooking (%) | 74% | 488 | 69% | 472 | 5% |
| Irritated throat while cooking (%) | 70% | 488 | 65% | 472 | 5% |
| Back pain while cooking (%) | 63% | 488 | 61% | 472 | 2% |
| Double Difference of Symptoms Associated with Cooking | | | | | |
| Sore eyes while cooking (%) | 9% | 447 | 4% | 428 | 5% |
| Headache while cooking (%) | -2% | 488 | -2% | 472 | 0% |
| Irritated throat while cooking (%) | 2% | 448 | 1% | 472 | 1% |
| Back pain while cooking (%) | 8% | 488 | 2% | 472 | 6% |

| First Difference of Respiratory Illness Symptoms | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Overall | | Treatment | | Control | | Percentage Point Change |
| Symptom 1: fever | .72 | 960 | .73 | 488 | .71 | 472 | 3% |
| Symptom 2: throat irritated | .41 | 960 | .42 | 488 | .41 | 472 | 2% |
| Symptom 3: stuffy nose | .57 | 960 | .59 | 488 | .54 | 472 | 9% |
| Symptom 4: cough | .58 | 960 | .62 | 488 | .54 | 472 | 14%** |
| Symptom 5: wheezing | .46 | 960 | .50 | 488 | .42 | 472 | 17%** |
| Symptom 6: woke up with chest heaviness at night | .54 | 960 | .57 | 488 | .51 | 472 | 11%* |
| Symptom 7: coughed up mucus | .48 | 960 | .51 | 488 | .45 | 472 | 13%* |

| Double Difference | | | | | |
|---|---|---|---|---|---|
| | Treatment | | Control | | Treament(a)-Control(a) |
| Symptom 1: fever | 0.22 | 488 | 0.23 | 472 | -1% |
| Symptom 2: throat irritated | 0.04 | 488 | 0.09 | 472 | -5% |
| Symptom 3: stuffy nose | 0.07 | 488 | 0.10 | 472 | -3% |
| Symptom 4: cough | 0.17 | 488 | 0.09 | 472 | 8% |
| Symptom 5: wheezing | 0.13 | 488 | 0.03 | 472 | 0% |
| Symptom 6: woke up with chest heaviness at night | 0.04 | 488 | 0.06 | 472 | -2% |
| Symptom 7: coughed up mucus | 0.07 | 488 | 0.03 | 472 | 4% |

Notes: ** (*) = statistically significant at the 1% (5%) level; The percent represents the population which responded experiencing the symptom both always and sometimes over the last week.

| Table 8: Regression Results Wood Consumption & Time Woman Spends Next to Fire | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Coefficient (standard error) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Dependent variable for models 1-8: Six Month Follow-up Daily Kg. of Wood used Yesterday; Dependent Variable for Model 9: Six Month Follow-up Total Time Woman Reports Spending Directly Next to Fire in Preparation of Cooking All Three Daily Meals | | | | | | | | | |
| Six month no. people cook for is 6 persons or less *Treatment indicator | 0.47 (0.72) | 0.43 (0.66) | 0.45 (0.66) | 0.50 (0.66) | | | | | |
| Six month no. people cook for is 7-12 persons *Treatment indicator | -1.34 (0.47)** | -1.17 (0.43)** | -1.10 (0.44)* | -1.10 (0.44)* | | | | | |
| Six month no. people cook for is 13 persons or more *Treatment Indicator | 0.03 (0.55) | -.19 (0.50) | -0.39 (0.50) | -0.37 (0.50) | | | | | |
| Six month no. people cook for 6 persons or less * Two or more treatments in 1 compound indicator | | | | | 1.16 (1.15) | 1.37 (1.07) | 0.72 (1.06) | 0.69 (1.06) | 15.17 (29.70) |
| Six month no. people cook for is 7-12 persons *Two or more treatments in 1 compound indicator | | | | | -2.00 (0.63)** | -1.58 (0.60)** | -1.65 (0.60)** | -1.64 (0.60)** | -40.84 (16.55)* |
| Six month no. people cook for is 13 persons or more *Two or more treatments in 1 compound indicator | | | | | 1.64 (0.67)* | 1.41 (0.62)* | 1.14 (0.61) | 1.05 (0.61) | -3.55 (16.92) |
| Six month no. people cook for is 6 persons or less | -1.50 (1.10) | -1.05 (1.01) | -1.07 (0.99) | 0.12 (1.11) | -1.41 (1.05) | -1.00 (0.96) | -0.95 (0.95) | 0.20 (1.08) | 17.70 (20.63) |
| Six month no. people cook for is 7-12 persons | 0.25 (1.04) | 0.46 (0.94) | 0.46 (0.93) | 0.83 (0.93) | -0.12 (1.01) | 0.11 (0.92) | 0.16 (0.90) | 0.50 (0.91) | 21.97 (13.39) |
| Six month no. people cook for is 13 persons or more | 2.12 (1.06)* | 1.68 (0.97) | 1.50 (0.95) | 0.30 (1.06) | 1.78 (1.02) | 1.28 (0.93) | 1.04 (0.92) | -0.07 (1.03) | 21. 71 (18.84) |
| Village fixed effects | | Yes*** | Yes*** | Yes*** | Yes*** | Yes*** | Yes*** | Yes*** | Yes*** |
| Baseline no. of people for whom woman prepared lunch | | | 0.04 (0.04) | 0.03 (0.00) | | | 0.04 (0.04) | 0.03 (0.04 | 0.63 (0.93) |
| Baseline no. of people for whom woman prepared lunch, centered[2] | | | 0.00 (0.00) | 0.00 (0.00) | | | 0.00 (0.00) | 0.00 (0.00) | 0.05 (0.06) |
| Baseline lunch kg. of wood used | | | 0.29 (0.08)*** | 0.27 (0.08)*** | | | 0.29 (0.08)*** | 0.27 (0.08)** | -1.09 (2.20) |
| Baseline amount of money spent last week on wood a | | | 0.00 (0.00) | 0.00 (0.00) | | | 0.00 (0.00) | 0.00 (0.00) | 0.06 (0.07) |
| Baseline amount of money spent last week on charcoal a | | | 0.00 (0.00) | 0.00 (0.00) | | | 0.00 (0.00) | 0.00 (0.00) | |
| Baseline amount of money spent last week on gas a | | | 0.00 (0.00)* | 0.00 (0.00)* | | | 0.00 (0.00)* | 0.00 (0.00)* | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Baseline kg of flour consumed per capita per week | | | 2.31<br>(1.57) | 1.63<br>(1.60) | | | 1.97<br>(1.57) | 1.34<br>(1.60) | |
| Baseline kg. of rice consumed per capita per week | | | 1.22<br>(0.90) | 1.08<br>(0.90) | | | 1.43<br>(0.90) | 1.29<br>(0.89) | |
| 2). Medium tercile: dummy woman's salary ($0.01-$6.00);[a] | | | 0.02<br>(0.35) | -0.04<br>(0.35) | | | -0.08<br>(0.35) | 0.12<br>(0.35) | |
| 3). Highest tercile: dummy woman's salary( $6.01-Max)[a] | | | 0.18<br>(0.40) | 0.08<br>(0.40) | | | 0.09<br>(0.39) | 0.01<br>(0.39) | |
| 2). Medium tercile: husband contributed $1-$21 | | | -0.46<br>(0.34) | -0.43<br>(0.34) | | | -0.60<br>(0.33) | -0.56<br>(0.33) | |
| 3). Highest tercile: husband contributed $22-Max | | | -0.29<br>(0.43) | -0.35<br>(0.42) | | | -0.38<br>(0.42) | -0.43<br>(0.42) | |
| Six month follow-up # of people woman prepared lunch for yesterday | | | | 0.18<br>(0.08)* | | | | 0.17<br>(0.08)* | |
| Six month follow-up # of people woman prepared lunch for yesterday, centered$^2$ | | | | -0.01<br>(0.00) | | | | -0.00<br>(0.00) | |
| Six month follow-up amount of money spent last week on wood | | | | 0.00<br>(0.00) | | | | 0.00<br>(0.00) | |
| Six month follow-up amount of money spent last week on charcoal | | | | -0.01<br>(0.00) | | | | -0.00<br>(0.00) | |
| Six month follow-up amount of money spent last week on gas | | | | 0.01<br>(0.00) | | | | 0.00<br>(0.00) | |
| Baseline amount of time woman reports spending directly next to fire in preparation of cooking all three daily meals | | | | | | | | | 0.03<br>(0.03) |
| Constant | 9.79<br>(0.98)*** | 13. 15<br>(1.08)*** | 7.40<br>(1.50)*** | 5.57<br>(1.87)** | 9.80<br>(0.98)*** | 13.08<br>(1.08)*** | 7.55<br>(1.50)*** | 5.99<br>(1.87)** | 199.78<br>(32.50) |
| $R^2$ | 0.09 | 0.28 | 0.32 | 0.33 | 0.10 | 0.28 | 0.32 | 0.33 | 0.08 |
| Observations | 809 | 809 | 809 | 809 | 809 | 809 | 809 | 809 | 941 |

Notes: ** (*) = statistically significant at the 1% (5%) level; †= statistically significant at the 10% level. Dependent variables are compressed to the 5th and 95% percentiles

a. As is normal proceedure for dummy variables one of the three income variables is dropped. The lowest tercile for both 1). Lowest Tercile of woman's salary: Dummy Woman reports no salary (Salary=0) and 2). Lowest tercile of Amount the Husband Gave to Wife Last Week for Household Expenditure in Tercile or the Husband gave no income ($0) is dropped.

**Figure2: Solar stove project study region and sample villages**

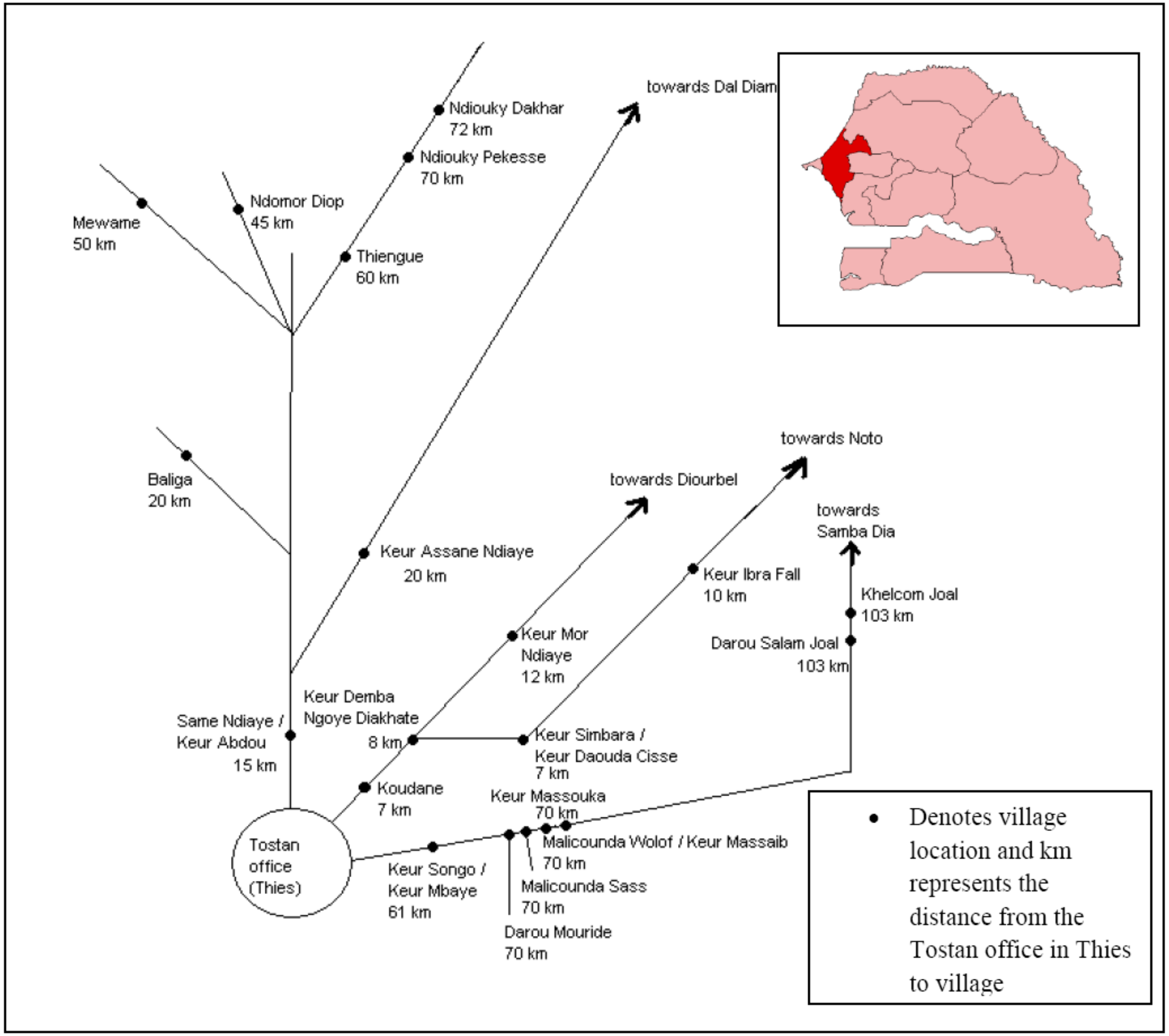


**Figure 3: Percent of households using solar oven in treatment group on day of household visit at the six month survey, conditional that weather was sunny.**

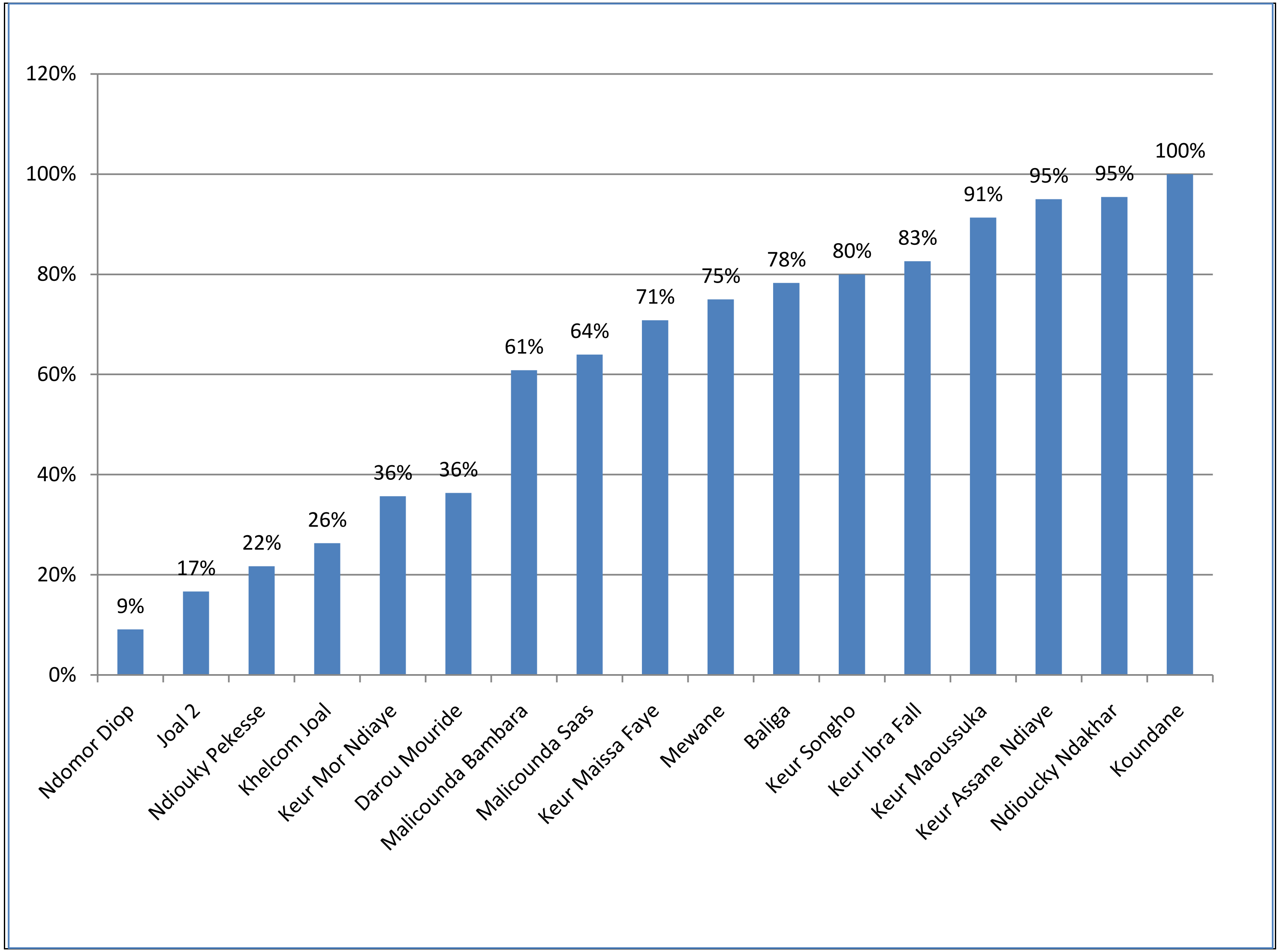


**Figure 4: Cooking hut for women cooks who participated in the Carbon Monoxide survey and sub-sample at the six month follow-up (N=367 households).**

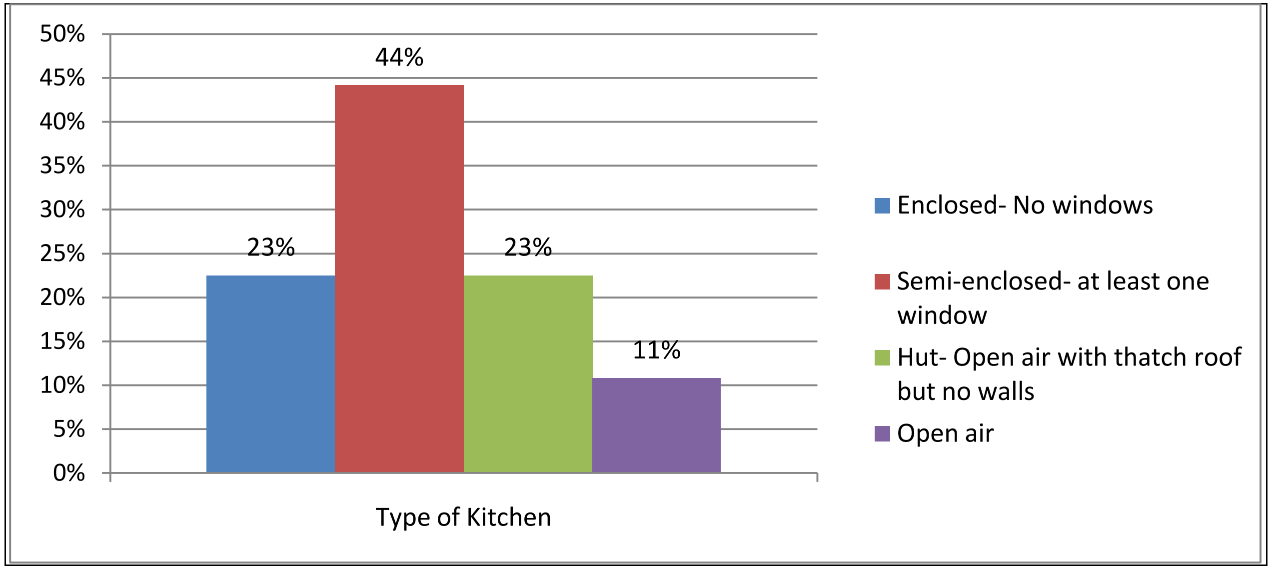



**Figure 5: Number of households who report buying fuel**

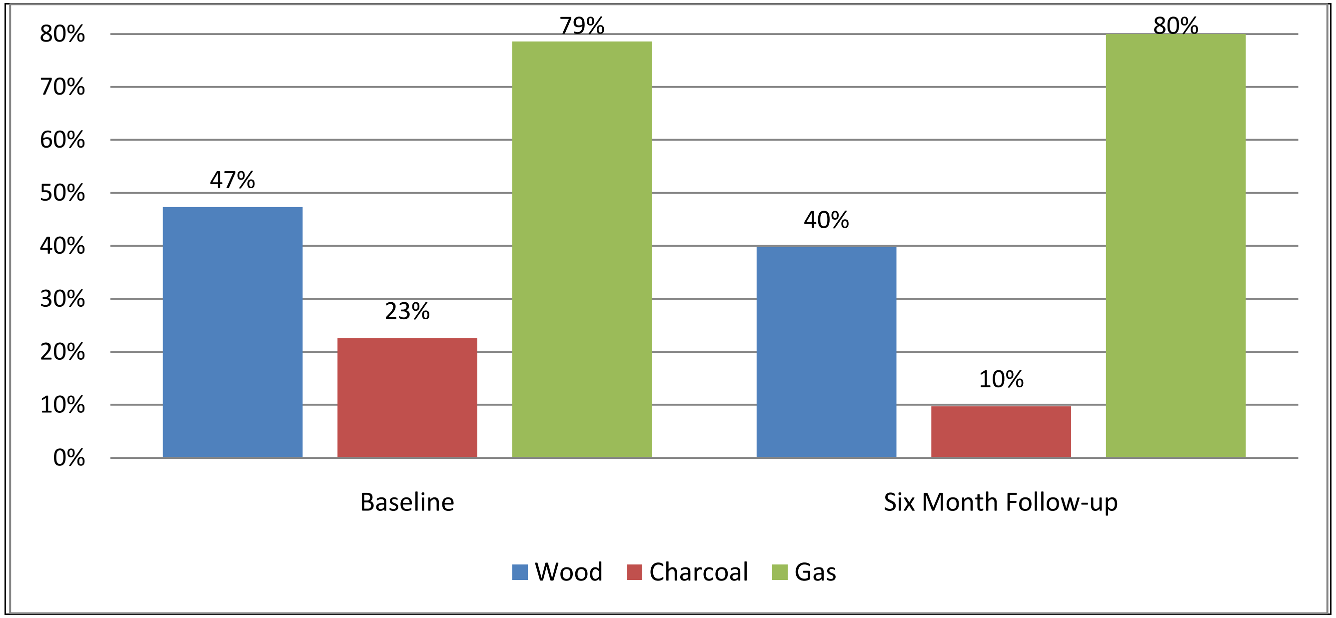


**Figure 6: Amount of money spent (USD $ equivalent) by households on wood, charcoal, and gas for cooking**

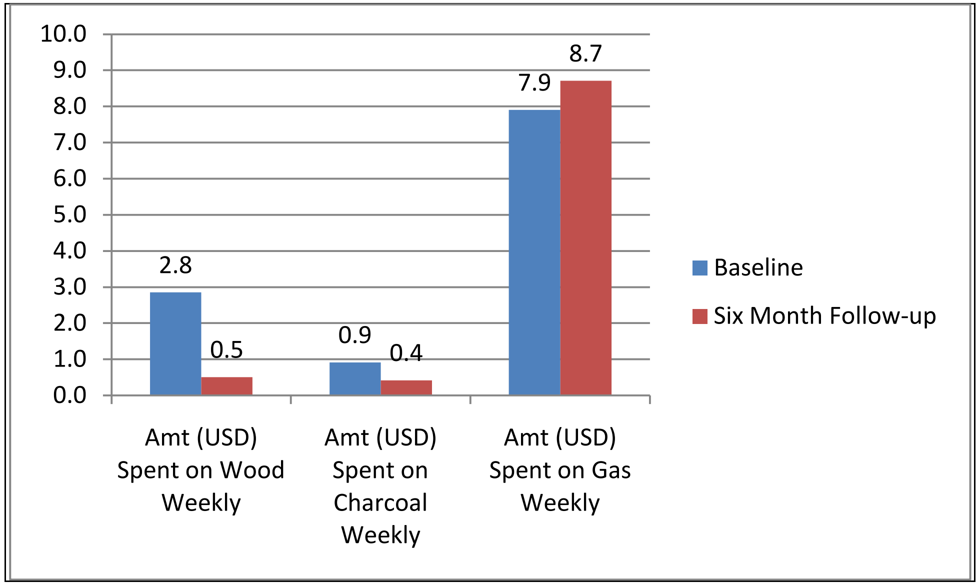



**Figure 7: Respiratory Symptoms for women participants in the program and their husband at the six month follow-up**

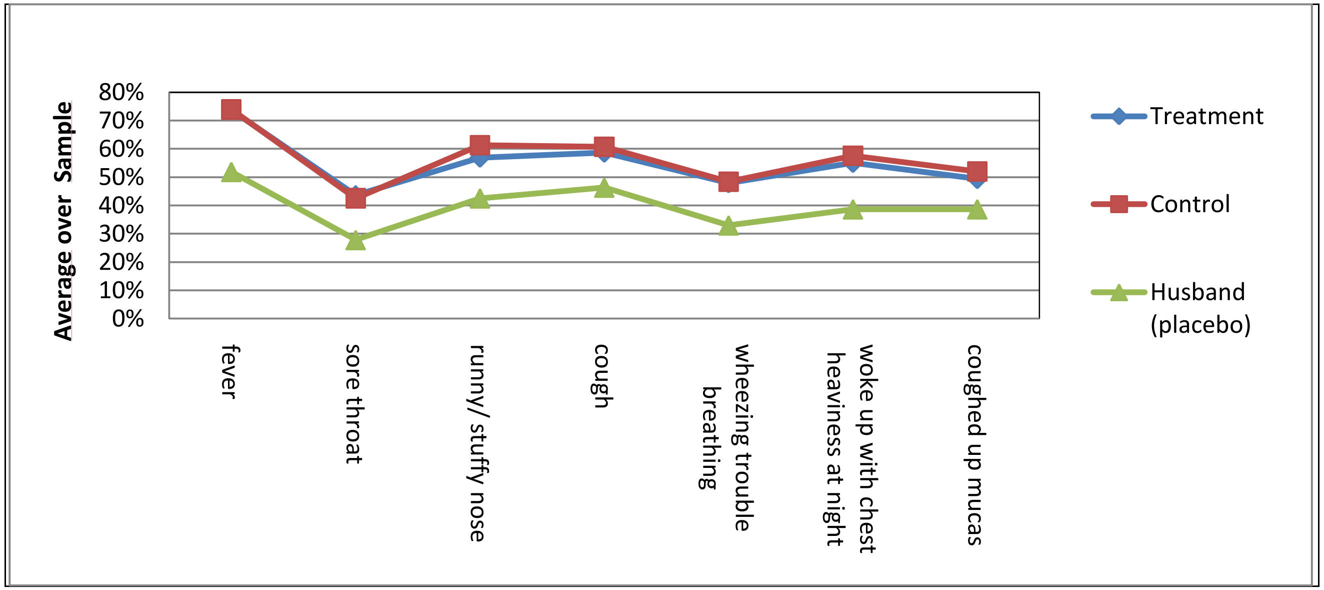
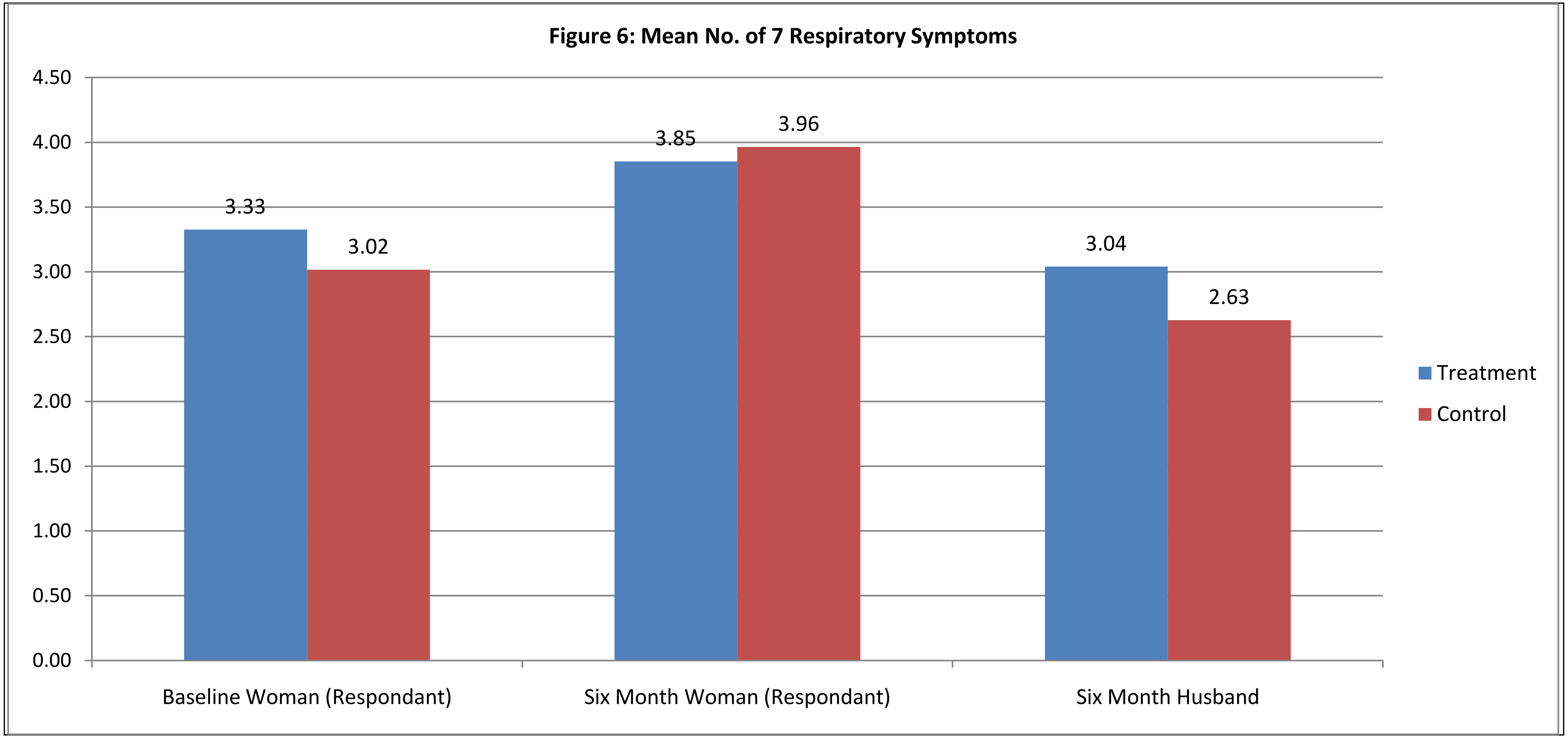
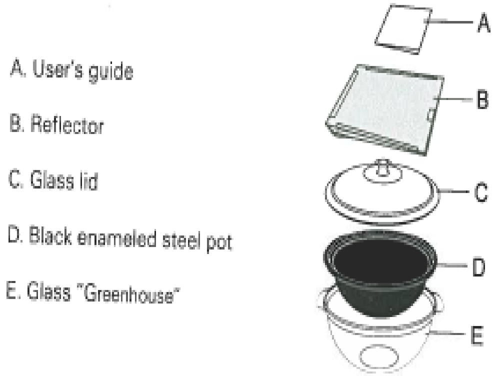


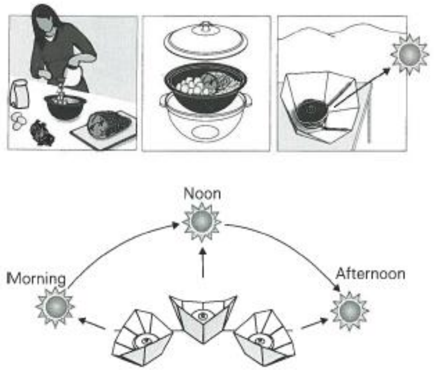
**Figure 8: Count of number of seven respiratory symptoms for women in the treatment and control groups and for their husbands**



**Appendix 1: HotPot Product Description**

The HotPot is manufactured by Energia Portatil S.A. de C.V. in Monterrey, Mexico and is of the panel solar cooker variety. The HotPot was developed by Solar Household Energy and consists of the parts A-E pictured below including a tempered glass bowl and lid with a black bowl which fits inside, a aluminum reflector, and user guide. In addition, women received a cloth bag to carry their solar oven in (not pictured below).

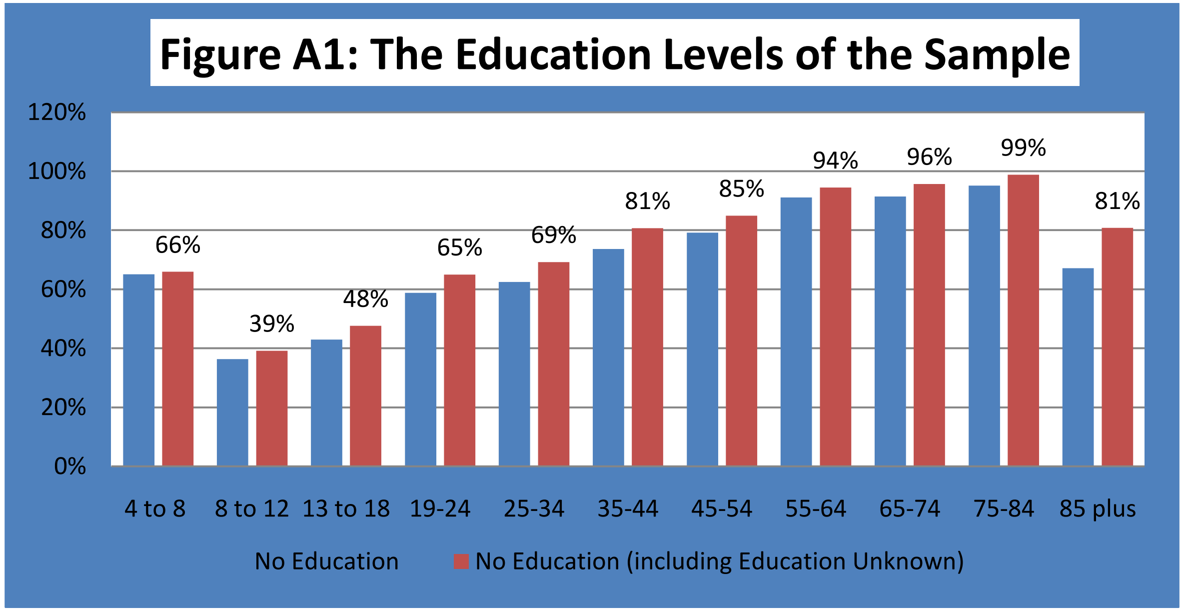



The HotPot cooks on solar energy properties and is fueled by direct and indirect solar energy captured by the oven's reflector. The sun's rays penetrate the tempered glass "greenhouse" bowl, strike the 5-liter black enameled steel pot and convert to heat. The heat is retained around the pot achieving cooking temperatures. The HotPot is most efficient under a cloudless sky, with limited winds and between the hours of 10 am and 4 pm. Ambient temperature has only slight impact on cooking performance. More important is the elevation of the sun in the sky. The higher the sun in the sky the better and thus the stove is most efficient in summer, spring, and fall.

To best use the HotPot it is best to select a site that will not be shaded by trees or buildings during the course of the day. Deploy your reflector on an elevated surface or the ground and orient the low side of the reflector to the sun. The performance of the stove depends on the reflector's orientation to the sun as it arcs across the sky. For maximum efficiency, the reflector should be re-orientated towards the sun about every hour or so.

## Appendix 2: Education Levels of the Sample




**Note: N=11,362 or all household members which reported educational outcomes from Baseline Survey.**

The education and age data are self-reported[3] and are generated from the baseline survey. The woman inscribed in the program were asked to list all members of her family currently living at her home (See Section 3.4 for exact definition of members of the household). Specifically, women were asked to report the last year attended in school for all members of the household. Overall the sample population have low levels of education relative to national levels. According to national statistics 43% of the population in Senegal are literate. The literacy level for our sample is presumably much lower if we assume that literacy is correlated with years of formal education. Our sample follows a predictable pattern for reported "No Education" which is positively correlated with age cohorts. In particular, if we include the education unknown category into the no education category, we see that 94% or above of the age cohort between ages 55-84 report "No formal Education".[4]

Of particular importance is that the secondary school age cohort aged 13-18 report 48% with zero formal education. This is particularly important when considering human capital as a driver to economic growth and the implications for future growth in Senegal. While we observe a generational improvement of almost half (94% of adults aged 55-84) vs. 48% of youth 13-18, report no education, the attendance in school of school age children is still quite low. In particular, given about half of the secondary age youth in rural areas today have never spent one day in school, low human capital today will only stagnate growth tomorrow.

[3] It proved difficult for some women to estimate the age of each of the members in the household and our NGO partner verified that it is difficult for people in general to estimate age in rural areas of Senegal.

[4] Interestingly, those aged 85 and higher have on average 81% no education or a higher education level than those aged up to 30 years younger. This could support the hypothesis that increased education is correlated with higher wealth levels and hence longer life spans.

**Appendix 3: SUM's Background on why 110°F is the Proper Cutoff Point**

| Table A3.1: Stove Usage Monitors Utilization Results | | | | | |
|---|---|---|---|---|---|
| First Month Usage of Stoves | | | | | |
| | 105 degrees F and below | 110 degrees F and below | 115 degrees F and below | 120 degrees F and below | n |
| Average Time Period Measured- No. of days (median) | 24 | 24 | 24 | 24 | 457 |
| Average # of Uses (mean) | 2.61 | 2.24 | 2.1 | 2.02 | 457 |
| Daily Usage Rate | 10.9% | 9.3% | 8.8% | 8.4% | 457 |
| Average # of uses without Beach Villages(mean) | 2.58 | 2.2 | 2.05 | 1.97 | 418 |
| Daily Usage Rate without 2 Beach Villages | 10.8% | 9.2% | 8.5% | 8.2% | 418 |
| 6 Month Usage of Stoves | | | | | |
| Average Time Period Measured-No. of days (median) | 25 | 25 | 25 | 25 | 438 |
| Average # of Uses | 5.11 | 4.76 | 4.74 | 4.77 | 438 |
| Daily Usage Rate | 20.4% | 19.0% | 19.0% | 19.1% | 438 |
| Average # of uses without Beach Villages(mean) | 5.47 | 5.1 | 5.09 | 5.12 | 396 |
| Daily Usage Rate without 2 Beach Villages | 21.9% | 20.4% | 20.4% | 20.5% | 396 |

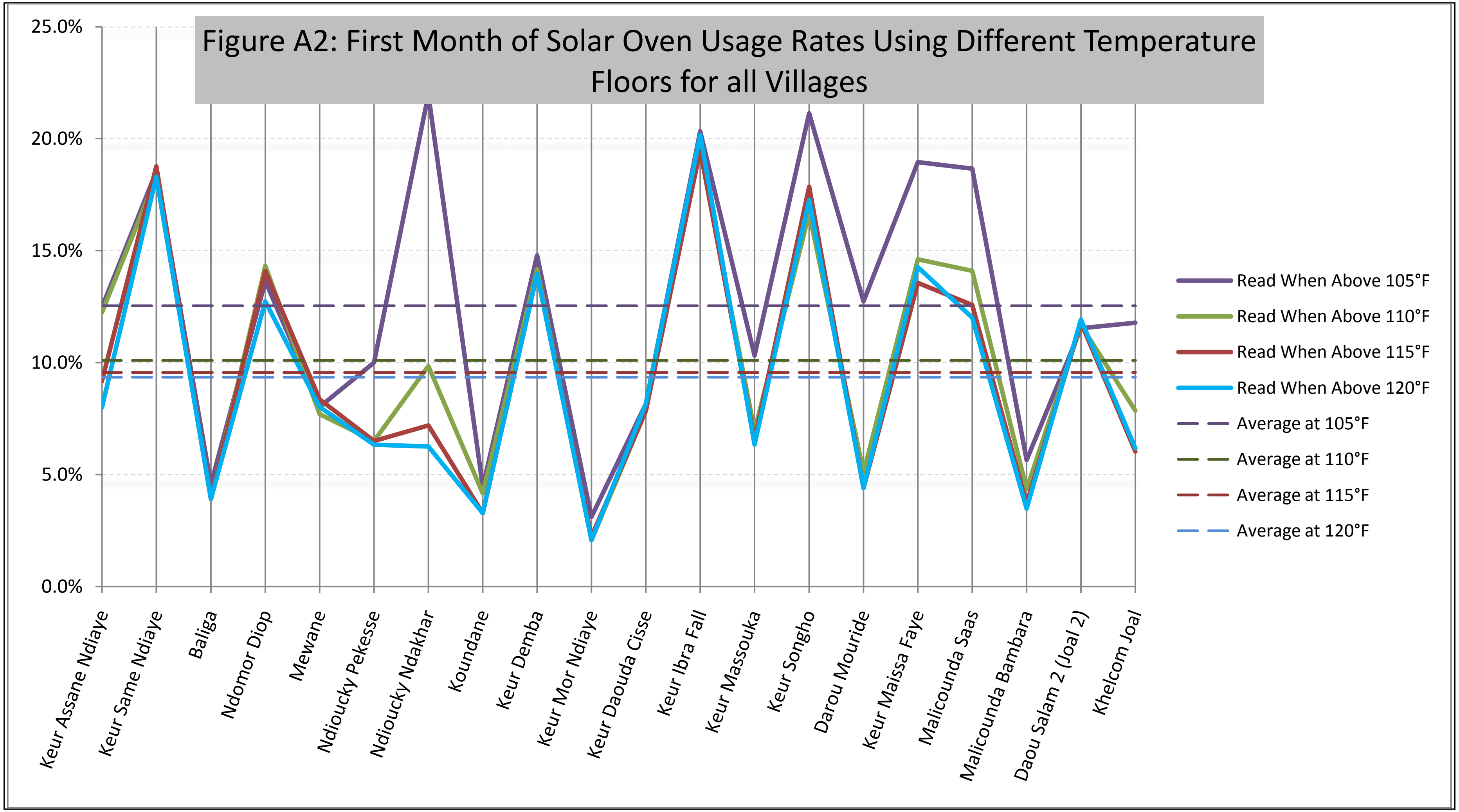
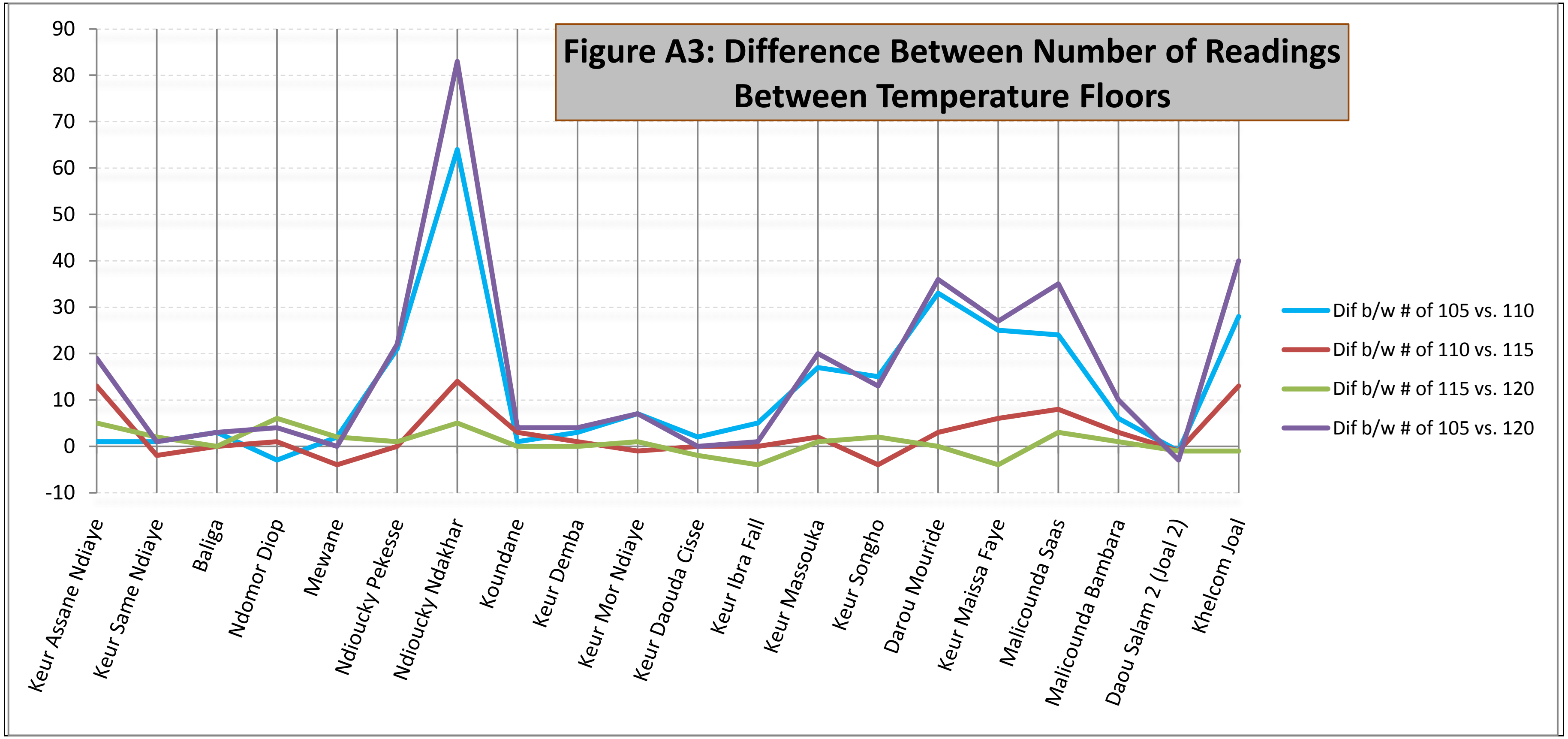


Figure A2: First Month of Solar Oven Usage Rates Using Different Temperature Floors for all Villages
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Keur Assane Ndiaye
Keur Same Ndiaye
Baliga
Ndomor Diop
Mewane
Ndioucky Pekesse
Ndioucky Ndakhar
Koundane
Keur Demba
Keur Mor Ndiaye
Keur Daouda Cisse
Keur Ibra Fall
Keur Massouka
Keur Songho
Darou Mouride
Keur Maissa Faye
Malicounda Saas
Malicounda Bambara
Daou Salam 2 (Joal 2)
Khelcom Joal
Read When Above 105°F
Read When Above 110°F
Read When Above 115°F
Read When Above 120°F
Average at 105°F
Average at 110°F
Average at 115°F
Average at 120°F




From Figure A2 and A3 we see that the there are many more recorded uses of the solar oven when the temperature floor is 105°F versus any of the other three temperature floor. In particular the purple line in Figure A3 shows the total difference in readings between 105°F and 120°F. A relatively large part of the observed discrepancy can be found in the blue line which reflects the total number of usage indicators between 105°F and 110°F indicators. Because the bulk of the discrepancy is between 105°F and 110°F, we reject the 105°F cutoff for a temperature floor reading indicating usage of the solar oven. Instead, we choose 110°F as a cutoff to indicate a usage of the solar oven as it is highly correlated with recorded temperature movements of 115°F and 120°F, and hence more robust overall.

## Appendix 4: Additional Impacts Tables

| Table A4.1: Household Size and Number of People for whom Women Cook | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total Sample | | | | Treatment | | | | Control | | | |
| | | n | mean | Med. | Std. Dev | n | mean | Med. | Std. Dev | n | mean | Med. | Std. Dev |
| | Household size[1] | 802 | 13.6 | 13 | 6.6 | 423 | 13 | 13.7 | 6.4 | 379 | 13.5 | 13 | 6.86 |
| Baseline | No. of people women cook report cooking for yesterday[2] | 772 | 13.4 | 12.5 | 6.5 | 459 | 13.8 | 13 | 6.7 | 313 | 12.8 | 12 | 6.1 |
| 1 month follow-up | | 826 | 12.8 | 11 | 6.8 | 448 | 13.2 | 12 | 7 | 378 | 12.3 | 10 | 6.7 |
| 6 month follow-up | | 843 | 11.4 | 10 | 6.3 | 434 | 11.7 | 10 | 6.5 | 409 | 11 | 10 | 6.1 |

1. The measure corresponds to women's response are you ever responsible for cooking for this household member. Then the total household size is number of household members who ever eat at the house. Household members are those currently living there.

2. This measure corresponds to the number of people women report actually cooking for yesterday when she weighed wood.

| Table A4.2 : Main Wood Results * | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Wood Kg Used at the lunch meal in households and compounds with 12 persons or less | | | | Wood Kg/pp Used at the lunch meal in households and compounds with 12 persons or less | | | |
| | Mean | Median | Std Dev. | No. Observ-ations | Mean | Median | Std Dev. | No. Obser-vations |
| Baseline Lunch Wood Use | | | | | | | | |
| Average- Over All Groups | 6.75 | 6.42 | 2.53 | 841 | 0.585 | 0.523 | 0.31 | 838 |
| Treatment | 6.81 | 6.49 | 2.45 | 439 | 0.566 | 0.507 | 0.28 | 438 |
| Control | 6.68 | 6.42 | 2.61 | 298 | 0.542 | 0.609 | 0.34 | 296 |
| Treatment with at least 1 other treatment study participant in compound | 7.06 | 6.65 | 2.35 | 170 | 0.512 | 0.453 | 0.27 | 170 |
| Treatment with only 1 study participant in compound | 6.65 | 6.22 | 2.50 | 269 | 0.600 | 0.549 | 0.29 | 268 |
| Control with at least one other treatment study participant in compound | 7.04 | 6.79 | 2.56 | 78 | 0.516 | 0.427 | 0.38 | 78 |
| Control with only 1 study participant in compound | 6.55 | 6.30 | 2.62 | 220 | 0.642 | 0.574 | 0.31 | 218 |
| Average-Over All Groups | 5.54 | 5.00 | 2.47 | 913 | 0.590 | 0.482 | 0.38 | 891 |
| Treatment | 5.47 | 5.00 | 2.45 | 419 | 0.568 | 0.476 | 0.37 | 407 |
| Control | 5.77 | 5.00 | 2.53 | 388 | 0.620 | 0.500 | 0.39 | 379 |
| Treatment with at least 1 other treatment study participant in compound | 5.71 | 5.26 | 2.50 | 167 | 0.536 | 0.450 | 0.31 | 164 |
| Treatment with only 1 study participant in compound | 5.31 | 4.75 | 2.40 | 252 | 0.590 | 0.500 | 0.41 | 243 |
| Control with at least one other treatment study participant in compound | 6.20 | 5.76 | 2.61 | 102 | 0.558 | 0.458 | 0.34 | 100 |
| Control with only 1 study participant in compound | 5.61 | 5.00 | 2.49 | 286 | 0.642 | 0.500 | 0.40 | 279 |
| Six Month Follow-up Daily Wood Usage | | | | | | | | |
| | Wood Kg used Daily in households with 12 persons or less | | | | Wood Kg/pp Used Daily in households with 12 persons or less | | | |
| | Mean | Median | Std Dev. | No. Observations | Mean | Median | Std Dev. | No. Observations |
| Average-Over All Groups | 9.93 | 9.00 | 4.69 | 915 | 1.07 | 0.87 | 0.74 | 893 |
| Treatment | 9.90 | 9.00 | 4.72 | 418 | 1.04 | 0.84 | 0.77 | 405 |
| Control | 10.28 | 9.52 | 4.67 | 391 | 1.12 | 0.90 | 0.74 | 383 |
| Treatment with at least 1 other treatment study participant in compound | 10.04 | 8.60 | 4.91 | 167 | 0.97 | 0.80 | 0.73 | 164 |
| Treatment with only 1 study participant in compound | 9.69 | 9.00 | 4.60 | 251 | 1.08 | 0.90 | 0.79 | 241 |
| Control with at least one other treatment study participant in compound | 10.83 | 9.07 | 4.94 | 103 | 0.97 | 0.80 | 0.62 | 101 |
| Control with only 1 study participant in compound | 10.08 | 9.52 | 4.56 | 288 | 1.18 | 0.94 | 0.77 | 282 |
| Note : All Data Presented has been top and bottom coded at the 5% level as is common practice to control for outliers. | | | | | | | | |

**Appendix 5: World estimates of Total Burden of Disease Attributable to Solid Fuel Use and Cost Benefit Analysis**

| Table 5.1[5]: Percentage of total Least Developing Countries (LDC) burden attributable to solid fuel use | | | | |
|---|---|---|---|---|
| Region | Deaths | Percent ARI | DALYs | Percent ARI |
| India | 5.3% | 81 | 5.5% | 87 |
| China | 5.8% | 25 | 4.5% | 50 |
| Other Asia & Pacific Islands | 3.8% | 75 | 3.7% | 85 |
| Sub-Saharan Africa | 5.2% | 85 | 4.9% | 90 |
| Latin America | 1.0% | 71 | 0.9% | 82 |
| Mid-East and North Africa | 3.6% | 89 | 3.7% | 93 |
| LDC Total | 4.7% | 67 | 4.2% | 81 |

| Table5.2: US$ Per Healthy Year Gained[6] | | | | | | |
|---|---|---|---|---|---|---|
| Intervention | Sub-Saharan Africa | Latin America and the Caribbean | Middle East and North Africa | Europe and Central Asia | South Asia | East Asia and the Pacific |
| LPG | 518 | 814 | 762 | 1,321 | 314 | 100 |
| Kerosene | 60 | 106 | 95 | 167 | 36 | 12 |
| Improved Stove | 20 | 1,101 | 368 | NA | 13 | 327 |

[5] Source Smith and Mehta (2000).
[6] Source Bruce et al. (2006).

# Changes in Bilateral Trade Costs between European Union Member States & Major Trading Partners: An Empirical Analysis from 1989-2006

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**Abstract:** Today, more than 50 years after the Rome Treaty, the EU has made great strides in its' economic integration and liberalization of movement of goods and people. Reductions of tariff barriers due to EU integration, which can be measured by a drop in trade costs, play an integral role in trade theory. International trade theory predicts deepening economic integration inside the European Union will increase regional trade and have large effects on agglomeration of industry patterns. In particular, the Core Periphery theory predicts the core of Western Europe and center of economic prosperity will spread economic growth to the periphery through increased integration. Thus, it is hoped that the EU Core,[2] who benefit from their central location and a long history of integration in Western Europe, will increase growth to the periphery through deepening integration and a relative drop in trade costs. Critics cite the Spring 2010 debt crisis in Greece and subsequent shock to Euro zone stability as an indication that EU integration has not been successful. Given increased skepticism of the Euro zone, measuring changes in trade costs between 2001 Euro adopters and the main trading partners provides one quantitative measure to better understand the depth of EU integration in the recent period from 1989-2006. Using the Novy (2008) model, which measures bilateral trade costs directly from trade flows, the measure includes all trade costs incurred in getting a good to its' final user, other than the production cost of the good itself. Results show the drop in trade costs over the more recent period 1995-2006 to be largest for trade between countries who adopt the Euro in 2001 (-53%). The second largest drop in bilateral trade costs is between 2001 Euro adopters and the Central Eastern European Countries who joined the EU in 2004 (-49%). The third largest drop in bilateral trade costs is between the 2001 Euro adopters group and the large non-continental Europe trading partners (-45%). Large differences in trade costs appear between countries within the 2001 Euro adopters who are considered members of the Core versus those in the Periphery. Over the 1995-2006 period trade costs drop by 24% more for trade within the Core versus Trade between the Core and the Periphery. While the Core-Periphery theory is slow to be realized in our empirical results of trade costs over the 1995-2006 period; trade costs among EU members and Euro adopters are relatively large- 33-53%- when compared to trade costs measured for the non-continental European trading partners-5%. This 7-11 times larger drop in trade costs for trade intra-EU and Euro adopter members- both original and accession- is an empirical testament to the EU's success at integrating diverse economies within the union.

[1] This work has greatly benefited from the advice and counsel of my thesis advisor Stefano Magrini. Special thanks is reserved for Jacque Thisse for his comments, as well as other participants who provided useful comments at the March 31, 2010 presentation at the Université Catholique de Louvain, Center for Operations Research and Econometrics (CORE), and participants who attended the April 23, 2010 Economics Department Seminar at the Advanced School of Economics in Venice, Università "Ca' Foscari" di Venezia, Italy. All errors in this paper are my own.

[2] The EU inner six consist of: Belgium, France, Germany, Italy, Luxembourg, and the Netherlands.

**Section 1: Introduction**

Today, over 50 years since its' official founding at the 1957 Rome Treaty[3], the European Union has made great strides in trade liberalization of goods between its' members. Fundamentally, not only has European Union integration lowered internal tariffs, thus reducing trade costs, which is trade creating for members; the EU has at the same time lowered multilateral tariffs, thus lessening the effects of trade diversion by creating a more open world trading system for goods. The reduction of trade costs over the geographical space between production sites and markets fueled by lowering tariff barriers due to formation of regional blocs like the European Union plays an integral role in international trade theory and trade policy. Further, trade costs are one of the core inputs to theories of spatial agglomeration in the sub-discipline of Economic Geography. The substantial role trade costs plays in international trade theory is captured by general equilibrium models of trade including the Home Market Effect and the New Economic Geography models published by Paul Krugman in 1980 and 1991 respectively. These two economic models of agglomeration provide an equilibrium story about the centripetal forces that pull economic activities together and those centrifugal forces that push them apart, relying directly on tradeoffs between various forms of increasing returns and mobility costs. In addition to the central role trade costs play in these two models, Obstfeld and Rogers (2000) argue that all major puzzles of international macroeconomics hang on trade costs.

Further, the ability to measure changes in trade costs as a result of the integration of the European Union is particularly salient given the recent troubles threatening the stability of the EU zone. The recent spring 2010 debt crisis in Greece which spread to Spain and Portugal, has been cited as evidence by critics that the EU integration is relatively shallow and has not been successful. Thus the measure of changes in trade costs, between 2001 Euro adopters and other EU members, non-members, and non-continental large trading partners provides a quantitative measure to better understand the depth of EU integration over the recent period 1989-2006. Understanding the relative depths of 2001 Euro adopter integration relative to integration with non-Euro adopter trading partners is one clear quantitative measure of the level of success of EU integration.

Trade costs have traditionally been hard to measure directly. Until recently, economists working with gravity regressions have implicitly assumed a trade cost function by focusing on certain trade cost proxies such as geographical distance, or tariff barriers to measure trade costs. Given trade costs constructed in this manner are estimated, no matter how good of a fit the proxy there remains a number of drawbacks associated with approximating trade functions. In the best case scenario, using a proxy for trade costs provides a good estimate of some of the barriers to trade. This method is hardly convincing as a true measure of trade costs and hence a measure of EU integration. Given these limitations, this work benefits from a new direct measure of trade costs introduced by Novy (2008) which instead of measuring trade costs through a proxy measures trade costs directly based on observed bilateral trade flows. In addition this new measure is a full measure of trade costs and follows Novy (2008), Portes and Rey (2005) and Anderson and Marcouiller (2002) definition of trade costs to include all costs incurred in getting a good to its' final user, other

[3] On March 25, 1957 six countries Belgium, France, the Federal Republic of Germany, Italy, Luxembourg, and the Netherlands signed the Treaties of Rome which gave birth to the European Economic Community (EEC) and to the European Atomic Energy Community.

than the production cost of the good itself. In this model, trade costs include transportation costs (both freight and time costs), policy barriers (tariffs and non-tariff barriers), information costs, contract enforcement costs, currency and language costs, legal and regulatory costs, hidden transaction costs due to poor security, and other red tape. To construct this measure of trade costs, this paper builds on the Novy (2008) model which innovates from the Anderson and van Wincoop (2003) model. The Novy model introduces a micro-founded measure of aggregate bilateral trade costs using a gravity model which solves explicitly for all trade costs and other macroeconomic frictions that impede international trade. This innovation provides a unique new model to measure bilateral trade costs for the EU member countries and large trading partners (26 nations) over the 1989-2006 period. Countries with similar policy as it relates to EU integration are averaged by group and then differences between bilateral trade costs between different groups of partners are compared using three and five year averages.[4] This empirical work further benefits from two natural experiments in the formation of the EU over the period which data is available- the Maastricht Treaty signed in 1992 and the introduction of the Euro in 2002. I aggregate countries with common policy and compare trade costs between the following groups over time:

Group 1: 2001 Euro adopters (11 countries)[5]

Group 2: 2001 EU members who do not adopt the currency (3 countries)[6]

Group 3: Other Western European nations who have not joined the EU (3 countries)[7]

Group 4: 2004 Central and Eastern European Accession members (4 countries)[8]

Group 5: Non-continental European large bilateral trading partners (5 countries)[9]

Relying on three year averages, the difference in trade costs between the period 2003-2006 and the period 1997-1993 is largest for bilateral trade intra-Group 1 with a drop of 53% (see Table 1). The second largest drop in trade costs over the same period is between Group 1 and Group 4 (-49%) and the third largest is between Group 1 and Group 5 (-45%). Preliminary results seem to point that the adoption of the Euro is key for countries who experience the largest drops in trade costs. This is supported by the results from the drop in trade costs between Group 1 and Group 2 (-33%) compared with a drop in trade costs between Group 1 and Group 3 (-37%). The near similar drop in trade costs between countries who are in the EU who do not adopt the Euro and those who are not in the EU, paired with 2001 Euro adopters seems to point out that it is the adoption of the Euro which promotes the highest drop in trade costs. This result is supported by trade theory which tells

[4] The format of this empirical analysis follows from Jacks, Meissner, and Novy (2008).

[5] The 2001 EU currency adopters with available data are the following 11 countries: Austria, Belgium, Finland, France, Germany, Greece, Italy, Luxembourg, the Netherlands, Portugal, and Spain.

[6] Members of the EU in 2001 who choose not to adopt the common currency with available data include: Denmark, Sweden, and the UK.

[7] In 2006, these countries with available data include: Iceland, Norway, and Switzerland. Though, Iceland has subsequently joined the EU in 2009.

[8] The 2004 Central and Eastern European Accession members with data available include: the Czech Republic, Hungary, Poland, and the Slovak Republic.

[9] The large non-continental Europe trading partners with data available include: Canada, South Korea, Japan, New Zealand, and the U.S..

us increased integration should decrease trade costs. Up to this point the drop in trade costs between 2001 Euro adopters and both EU members and large non-continental trading partners shows a relatively large decline over the period (33-53%). To understand whether this is a direct result of EU integration or a reflection of a globally wider trend, I use trade costs intra-non continental European large bilateral trading partners as a proxy for a global trend in trade costs over the period. The result is an overall 5% drop in trade costs intra-non continental Europe's large trading partner (intra-Group 5) which is nearly 11 times smaller than the drop in trade costs intra-2001 Euro adopters (53%). Thus, even if 5% is a low global proxy of the global trend in trade costs over the period, it is clear that EU integration, and particularly the introduction of the Euro, is having a net positive effect on trade costs with all bilateral partners, even those not in the EU.

Further, the empirical measure of bilateral trade costs allows us to test the Core Periphery theory which predicts the core of Western Europe who benefit from their central location and a long history of integration in Western Europe, will increase growth to the periphery through deepening integration and hence a relative drop in trade costs. By including additional groupings measuring trade costs between the Core and the Periphery over the period 2003-2006 and the period 1997-1993, trade costs between the inner six has the largest drop of any bilateral groupings (-73%) over the period, while trade intra-non-inner six[10] has a drop in trade costs (-9%). This result is not surprising since we would expect intra-periphery trade to be low. A more apt measure is core-core vs. core-periphery trade between the period 2003-2006 and the period 1997-1993. Table 7 shows the differences between Core-Core trade costs in Western Europe vs. Core- Periphery trade costs. Core-core trade costs are on average 24% lower than Core-Periphery trade costs over the period indicating the periphery is slow in integrating with the core inside the EU.

Assuming the change in trade costs can serve as a proxy for the level of EU integration between different member states; this paper aims to add value to the literature by supplying a measure of EU integration among different bilateral trading partners. The goal of this research is to provide policymakers with a quantitative measure of EU integration both between member states and non-member states, and to facilitate welfare enhancing policy. Further, this paper hopes to add value to the literature by addressing the question posed by Jagdish Bhagwati's of whether PTAs, such as the EU, are 'building blocks or stumbling blocks' to multilateral integration. The paper is organized as follows. Section 2 and 3 outline the relevant theoretical and empirical existing work and historical framework leading to today's paper. Section 4 details the trade cost model and methodology used in this paper and Section 5 outlines the data. Section 6 summarizes the empirical results and Section 7 concludes.

[10] Non-inner six for which data is available include: Austria, Finland, Greece, Portugal, and Spain.

## Section 2: Earlier Empirical Evidence

### 2.1: Role of International Trade in Economic Growth

International trade theory and empirical studies firmly establish a positive relationship between a nation's ability to trade freely and economic growth. Alfred Marshall stated in his book The Principles of Economics (1890) "the causes which determine the economic progress of nations belong to the study of international trade." Recent empirical work by Silvi Nenci (2009) analyzing the relationship between tariff barriers and world trade growth over the period 1870-2000 confirms the existence of a worldwide level long-term relationship between tariff reductions and trade growth. Thus in both International trade theory and empirical applications there is widespread evidence that reducing frictions on trade is welfare promoting and promotes economic growth.

### 2.2: Welfare Effects of Preferential Trading Agreements on the Multilateral Trading System

The argument over whether bilateral reductions of frictions on trade created by regional trading blocs are welfare creating for the multilateral trading system has been widely debated among economists. Jagdish Bhagwati in his famous analogy asks whether regional integration, i.e. preferential trading arrangements (PTAs) such as the EU, are "building blocks, or stumbling blocks" to multilateral integration. In his empirical work, Andrew Rose (2004) finds no correlation between membership in the GATT/WTO and a nation's level of trade, and concludes PTAs do not increase multilateral integration. Subramanian and Wei (2003) find instead that the WTO has had a powerful and positive impact on trade, amounting to about 120% of additional world trade (or US$8 trillion) in 2003 alone. Alan Winters switches the focus to the question of whether regionalism sets up forces that encourage or discourage evolution toward a globally freer trading system. The results he finds are inconclusive, as "one can build models that suggest either conclusion, but these models are still so abstract that they should be viewed as parables rather than sources of testable predictions." The jury is still out as to whether regional trading agreements are 'building or stumbling blocs' to multilateral integration. Given the world trading systems over the period 1989-2006 generally followed the trend towards regional instead of multilateral trade agreements, the question has never been more pertinent.

In order to understand the welfare effects of the EU it is important to frame EU integration in the wider global trade setting. There is general agreement among economists that the global trade system took a policy shift away from multilateralism and towards regionalism with the formation of the European Economic Commission (EEC) in 1957. The Treaty of Rome is widely agreed upon by economists as the point of departure for what is referred to as the age of "First Regionalism"[11] or what theorists refer to as the first substantial world trade policy shift towards Preferential Trading Areas (PTAs) (and away from multilateralism). The age of "First Regionalism" and trend towards PTAs did not meet much success beyond

[11] Jagdish Bhagwati (1991) is credited with framing the two world trade policy movements into the ages of First and Second Regionalism. Both periods reflect the move in global trading agreements towards preferential trading agreements and away from multilateralism. His work has roots in Jacob Viner's (1950) work which identified the period from the late 1950s through the 1960s as a period characterized by a global movement towards PTAs.

the European community and its' offshoot the EFTA[12]. Regionalism as a global trend in trade policy is widely considered by economists to have become relevant again in the early 1980s. This period, dubbed by Bhagwati (1991) as the age of "Second Regionalism", began with the shift of U.S. policy towards PTAs and is widely agreed upon to have begun with the Canada-US Free Trade Agreement (CUFTA) signed in 1988 which later expanded to include Mexico in the North American Free Trade Agreement (NAFTA) in 1994. Fujita and Mori (2005) measure levels of agglomeration of GDP by regional trading blocs and find NAFTA yields 35% of world GDP, EU (15 countries) 25%, and East Asia 23%. Thus, 83% of the world's GDP is concentrated in the three regions in 2000. In 1980, the corresponding shares were 27% for NAFTA, 29% for EU, and 14% for East Asia; or the three regions together 70%.[13] Hence, the concentration of the world GDP in the three regions has intensified recently and raises the question again whether regional trade agreements are growth creating.[14] The empirical results of this paper show trade costs declined by 45% on average over the period 1995-2006 between Euro adopters in 2001 and the five major trading partners for which data is available.[15] This large reduction of trade costs between 2001 Euro adopters and the five non-continental European large trading partners (-45%) suggests the EU is a building bloc rather than a stumbling bloc to multilateral trade.

### 2.3: Welfare Effects on Nation's Internal Growth as a Result of PTAs

An additional aspect to consider when measuring trade costs is the welfare effects inside a country that occur as a result of joining a regional bloc. Three influential papers (Behrens et al. (2003), Krugman (1991), and Fujita et al. (1999). are cited as evidence of uneven, or lumpy growth in industry between regions of a nation as a result of regional integration. The degree of agglomeration which results from regional integration is an important welfare effect to consider when assessing the effects of regional integration.

Behrens et al. develop a model, consistent with the framework of the theory of new economic geography (Krugman, 1991; Fujita *et al.*, 1999), to test the effects of regional integration on a nation's internal intra-regional growth. They find that lowering international trade costs may lead to the dispersion of skilled labor within each country, while reducing inter-regional transport costs is likely to foster its agglomeration.[16] Particularly, the costs to international trade from the transportation of goods and its' role in promoting equitable returns of welfare from trade across regions of nations must be considered when contextualizing gains in trade and hence drops in trade costs.

The empirical work by de la Fuente and Vives (1995), show that economic integration within the EU fosters international convergence across countries but not inter-regional convergence across regions within countries. Further, Hayward (1995) notes that the impact of European integration on the US might differ from American state to state. Or, critically,

[12] The European Free Trade Association (EFTA) was established on May 3, 1960 as a trade bloc alternative for European states who were either unable to, or chose not to, join the then European Economic Community (EEC).

[13] See Fujita and Mori (2005).

[14] More background on the pertinent discussion of whether regional trade agreements lead to a more global free trading system can be found in Bhagwati and Arvine (1996a), Winters (1996), and Behrens et al (2006).

[15] These trading partners are Canada, South Korea, Japan, New Zealand, and the U.S. Data is measured in 3 year averages (2006:2004)- (1997-1995).

[16] Ades and Glaeser (1995) find that good internal transportation infrastructure decreases urban concentration and hence should provide more equitable returns to increased regional integration.

that some U.S. states will thrive while others suffer from stronger import or export competition. The welfare effects of trade integration are thus very relevant for PTAs, and particularly merit consideration of how equitable is the growth internally for member states within the EU. The EU, like other regions, is characterized, even among the most industrialized country by wide and varying levels of regional disparity and heterogeneous agglomeration forces where some industries manifest high degrees of local specialization and others less so. Behrens et al. (2003) note the issue of unequal distribution of benefits across member states is an increasingly pertinent issue in the EU with the 10 new accession countries. Particularly it is likely that membership in the EU will have different welfare benefits for different regions depending on their transportation infrastructures, spatial proximity to the core, and ability to transport goods. The authors argue policy should be directed towards equalizing these welfare benefits to avoid major political disturbances and social turmoil which could be triggered by the potentially uneven distribution of the gains and losses from regional integration. In fact as part of an effort to promote regional integration, EU policy has targeted increasing the transportation network between members. An initial estimate of present and future costs of construction and restoration of the transportation network up to 2015 is EUR 91.5 billion- with 48% of the total transportation budget for the road network and 40.5% for rail.[17] Despite the increased transportation linkages in the EU designed to facilitate movement of goods, spatial agglomeration patterns of industry may remain rigid and serve as an obstacle to equitable growth. This research agenda is of essential importance to understanding the internal, more detailed effects of regional integration in the EU on its' member states and ensuring its' long-term stability. Due to data limitations it was not possible to measure bilateral trade costs between a nation's individual regions for EU member nations. This paper instead measures bilateral trade costs between nations.

Understanding such phenomenon and the underlying drivers of international trade are critical for the European Union's design of efficient urban, regional, and national policies. These ideas, based on the core periphery theory, central in new economic geography models, have been considered carefully in construction of EU policy. Table 7 shows the differences between bilateral trade costs for intra-2001 Euro adopters Core-Core trade and Core-Periphery partners.[18] Core-core trade is on average 24% lower than Core-Periphery trade over the period indicating that the Core-Periphery theory is slow in being realized empirically. This could be a sign of caution for EU policymakers in enlarging the Union. Particularly, given the Core-Periphery trade costs lag by nearly 25% than compared to the Core-Core trade costs among the 11 Western European members who are first to adopt the Euro in 2001 and whose nations are by far much closer in history and past trading patterns,

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[17] In 2000 and 2001, the Commission approved EUR 6 billion ISPA funding, with 61 % going to transport projects, equally shared between rail and road (European Commission, 2001). The few statistics available on transport infrastructure investments show that between 1993 and 1995 47 % of infrastructure spending in the ACs went to roads and 42 % to railways. In the EU, road received 62 % of total investment, and rail 29 %, i.e. a larger share than its share in transport volume. Between 1998 and 2000, the Phare programme contributed funding to 52 transport infrastructure projects in the ACs (for a total of EUR 120 million a year), 60 % of which were road projects (IEEP, 2001).Source European Environment Agency (2002)

[18] Of the 11 countries which adopted the Euro in 2001 and we have data for the most standard frequent definition of the Core includes: Austria, Belgium, France, Germany, Italy, Luxembourg, Netherlands, and the UK. While thePeriphery is Finland, Greece, Portugal, Spain, and Switzerland. Though because there is no absolute definition we try different groupings see Figure 7 & 8.

this could bode poorly in the medium term for the Central European Countries who joined the Euro zone in 2004.

**2.4: Welfare Effects of EU Regional Integration versus the Costs**

What are the welfare aspects to consider when a country decides to enter the EU? A nation should join the EU if the costs of integrating are less than the gains. Clearly, it is difficult to quantify short, medium, and long term costs and gains for a country in joining the EU. Yet, by assessing the relative decrease of trade costs over time between EU members who adopted the currency in 2001 and EU trading partners who are both members and non-members of the EU who do not adopt the common currency, this paper offers a framework to compare experiences of different nations with varying levels of integration within the EU. Further, this work offers a quantitative measure of trade costs to analyze the different decisions Western European countries have made in relation to the EU. This unique dataset offers the ability to measure at the macroeconomic level the decision by Switzerland and Norway not to join the EU vs. the decisions of Denmark, Sweden, and the UK who have joined the EU but opted not to adopt the common currency.

From NEG models we know that there is a decisive role for history in trade patterns. Thus, the high level of historical integration between these Denmark, Norway, Sweden, Switzerland, and the UK with the 2001 Euro adopters makes their potential recent gains from integration potentially less given hundreds of years of trading and relatively low initial trade costs in 1988.[19] Further, these five countries have dynamic extremely competitive economies and the benefits of joining the EU, particularly exchange rate stabilization, may not outweigh the costs of limiting monetary policy. The Euro zone offers the benefits of lowering uncertainty in pricing and transaction costs of cross-border trade. In addition, a positive benefit of the monetary union is it eliminates speculators from making money on exchange rate arbitrage. Economic theory tells us the main cost in joining the Euro zone is the loss of independent monetary policy. This one size fit all approach to monetary policy limits nation's abilities to respond to national asymmetric shocks in business cycles. The recent economic crisis in Greece is one example where a country in crisis was unable to increase its' money supply to increase employment due to restrictions on Greece's monetary policy due to the Euro. For nations, that join the EU, regardless if they join the Euro zone, there are additional costs for integration. The creation of the European Union has required large resources from member states including the creation of EU institutions such as the European Parliament, Council of Ministers, European Commission, European Court of Justice and European Court of Auditors. The effort to bring together more than 495 million people, who speak many different languages and have different cultural backgrounds, will cost in 2010 a total of €141.5 billion. While member contributions are small when compared to total annual revenue for individual nations, administrative costs of harmonizing policy are still worth mentioning.

[19] The European Commission reports the 2010 budget adopted by the European Parliament plenary on 17th December 2009 is €141.5 billion. Of the total budget, the European commission reports spending about six cents of every euro of its' budget on running the European Union. From the 2010 budget this equates to €8.5 billion alone for administration. While this is a relatively small percent of GDP for member nations, it highlights the importance that there must be tangible gains from integration to induce membership.

Focusing back on the choice of some Western European nations decisions not to join the Euro zone, in order to justify the gains of EU integration for Denmark, Sweden, and the UK, the average gains over the period 1995-2006 should be relatively larger than those of Iceland, Norway, and Switzerland. We find the drop in trade costs is larger for the 3 non-member states (-37%) over the period 1995-2006 than the 3 member states who do not adopt the euro (-33%). Clearly, it is simplified logic to only consider the change in trade costs as a value of joining the EU or not. However, it is interesting that the trade costs between these two groups are relatively the same and even higher for Iceland, Norway, and Switzerland who do not join the EU (Iceland does join the EU but not during the 1989-2006 period studied). Due to the heterogeneous history of integration for the six nations discussed above with the 2001 Euro adopters, the comparison between them is not straight forward. This said these results may help explain the decisions by some countries not to join the EU, and particularly why all six countries do not join the Euro zone.[20]

### 2.5: Role of Trade Costs in Trade and Economic Unions

The available evidence suggests that trade costs can have a large effect on goods traded. Behrens et al. (2005) find a decrease in trade costs and/or in transportation costs to have a direct impact on prices and wages, and thus a significant impact on the economic geography and welfare of each country. Further Anderson and van Wincoop (2003) argue trade costs, defined as all costs to getting a good to market outside of its' production costs, are large, even aside from trade policy barriers and even between apparently highly integrated economies. In their empirical analysis they find total trade costs in rich countries are equivalent to an upward bound on an ad valorem tax equivalent of about 170%- an astonishing result for highly integrated economies. In the recent 2008 article Jacks, Meissner, and Novy (2008) show for France, the UK, and the US that the decline of trade costs explains roughly 55% of the trade boom pre WWI and 33% of the post WWII trade boom. Correspondingly, in the inter-war years (1914-1949) characterized by high tariff barriers, they found a rise in trade costs explains the entire inter-war trade bust. This empirical evidence reflects the significant role trade costs play in patterns of agglomeration and economic growth.

### 2.6: Measuring Trade Costs

The first best solution to measuring trade costs would be to measure each piece of trade costs directly including among others: tariffs; language barriers; currency barriers; information barriers; contracting costs and insecurity; and non-tariff barriers (NTB)'s- including para-tariff measures such as customs surcharge, tax; price control measures like minimum pricing constraints, anti-dumping measures; finance measures; automatic licensing measures; quality control measures including quotas; monopolistic measures; and technical measures and regulations[21]. However direct measures of trade costs are remarkably sparse and inaccurate. In a review of empirical economic work done on trade costs, Anderson and van Wincoop (2003) cite two general types of indirect trade costs

[20] Iceland application to join the EU was filed on July 16, 2009 and accepted on July 27, 2009. On June 2010, the EU granted candidate status to Iceland by formally approving the opening of membership talks.

[21] NTB categories are based on UNCTAD Coding System of Trade Control Measures.

measures which have been traditional sources used in the literature. The first is inference of trade costs from quantities of goods traded and the second relies on inference of trade costs from prices. Both methods require assumptions in defining a trade cost function. Assumptions in trade cost functions might well be misspecified and its' functional form could omit important trade cost determinants.

Another issue is in practice trade barriers are time varying. For example trade costs change when countries phase out tariffs. Thus, time invariant trade costs proxies such as distance are hardly useful in capturing dynamic trade costs changes over time. Given these types of simplifying assumptions to proxy for trade costs, in the past, researchers have, at best, given good estimates of trade costs using quantities or prices of goods traded.

One of the earliest tractable trade costs measures invented for general equilibrium models comes from Paul Samuelson in 1954 with the idea the 'cost of transporting a good which can be measured as some fraction of the good itself.' Rather than introducing formally a trade cost variable, the costs of trade can be introduced easily into general equilibrium models as a factor of decay. This idea is often framed as that of a floating iceberg, costless, except for the amount of the iceberg itself that melts in transport. This measure is very tractable for modeling transport costs since it impacts no other market and iceberg transport costs have been widely applied in empirical models. In fact, the idea of trade costs as a factor of decay remains a major building block for theoretical models today.

This paper builds on the recent work by Anderson and van Wincoop (2003) whose important work generates a new gravity model. Their model includes multilateral resistance terms, i.e., terms which capture the fact that bilateral trade flows do not only depend on bilateral trade barriers alone but also on relative trade barriers across all trading partners. Anderson and van Wincoop (2003) use a trade function to proxy for trade costs. However, as mentioned above making assumptions on the trade cost function is an approximation and an incomplete measure. Thus to find a quantifiable measure this work follows Novy (2008) who derives an analytical solution for time-varying multilateral trade barriers, or multilateral resistance variables by showing that multilateral resistance variables are a function of how much a country trades with itself, that is intranational trade flows. With the multilateral resistance variable analytically defined from observable trade flow data, one can easily solve the model's gravity equation for a micro-founded bilateral trade cost measure. The benefits of this innovation are two-fold. First, the trade cost measure does not impose bilateral trade cost symmetry. It represents, instead, an average of bilateral trade barriers in both directions and it is therefore consistent with asymmetric trade costs. Secondly, this measure of trade costs is consistent with our definition of trade costs and includes all the costs associated with bringing a good to market, outside of the production costs. This is therefore, a much more comprehensive measure of trade costs, reflecting the full set of trade frictions associated with international trade. Novy (2008) argues the trade cost measure can be interpreted as a 'gravity residual' from the standard gravity equation and the empirical model is outlined in detail in section 4. First, let's zoom out and fit trade costs into gravity models and then into the wider theoretical framework of the field of economic geography.

## Section 3: Theoretical Predictions of Trade and Growth

**3.1: New Economic Geography Theory** Masahisa Fujita describes, “The defining issue of the new economic geography is how to explain the formation of a large variety of economic agglomeration (or concentration) in geographical space.” Agglomeration or the clustering of economic activity occurs at many geographic levels, having a variety of compositions including neighborhood, cities and industrial centers, and can often be characterized by high levels of inequality. Understanding what drives patterns of agglomeration is critical to understanding the complex global system of growth and competitiveness.

The current NEG model introduced by Paul Krugman in 1991 builds off of what Nicholas Kaldor calls ‘the irrelevance of equilibrium economics’ which refers to the long shadow cast by history and accident over the location of production. The home-market effect, an important fundamental in NEG models, is the tendency for large countries to be net exporters of goods with high transport costs and strong scale economies (Krugman (1980) and Helpman and Krugman (1985)). It is predicted by models of trade based on increasing returns to scale but not by models of trade based on comparative advantage. Thus, the NEG model is really a new trade model that includes pervasive increasing returns and imperfect competition; multiple equilibria; and an often decisive role for history, accident, and perhaps sheer self-fulfilling prophecy when measuring agglomeration patterns in trade. The 1991 introduction of the Core and Periphery Model tracks the distribution of economic activity across space as determined by a tension between both agglomeration and dispersion forces. The two agglomeration forces producing the “home market effect” are 1). increasing returns to scale and 2). transport costs which imply that firms want to concentrate production near to large markets. In addition, the “Price Index Effect” or consumer love of variety imply a lower cost to consumers of living near to large markets. These models characterized by the presence of increasing returns, monopolistic competition, and trade costs typically give rise to a more-than-proportional relationship between a country’s share of world production of a good and its share of world demand for the same good. Exporters in this scenario, prefer to use a large home market as an export platform. This effect can then be amplified by high trade barriers. It can also work contrary to traditional notions of comparative advantage in factor endowments or productivity. In the NEG model the key innovation is - endogenous location of demand where mobile workers consume where they work and firms require the outputs of the sector as intermediate inputs. The locational co-movement of productive factors and consumers is a prerequisite for agglomeration. From this theoretical framework of agglomeration outlined in NEG models above, the paper will focus on one of the five underlying forces in agglomeration- trade costs.

### 3.2: Gravity Models

NEG models are founded in general equilibrium and gravity based models. Gravity models are mathematical models based on Newton’s gravitational law and used to account for aggregate human behaviors related to spatial interaction such as migration, traffic flows, and trade. For trade flows the gravity model states that the volume of trade can be estimated as an increasing function of the national incomes of trading partners, and a decreasing function of the distance between them. Gravity based models have had great empirical success in explaining bilateral trade flows. In its simplest form the gravity equation explains flows of a good between pairs of countries in terms of the countries' incomes, distance, and a host of idiosyncratic factors- such as common border, common language, and common money- that enhance or reduce bilateral trade flows. The gravity equation can be written analytically:

$$M_{ijk} = A_{0k} Y_{ik}^{\alpha_{1k}} Y_{jk}^{\alpha_{2k}} d_{ij}^{\alpha_{3k}} U_{ijk} \quad \text{Model (1)}$$

Here $M_{ijk}$ denotes that the k good is exported by country i and imported by country j. $Y_{ik}$ & $Y_{jk}$ are expenditures on the k good by the two countries while d represents distance. A and α's are coefficients and U is a well behaved error term. Aggregating over all k goods, the gravity equation of a given product can be transformed into total exports of country i where now Y can be interpreted as GDP of a country i and j respectively:

$$M_{ijk} = A_0 Y_i^{\alpha_1} Y_j^{\alpha_2} d_{ij}^{\alpha_3} U_{ij} \quad \text{Model (2)}$$

Typically, equation 2 is specified in log linear form and estimated either with cross-section or panel data. In the latter case, a time subscript τ is added, except for the time-invariant physical distance and can be written analytically:

$$\ln(M_{ij\tau}) = \alpha_0 + \alpha_1 \ln(Y_{i\tau}) + \alpha_2 \ln(Y_{j\tau}) + \alpha_3 \ln(d_{ij}) + \alpha_4 F_{ij} + u_{ij\tau} \quad \text{Model (3)}$$

For simplicity in (3) the following terms are shortened: $\ln(A_0) = \alpha_0 \; and \; u_{ij\tau} = \ln(U_{ij\tau})$. The vector of idiosyncratic factors $F_{ij}$ has been included in equation 3 for completeness. The coefficients $\alpha_1 to \; \alpha_3$ are interpreted as elasticities or as percent changes in bilateral trade for one percentage change in income and distance. The coefficient $\alpha_4$ is positive if the factor is trade enhancing (e.g. common language) and negative if trade reducing (e.g. terrorism).

The NEG model introduced by Krugman in 1991 represents a new branch of economic geography, which aims to explain the formation of a large variety of economic agglomeration in geographical space, using a general equilibrium framework. To date, the NEG remains the only general equilibrium framework in which the location of agglomeration is determined explicitly through a micro-founded mechanism.[22] In particular, NEG models provide an innovation from classic trade theory in that they provide the analytical tools to incorporate: 1). Increasing Returns to Scale (IRS) that are internal to the firm; 2. Imperfect Competition; 3. Trade costs- including transportation costs; 4. Endogenous firm locations: firms enter and exit in response to probability at each possible location. IRS implies that firms have the incentive to select a single site; and 5. Endogenous location of demand-expenditure in each region depends upon the location of firms.

### 3.3: Location Theory

Gravity and NEG models find their roots in location theory which is concerned with the geographic location of economic activity. Location theory addresses the questions of what economic activities are located where and why. Location theory rests, like classic

[22] See Fujita and Mori (2005)

microeconomic theory, on the assumption that agents act in their own self interest, firms choose locations that maximize their profits and individuals choose locations that maximize their utility. While others including Richard Cantillon, David Hume, Sir James D. Steuart, Walter Isard, David Ricardo, and David Starrett have made core contributions, it was Johann Heinrich von Thünen's first volume of *Der Isolierte Staat* in 1826 that gave birth to location theory. In *Der Isolierte Staat*, von Thünen notes that the costs of transporting goods consumes some of Ricardo's economic rent and transportation costs vary across goods. Thus depending on economic rents, different land uses and use intensities he explains a product's location choice and distance from the marketplace. In his explanation of what factors lead to economic agglomeration, von Thünen, is not only considered the founder of location theory or modern day economic geography, but Paul Samuelson deems him one of the great economists who helped birth the modern economic 'model' which integrates logical deduction with factual experiment.

### 3.4: The First Law of Geography

Economic Geography's name departs from one of its' founding principles, the first law of geography. In short, the first law of geography states 'everything is related to everything else, but near things are more related than distant things'.[23] This principle is related to the law of universal gravitation which is synonymous with the concept of spatial dependence that forms the foundation of economic geography and NEG models. The spatial configuration of economic activities is the outcome of a process involving two opposing types of forces that is agglomeration (or centripetal) forces and dispersion (or centrifugal) forces. The observed spatial configuration of economic activities is then the result of a complicated balance of forces that push and pull consumers and firms. The gravity model has been widely used in empirical analysis and has been very successful in inferring effects of institutions such as customs unions, exchange rate mechanisms, ethnic ties, linguistic identity and international borders on trade flows. While gravity equations used in empirical applications are known for their strong fit to the data, the estimated empirical equations do not always correspond to those derived theoretically. The theory, first developed by Anderson (1979), tells us that after controlling for size, trade between two regions is decreasing in their bilateral trade barrier relative to the average (multilateral) barrier to trade of the two regions to trade with all their partners. The intuition then is the more resistant to trade a region has with all others a regions, the more it will trade with a given bilateral partner where barriers are relatively lower. Critical to the gravity model used in this paper, Anderson and van Wincoop (2003) define an average trade barrier based in theory and call it multilateral resistance with all other trading partners. Based on the importance of including multilateral resistance variables in gravity equations to obtain theoretically founded empirical results, this paper follows Novy (2008) gravity model based on Anderson and van Wincoop (2003) which defines trade costs directly from trade flows.

**Section 4: Empirical Strategy:** The structure of this paper follows from the format of Jacks, Meissner and Novy (2008) who focus on measuring trade costs in developed countries, particularly the US, the UK and France over the period 1870-2000. To measure trade costs between bilateral trading partners, they calculate trade costs between years which mark a

[23]See Tobler (1979)

significant shift in global trade- the prewar period (1870-1913); the interwar period (1921-1939); and the post-war period (1950-2000). Following their example, two important events occur over the period 1988-2006 in EU integration which can serve as natural experiments. The first, the Maastricht Treaty, or formally the Treaty of the EU, signed Feb. 1, 1992 by the European Community, led to the creation of the EU and the Euro. The second event is the Jan. 1, 2002 formal adoption of the euro by 12 countries.[24] Because both events were widely anticipated I assume instead of having strict regression discontinuities on the exact year 1992 and 2002, that there is a broader bandwidth of time which absorbss the effects of the events both before and after. For example, the introduction of the Euro in the 12 countries was widely anticipated prior to 2002 and thus it is plausible that the effects on trade costs may appear before the year 2002. For this reason, and as well as to avoid individual year biases, I choose to take three year averages of trade costs between groups as the primary measure of analysis. Finally, because of data limitations, the effects of the Maastricht treaty (1992) is hard to measure. Thus, I focus mainly on the introduction of the common currency in 2002 and the change in trade costs as a result between all EU members, non members, and large trading partners.

Given the available data from 1988-2006, this paper analyzes trade costs for 26 countries for which data is available including: 11 2001 Euro adopters, 3 EU member states who do not adopt the euro in 2001, 4 Central Eastern European Nations who join the EU in 2004, 3 continental Western European states who are not EU members by 2006[25], and 5 large non-continental trading partners of the EU. Because 1988 has the fewest observations of trade costs, I start my three year averages in 1989 and have the following six periods of time for my analysis: Period 1 (1989-1991); Period 2 (1992-1994); Period 3 (1995-1997); Period 4 (1998-2000); Period 5 (2001-2003); Period 6 (2004-2006). I focus on the 1995-2006 period instead of 1989-2006 because many countries in the data set lack data from 1989-1994. Thus, because in period 3 there is a large jump in sample size in trade costs values comparing period 3-6 with period 1 and 2 may have a composition effect, and hence the difference in means may be driven by number of observations instead of actual differences. Thus, I chose to compare periods which have only relatively similar number of observations. As a result, I compare periods 3-6 and periods 1-2, but not periods 1-6 (see Table 1).

**The Anderson and van Wincoop Gravity Model:** Anderson and van Wincoop (2003) develop their gravity model to measure the effects on trade of borders both intranationally between states and provinces inside the U.S. and Canada and the effects on trade by the international border between the U.S. and Canada. Their paper is a response to the McCallum (1995) empirical work, published in the American Economic Review, which measures similarly the effects on trade of borders between states and provinces and the international border between the US and Canada. For the year 1988, McCallum using gravity based equations in regression analysis, finds that trade between two provinces in Canada is 22 times larger than trade between a province in Canada and a U.S. state. This result created a large stir in the trade literature, prompting Gene Grossman (1998) to classify this result as unexpected, even more unexpected that Trefler's (1995) 'mystery of missing

[24] Countries who adopted the euro in 2002 include: Austria, Belgium, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Portugal, and Spain.

[25] Note among these 3 Western European states Iceland is included as Iceland's application for the EU was only recently accepted in 2009.

trade'.[26] Anderson and van Wincoop (2003) refute McCallum's (1995) findings and cite two key problems that contributed to McCallum's surprising results of large intra-provincial vs. province-state trade. First, they cite his regression analysis suffers from the problem of omitted variables particularly that of multilateral resistance terms which they correct for and introduce in their 2003 model.[27] Using their model, they find in the case of U.S. and Canada, that even a moderate multilateral barrier between Canada and the rest of the world has a large effect on intra-provincial trade.[28] They argue when economists take into account the multilateral barrier, McCallum's results that trade between two provinces in Canada is 22 times larger than trade between a province in Canada and a U.S. state are severely diminished. Given this example, I conclude the inclusion of multilateral resistance terms is imperative when measuring trade costs.

In their model, they define price differences between locations to represent trade costs that are not directly observable. They define $p_i$ to denote the exporter's supply price in country i, net of trade costs, and assume $t_{ij}$ to be the unobservable trade cost factor between i and j. Then $p_{ij}=p_i t_{ij}$. The exporter passes on these trade costs to the importer. Importantly they assume trade costs are symmetric, that is $t_{ij}=t_{ji}$, They model the unobservable trade cost factor $t_{ij}$ as a log linear function of observables where $b_{ij}$ is a border-related indicator variable, $d_{ij}$ is bilateral distance and ρ is the distance elasticity. Model 4 below is a formal representation of their definition of trade costs.

$$t_{ij} = b_{ij} d_{ij}^{\rho} \quad \text{Model (4)}$$

The key innovation of the Novy (2008) paper is the creation of a direct measure of trade costs ($t_{ij}$). This is an innovation because it does not assume a trade cost function (like the one illustrated in Model 4) when deriving trade costs. This avoids the potential problem in the Anderson and van Wincoop (2003) model where the trade cost function might omit important trade cost determinants and hence be misspecified. For example their trade cost function (shown above in Model (4)) omits tariffs among other factors affecting trade costs. Second, Novy's (2008) derivation of trade costs follows directly from trade flows which allows trade costs to be asymmetric, or one country to have higher tariffs than another. And third, the Novy (2008) model allows for trade costs to be time variant. The Anderson and van Wincoop (2003) micro-founded gravity equation which measures trade flows is represented in equation 5 below for the two country case:

$$x_{ij} = \frac{y_i y_j}{y^w} \left(\frac{t_{ij}}{\pi_i P_j}\right)^{1-\sigma} \quad \text{Model (5)}$$

Here $x_{ij}$ denotes nominal exports from i to j, $y_i$ is nominal income of country i and $y^w$ is world income defined as $y^w \equiv \sum_j yj$. Further, $\sigma > 1$ is the elasticity of substitution across goods and $\pi_i$ & $P_j$ represent country i's and country j's price indices. Bilateral trade costs ($t_{ij}$) decrease bilateral trade and in their model expressed by the equation 4 above and are measured against the price indices $\pi_i$ & $P_j$. Anderson and van Wincoop refer to these

[26] See Anderson and van Wincoop (2003)

[27] Multilateral resistance terms take into account the bilateral trade resistance barriers relative to all trade resistance barriers worldwide.

[28] This is mainly because Canada is a small open economy that trades a lot with the rest of the world.

aggregated price indices (6) and (7) below as multilateral resistance variables and assume trade costs with all other partners should be interpreted as average trade costs.

The exact expressions are given by:

$$\pi_i^{1-\sigma} = \sum_j P_j^{\sigma-1}\theta_j t_{ij}^{1-\sigma} \quad \forall_i \quad \text{Outward Multilateral Resistance Variable (6)}$$

$$P_j^{1-\sigma} = \sum_i \pi_i^{\sigma-1}\theta_i t_{ij}^{1-\sigma} \quad \forall_j \quad \text{Inward Multilateral Resistance Variable} \quad (7)$$

Here $\theta_j$is the world income share of country j defined as $\theta_j \equiv \frac{y_j}{y^W}$. While $\pi_i$ is the outward multilateral resistance variable as it includes bilateral trade costs $t_{ij}$ summed over and weighted by all destination countries j, whereas $P_j$ is the inward multilateral resistance variable as it includes bilateral trade costs $t_{ij}$ summed over and weighted by all origin countries i. There has been wide support in the economics field for the Anderson and van Wincoop (2003) gravity model as it is considered to be an empirical model which is well-founded in economics theory. In particular, model (5) above has theoretical foundations in Anderson's (1979) gravity model which is founded on preferences which are consistent with constant elasticity of substitution (CES) and goods which are differentiated by region of origin. Further model (5) applies the extension of Bergstrand (1989, 1990) and Deardorff (1998) who add monopolistic competition or a Hecksher-Ohlin structure to explain specialization. With the Anderson and van Wincoop (2003) model economists can derive a decomposition of trade resistance into three components: (i) the bilateral trade barrier between region i and region j; (ii) i's resistance to trade with all regions; and (iii) j's resistance to trade with all regions.[29] In the literature, these multilateral resistance variables (6 and 7) have traditionally been difficult to express explicitly. It is Novy's (2008) key innovation, building from the Anderson and van Wincoop (2003) gravity model expressed above in Model (5) that an analytical solution for multilateral resistance variables and hence an analytical measure of trade costs is derived directly from observed trade flows.

In order to do this, Novy uses the insight that a change in bilateral trade barriers does not only affect international trade but also intranational trade. For example, suppose that country i's trade barriers with all other countries increase. In that case, some of the goods that i used to ship to foreign countries are now consumed domestically, i.e., intranationally. It is therefore not only the extent of international trade that depends on trade barriers with the rest of the world but also the extent of intranational trade. To express this formally, beginning from the Anderson and van Wincoop (2003) model (5) he finds an expression for country i's intranational trade (5b).

$$x_{ij} = \frac{y_i y_j}{y^w}\left(\frac{t_{ij}}{\pi_i P_j}\right)^{1-\sigma} \quad (5) \qquad\qquad x_{ii} = \frac{y_i y_i}{y^w}\left(\frac{t_{ii}}{\pi_i P_i}\right)^{1-\sigma} \quad (5b)$$

Next he solves equation (5b) for the product of outward and inward multilateral resistance as:

$$\pi_i P_i = \frac{x_{ii}/y_i}{y_i/y_w}\ 1^{1/(\sigma-1)} t_{ii} \qquad (8)$$

[29] For further theoretical foundations of the model see Anderson and van Wincoop (2003).

For the explicit solution of multilateral resistance variables he multiples gravity equation (5) by the corresponding gravity equation for trade flows in the opposite direction $x_{ji}$ to obtain a bidirectional gravity equation (9) that contains both countries' outward and inward multilateral resistance variables.

$$x_{ij}x_{ji} = \left(\frac{y_i y_j}{y^w}\right)^2 \left(\frac{t_{ij}t_{ji}}{\pi_i P_i \pi_j P_j}\right)^{1-\sigma} \quad (9)$$

Next by substituting equation (8) into equation (9), Equation (10) follows:

$$x_{ij}x_{ji} = x_{ii}x_{jj}\left(\frac{t_{ii}t_{jj}}{t_{ij}t_{ji}}\right)^{\sigma-1} \quad (10)$$

Now the size variable in (10) is not total income $y_i y_j$ as in traditional gravity equations but intranational trade $x_{ii}x_{jj}$. Equation (10) can be rearranged and is represented in equation (11).

$$\frac{t_{ij}t_{ji}}{t_{ii}t_{jj}} = \left(\frac{x_{ii}x_{jj}}{x_{ij}x_{ji}}\right)^{\frac{1}{\sigma-1}} \quad (11)$$

Now shipping costs between i and j can be asymmetric ($t_{ij} \neq t_{ji}$) and domestic trade costs can differ across countries ($t_{ii} \neq t_{jj}$). Thus, it is useful to take the geometric mean of the barriers in both directions. Finally, to get the final expression for the tariff equivalent we subtract one.[30] Novy's new model represents micro-founded trade costs and is represented analytically in equation 12 below.

$$\tau_{ij} = \left(\frac{t_{ij}t_{ji}}{t_{ii}t_{jj}}\right)^{\frac{1}{2}} - 1 = \left(\frac{x_{ii}x_{jj}}{x_{ij}x_{ji}}\right)^{\frac{1}{2(\sigma-1)}} - 1 \quad (12)$$

To estimate a country's trade with itself, represented in the equation above as the $x_{ii}$ variable, I follow Shang-Jin Wei (1996) and Novy (2008). They show, due to market clearing, intranational trade $x_{ii} = y_i - x_i$ where $y_i$ is equal to GDP and $x_i$ is equal to total exports, defined as the sum of all exports from country i to the rest of the world. In a two country model of trade between countries i and j the sum of all exports to the rest of the world for country i can be represented as: $x_i = \sum_{j \neq i} x_{ij}$.[31] Thus, the $x_{ii}$ measure is most simply thought of as home demand or a country's total production minus its' total exports.

To ensure that the $y_i$ variable is consistent with the $x_i$ variable, I have to take into account that commonly GDP measures for the $y_i$ variable are based on value added accounting while the $x_{ij}$ or bilateral trade variables use gross shipments accounting. In order to compare like with like, I rely on GDP measures based on gross shipments accounting. To get the gross shipment counterpart of GDP I construct the $y_i$ variable using total goods production accounting. Further, because up to this point the EU is focused on the liberalization of goods I construct all the variables for only the three main tradeable goods sectors- agriculture, mining, and total manufacturing.[32] All variables were transformed to purchasing power parity (PPP) in US dollars by sector to equalize the purchasing power of different countries and thus eliminate differences in price levels between countries. When converted to PPP, the expenditures on GDP for different countries are in effect expressed at the same set of

[30] See Novy (2008) for details.
[31] The $x_{ij}$ variable is simply the exports from country i to country j.
[32] This is consistent with Novy (2008).

prices so that comparisons between countries reflect only differences in the volume of goods purchased. I use the GDP deflator for US$ PPP and hence make the implicit assumption that the inflation rate for the other countries have a similar sectoral composition. This assumption has the potential to bias for economies that are like the US in sectoral composition. However, in my view, the benefits of comparing trade costs in PPP outweigh the lesser costs which come from this transformation.

I follow directly Anderson and van Wincoop (2003) who recommend the optimal level for the elasticity of substitution for industrialized countries be set at σ=8. They cite this elasticity as it is the middle number of the common empirical range of 5 to 10 found for the elasticity of substitution among a survey of empirical work. Intuitively a higher elasticity of substitution means that goods are less differentiated and consumers are more price-sensitive. The more price-sensitive consumers are the fewer foreign goods they would consume if a positive trade cost is associated with foreign goods.[33] It could be argued that the assumption of identical elasticities across sectors is not realistic and should be at least set by sector. But although the elasticity of substitution effects the level of $\tau_{ij}$, it hardly affects the change of $\tau_{ij}$ over time. Thus I choose to set the elasticity of substitution at 8.

Finally, the overall intuition behind the trade costs measure, $\tau_{ij}$, expressed in equation (12) is if bilateral trade flows $x_{ij}x_{ji}$ increase relative to domestic trade flows $x_{ii}x_{jj}$ it must have been easier for the two countries to trade with each other. This new measure is more accurate as it is not an estimation of trade costs indirectly through an assumption, but a measure derived directly from the data.

**Section 5: Data**

All the data for the 26 countries comes from the OECD Structural Analysis (STAN) database. Each of the variables is constructed only to include the tradeable goods sectors- agriculture, mining, and manufacturing. The data was carefully constructed also to ensure that if one of the time series variables was missing a sector, all the other variables dropped that sector as well to make the data for a country comparable over time.[34] Finally, the data was triple checked to avoid measurement error. Given the available data from 1988-2006, this paper computes trade costs for 26 bilateral country pairs. Available data allowed us to measure 11 EU member states who adopt the euro in 2001, three EU member states who do not adopt the euro in 2001, three Western European nations who are not part of the EU, four 2004 Central Eastern European member accession states, and five non-continental European large trading partners.[35] The split between former Czechoslovakia is a non-issue in data

[33] Here I assume that all trade costs are directly passed on to the consumer.

[34] Note both France and Portugal are missing all mining data for the yi variable and thus all other variables have been created to include only the agriculture and manufacturing sector. For the xi variable the following sectors are missing and have been corrected for all other relevant variables: 1).Luxembourg missing entire sector of mining data for the following four countries: Greece, Korea, New Zealand, Slovak Republic; and missing the entire Agricultural Sector for New Zealand; 2). Iceland is missing entire sector of mining data for both Luxembourg and New Zealand; 3). Korea is missing the entire sector of mining and agriculture for Luxembourg; 4). Japan is missing the entire sector of mining for Luxembourg; 5). Hungary is missing the entire sector of mining for Finland; 6). Greece is missing the entire sector of mining for New Zealand; 7). Czech Republic is missing the entire sector of mining for New Zealand; 8). Norway is missing the entire sector of mining data for the following three countries: Czech Republic, Luxembourg, Slovak Republic.

[35] The 11 EU member states who adopt the euro in 2001 include: Austria, Belgium, Finland, France, Germany, Greece, Italy, Luxembourg, Netherlands, Portugal, and Spain. The three EU member states who do not adopt the euro in 2001 are Denmark, Sweden, and the UK and the three Western European nations who are not part of the EU in 2006 are Iceland,

analysis because data available from the former Czechoslovakia is not sufficient to construct the trade costs measure and thus it is not included.

To test robustness I measure trade costs over three year averages and again for five year averages. The results are very similar for trade costs across both three and five-year averages and no large difference is observed (see Figure 2). Given the large similarity between the three-year and five-year trade costs measures across all bilateral partners, I focus on three-year averages as the main form of analysis.

**Section 6: Empirical Results**

The main outcome indicator is the net change in trade costs between bilateral trade grouping partners over three year average periods. Let's begin by looking at the macro changes over comparable periods from Period 6 (2004-2006) and Period 3 (1995-1997). Importantly, all the different trade group pairings show a drop in trade costs over the period (see figure 1). This supports the argument that regionalism in the case of the EU is a building bloc towards multilateralism. Given prolific expansion of regional trading agreements, one would expect this second wave of regionalism to be accompanied by a drop in trade costs at a global level. This has been the case as the five large non-continental Europe trading partners- Canada, Japan, New Zealand, South Korea, and the U.S. exhibit a 5% drop in trade costs with each other over this period. Despite the fact that these five countries are a small sub-sample of trade costs between large industrialized non-continental European countries, it reflects an important trend. Particularly, this 5% drop is much less than the intra 2001 Euro adopters drop in trade costs of 53% over the same period. And even if the 5% drop in trade between Canada, Japan, New Zealand, South Korea, and the U.S. from Period 6 (2004-2006) and Period 3 (1995-1997) is not representative of a global trend and is relatively low compared to trade costs drops between other highly industrialized countries without data available; the relative drop in trade costs among 2001 Euro adopters over the same period is substantially larger. This indicates a higher rate of change in drop of trade costs between Euro adopters than between large industrialized non-European partners over the same period.

From Table 1, figure 1, and figure 6, using three-year averages, the results in changes in trade costs between period 6 (2004-2006) and period 3 (1995-1997) reinforce that history and patterns of integration matter. Trade costs drop the most during this period for nations which share the highest level and the longest history of integration. Trade costs over this period for the inner six- founders of the 1952 European Coal and Steel Community- Belgium, France, Germany, Italy, Luxembourg, and the Netherlands fell by 73%. It is not surprising that these six nations exhibit the largest drop in trade costs as not only have they been integrating since the 1950s but they all adopted the common currency in 2001. The second largest drop in trade costs is for trade between 2001 Euro adopters (53%).

In order to assess whether our empirical results concur with the core periphery theory which predicts the Core of the EU should successfully spread growth to the Periphery we

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Norway, and Switzerland, the four 2004 Central Eastern European EU member accession states include the Czech Republic, Hungary, Poland, and the Slovak Republic, and the five non-continental European large trading partners including Canada, South Korea, Japan, New Zealand, and the U.S..

group our bilateral trade costs measures to reflect Core-Periphery. To experiment with different identities of which countries make up the Core and which make up the Periphery of the 2001 Euro adopters I include the following three groupings of the Core and Periphery:

Group 1). Core: Austria, Belgium, France, Germany, Italy, Luxembourg, the Netherlands and the UK; Periphery: Greece, Finland, Portugal, Spain, and Switzerland

Group 2). Group 1 Core + Switzerland; Group 1 Periphery – Switzerland

Group 3). Group 1 Core- Italy; Group 1 Periphery + Italy

Figure 7 shows the main results of these three different Core-Periphery groupings and particularly how the trade costs intra-Core differ in relation to the trade costs of Core-Periphery between the period 6 (2004-2006) and period 3 (1995-1997). Among the 2001 Euro adopters plus Switzerland and the UK, trade costs are on average 24% lower intra-Core than Core-Periphery. Thus the empirical results show even among the highly integrated economies who lead growth in Western Europe, there is evidence that the Core-Periphery theory is slow in being realized empirically.

Switching back to our analysis of how the introduction of the euro fared on different EU trading partners, let us examine the empirical results for the change in trade costs for the Central Eastern European countries who became EU members in 2004. As previously stated, from figure 1, the second largest drop in trade costs (not including the Core-Periphery specifications) is for trade between 2001 Euro adopters and the 2004 Central European accession states. The drop is a striking 49% on average over the period. Much of this large drop in trade costs can most likely be attributed to extra-EU policy and particularly the regime policy shift by the Central Eastern European countries over this period from centrally planned economies to that of free market economies. In order to interpret these results, it is important to attempt to disaggregate the two effects- that of the large removal of barriers on trade associated with the shift to a free market economy and that of accession into the European Union. To disaggregate the country level effects from the wider policy shift towards free market policies in the Central Eastern European countries, I compare bilateral trade costs between a). the Central Eastern European countries and 2001 Euro adopters and b). the Central Eastern European countries and the non-continental Europe large trading partners. Figure 4 shows between period 6 (2004-2006) and period 3 (1995-1997) Group a's bilateral trade costs drop on average by 49% while group b's average trade costs drop by 32%. Thus, about two-thirds of the 49% drop in trade costs with EU 2001 euro zone members can be attributed to the wider policy shift towards free market economies in Central Eastern Europe. Assuming the 32% trade costs drop over the period with the large non-continental Europe trading partners is indicative of the overall trend, we can conclude that the drop in trade costs between Central Eastern Europe 2004 accession members and 2001 euro adopters remains large, at least 17% larger than with other non-continental European large trading partners over the same period.

In figure 1, the third position for the largest drop in trade costs is that between 2001 currency adopters and the five large non-continental Europe trading partners (not including the Core-Periphery groupings), of 45%. This relatively large drop in trade costs between

2001 Euro adopters and the five large non-continental European countries demonstrates the EU has had net positive effects on the multilateral trading system.

The fourth and fifth position for largest drop in trade costs are very close in values and are as following. The fourth position is for a drop of 37% over the period for 2001 currency adopters paired with other European countries not in the EU. The fifth position represents a drop of 33% between 2001 currency adopters paired with members in the EU who did not adopt the common currency. This comparison between these two groups can be seen in Figure 5. The results that non members of the EU had larger gains in trade or bigger drops in trade costs over the period than those who are members but did not adopt the common currency could have several implications. In particular, for the three nations which make up the group of European countries which are not members of the EU in 2006- Iceland, Norway, and Switzerland- there are good reasons why these nations may have low trade costs with the EU. Both Norway and Switzerland have long harmonization and trading histories with the EU 2001 currency adopters. And Iceland, as a small economy, is a net importer nation and thus has large incentives to keep trade barriers to a minimum to stay competitive. Notably, Norway was previously part of a currency union with two current EU members- Denmark and Sweden- indicating high levels of economic integration between the three economies.[36] Switzerland is also a special case due to the banking sector's large success and historical role among nations in Western Europe. Further, while not a formal member of the EU, Switzerland has ratified several integration measures including the free movement of people. All these factors point out that these three countries trade costs with the 2001 Euro adopters may be slightly lower than trade costs between Denmark, Sweden and the UK, due to the particular case of each of these three countries. While one cannot ignore trade theory which predicts deepening regional integration will increase trade and lower trade costs. And the slightly larger drop in trade costs between non EU members and 2001 Euro adopters vs. EU members who do not adopt the currency and 2001 Euro adopters could be interpreted as a contradiction to this theory. Yet, given the very heterogeneous starting conditions and high levels of integration for all 6 countries historically with the 2001 Euro adopters, I interpret these results to indicate that for these 6 nations an almost equal drop in trade costs is observed (33% vs. 37%). Of course, ex post it is difficult to say whether the trade costs drop observed between Denmark, Sweden, and the UK and the 2001 Euro adopters would have been at least as good if they had not joined the EU. These results confirm a much more in depth study focused on the 5 countries is merited (Iceland has subsequently joined the EU). Finally, the similar drop for non-EU members with 2001 Euro adopters is another sign that the EU as a regional bloc is trade creating for multilateralism.

The lowest drop in trade costs is associated with internal trade between large trading partners from non-continental Europe. Thus, the 5% aggregated drop in trade costs between Canada, Japan, Korea, New Zealand, and the U.S. can be viewed as an indicator of the movement of global trade in industrialized nations over the period. This 5% drop over the 1995-2006 period is much smaller than the drop in trade costs between 2001 currency adopters and any other bilateral pair-grouping in our analysis. Assuming the change in trade costs can serve as a proxy for the level of EU integration between different member states,

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[36] Past research, Foss et al (2000), suggest that Norway and Sweden are two relatively similar countries in many respect, with both countries' regional policy aims and measures moving towards the EU's. However, because of EU membership Sweden's regional policy is moving faster than Norway's.

this relatively larger trade costs drop intra 2001 Euro adopters (-53%) vs. intra-non-continental European large trading partners (-5%) indicate a high level of integration intra 2001 Euro adopters relative to integration of other large trading partners outside the EU. This result empirically supports the first law of geography and NEG models as we observe nations which are physically closer have lower bilateral trade costs indicating a negative relationship between trade and distance. The nearly 11 times observed larger drop in trade costs between intra-EU 2001 currency adopters and 2001 currency adopters and large non-continental trading partners indicates that the EU is functioning and creating relatively higher levels of integration between its' members than outside partners.

**Section 7: Conclusions and Recommendations for Future Research**

This work benefits from a new direct measure of trade costs introduced by Novy (2008) which instead of measuring trade costs through a proxy measures trade costs directly based on observed bilateral trade flows. The empirical results of trade costs over the period 1988-2006 and particularly focused on the comparable period 1995-2006 are clear. The biggest drop in trade costs over the 1995-2006 period is for intra-EU members who adopt the 2001 currency (53%). Thus, despite skeptics critique that the EU integration is relatively shallow and has not been successful, the quantitative comparative measures of country groupings' bilateral trade costs prove the Euro zone has had substantial effects on its' members trade costs. A more detailed look at trade costs between different Core and Periphery members of the 2001 Currency adopters shows among the 2001 Euro adopters plus Switzerland and the UK, over the main period of study 1995-2006, trade costs are on average 24% lower intra-Core than Core-Periphery. Thus the empirical results show even among the highly integrated economies who lead growth in Western Europe, there is evidence that the Core-Periphery theory is slow in being realized empirically. This could be a sign of caution for EU policymakers in enlarging the Union. In particular, if trade costs are relatively higher for the Periphery and Core of the 2001 Euro adopters, whose nations are by far much closer in history and past trading patterns, other more recent members could expect longer lag times for real economic integration.

While the Core-Periphery theory is slow to be realized in our empirical results of trade costs over the 1995-2006 period; trade costs among EU members and Euro adopters are relatively large- 33-53%- when compared to trade costs measured for the non-continental European trading partners-5%. The second largest gain is that of the Central Eastern European countries paired with 2001 Euro adopters, with a 49% drop. After I net out the wider policy shift of the Central Eastern European economies to free market economies, trade costs between the 2001 EU currency adopters and the Central European Economies remain a sizeable 17% above the global average drop in trade costs.

The third largest drop in trade costs over the 1995-2006 period are aggregated trade costs between the non-continental European large trading partners and the 2001 Euro adopters, a 45% drop. Thus, even large trading partners outside of continental Europe have seen large relative gains in competitiveness (large drops in trade costs) due to EU integration and particularly due to the adoption of the Euro. Given these empirical results, this research points towards EU integration as a 'building bloc' rather than a 'stumbling bloc' to multilateral integration. The experience of Non-EU Western European countries-Iceland, Norway, and Switzerland- 37% drop in trade costs- and the 2001 EU members-Denmark, Sweden, and the UK- 33% drop in trade costs- with 2001 Euro adopters support that the EU is trade creating also for Western European nations which do not adopt the Euro, both inside and outside the EU.

Even for new accession members with vastly different economic history and trading patterns, membership in the EU has lead to relatively large drop in trade costs, 7-11 times that of intra-EU non continental large trading partners in the recent period (1995-2006). These results point out the EU is fulfilling its' purpose by increasing regional integration among its' members and is an empirical testament to the EU's success at integrating diverse economies within the union.

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## Contents for Tables, Figures, and Appendices

## Table 1: Changes in Trade Costs (TC) over the Period 1989-2006 for 2001 Euro Adopters[1] and Other Relative Country Groupings (Three Year Averages)[2]

| Country Groups (a-h) | | | Changes in Trade Costs Period 2-1 | Changes in Trade Costs Period 4-3 | Changes in Trade Costs Period 5-3 | Changes in Trade Costs Period 6-3 |
|---|---|---|---|---|---|---|
| | | | (1994:1992)-(1991:1989) | (2000:1998)-(1997:1995) | (2003:2001)-(1997-1995) | (2006:2004)-(1997:1995) |
| a | Intra-2001 Euro adopters | TC | -4% | -43% | -50% | -53% |
| | | n | 193 | 281 | 293 | 293 |
| b | 2001 Euro adopters paired with Members of the EU in 2001 who did not adopt the common currency[3] | TC | -3% | -25% | -30% | -33% |
| | | n | 156 | 162 | 183 | 183 |
| c | 2001 Euro adopters paired with Central Eastern European Countries who become EU members in 2004[4] | TC | ... | -27% | -42% | -49% |
| | | n | 0 | 226 | 232 | 232 |
| d | 2001 Euro adopters paired with other European countries not in the EU[5] | TC | -2% | -27% | -32% | -37% |
| | | n | 159 | 184 | 186 | 187 |
| e | 2001 Euro adopters paired with Large Trading Partners from Non-Continental Europe[6] | TC | -1% | -26% | -33% | -45% |
| | | n | 225 | 307 | 312 | 285 |
| f | Bilateral Trade between Large Trading Partners from Non-Continental Europe[6] | TC | 5% | -4% | -4% | -5% |
| | | n | 40 | 60 | 60 | 49 |
| g | Bilateral Trade between Inner Six-France, Germany, Italy, Belgium, Netherlands, and Luxembourg | TC | -2% | -65% | -71% | -73% |
| | | n | 54 | 65 | 72 | 72 |
| h | Bilateral Trade between Non-Inner Six 2001 Euro adopters-Austria, Finland, Greece, Portugal, & Spain | TC | -5% | -8% | -8% | -9% |
| | | n | 36 | 60 | 60 | 60 |

1. 2001 EU Member and Currency Adopters include the following 11 countries: Austria, Belgium, Finland, France, Germany, Greece, Italy, Luxembourg, the Netherlands, Portugal, and Spain. Data was not available for Ireland.

2. Data is from the OECD STAN Database and is available only for the following 26 EU, European, and other Trading Partners: Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Japan, Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Poland, the Slovak Republic, Spain, Sweden, Switzerland, UK, and the US.

3. Members of the EU in 2001 who did not adopt the common currency include: Denmark, Sweden, and the UK.

4. The Central Eastern European Countries who are EU Accession members and Currency Adopters in 2004 include: the Czech Republic, Hungary, Poland, and the Slovak Republic

5. Other European Countries not in the EU during this time period include: Iceland, Norway, and Switzerland.

6. Large Trading Partners from Non-Continental Europe include: Canada, Korea, Japan, New Zealand, and the U.S.

| Table 1B: Trade Costs over the Period 1989-2006 for 2001 Euro Adopters[1] and Other Relative Country Groupings (Five Year Averages)[2] | | | | | |
|---|---|---|---|---|---|
| Country Groups (a-h) | | | Changes in Trade Costs Period 2-1 | Changes in Trade Costs Period 3-2 | Changes in Trade Costs Period 4-2 |
| | | | (1997:1993)-(1988:1992) | (2002:1998)-(1997:1993) | (2006:2003)-(1997-1993) |
| a | Intra-2001 Euro adopters | TC | -5% | -46% | -52% |
| | | n | 353 | 456 | 413 |
| b | 2001 Euro adopters paired with Members of the EU in 2001 who did not adopt the common currency[3] | TC | -4% | -26% | -31% |
| | | n | 268 | 296 | 267 |
| c | 2001 Euro adopters paired with Central Eastern European Countries who become EU members in 2004 and adopt currency[4] | TC | -2% | -36% | -50% |
| | | n | 156 | 360 | 322 |
| d | 2001 Euro adopters paired with other European countries not in the EU[5] | TC | -4% | -29% | -35% |
| | | n | 267 | 302 | 273 |
| e | 2001 Euro adopters paired with Large Trading Partners from Non-Continental Europe[6] | TC | -6% | -30% | -43% |
| | | n | 401 | 496 | 420 |
| f | Bilateral Trade between Large Trading Partners from Non-Continental Europe[6] | TC | 9% | -2% | -3% |
| | | n | 73 | 96 | 75 |
| g | Bilateral Trade between Inner Six-France, Germany, Italy, Belgium, Netherlands, and Luxembourg | TC | 1% | -64% | -69% |
| | | n | 90 | 113 | 105 |
| h | Bilateral Trade between Non-Inner Six 2001 Euro adopters-Austria, Finland, Greece, Portugal, & Spain | TC | -10% | -9% | -11% |
| | | n | 72 | 92 | 82 |

1. 2001 EU Member and Currency Adopters include the following 11 countries: Austria, Belgium, Finland, France, Germany, Greece, Italy, Luxembourg, the Netherlands, Portugal, and Spain. Data was not available for Ireland.

2. Data is from the OECD STAN Database and is available only for the following 26 EU, European, and other Trading Partners: Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Japan, Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Poland, the Slovak Republic, Spain, Sweden, Switzerland, UK, and the US.

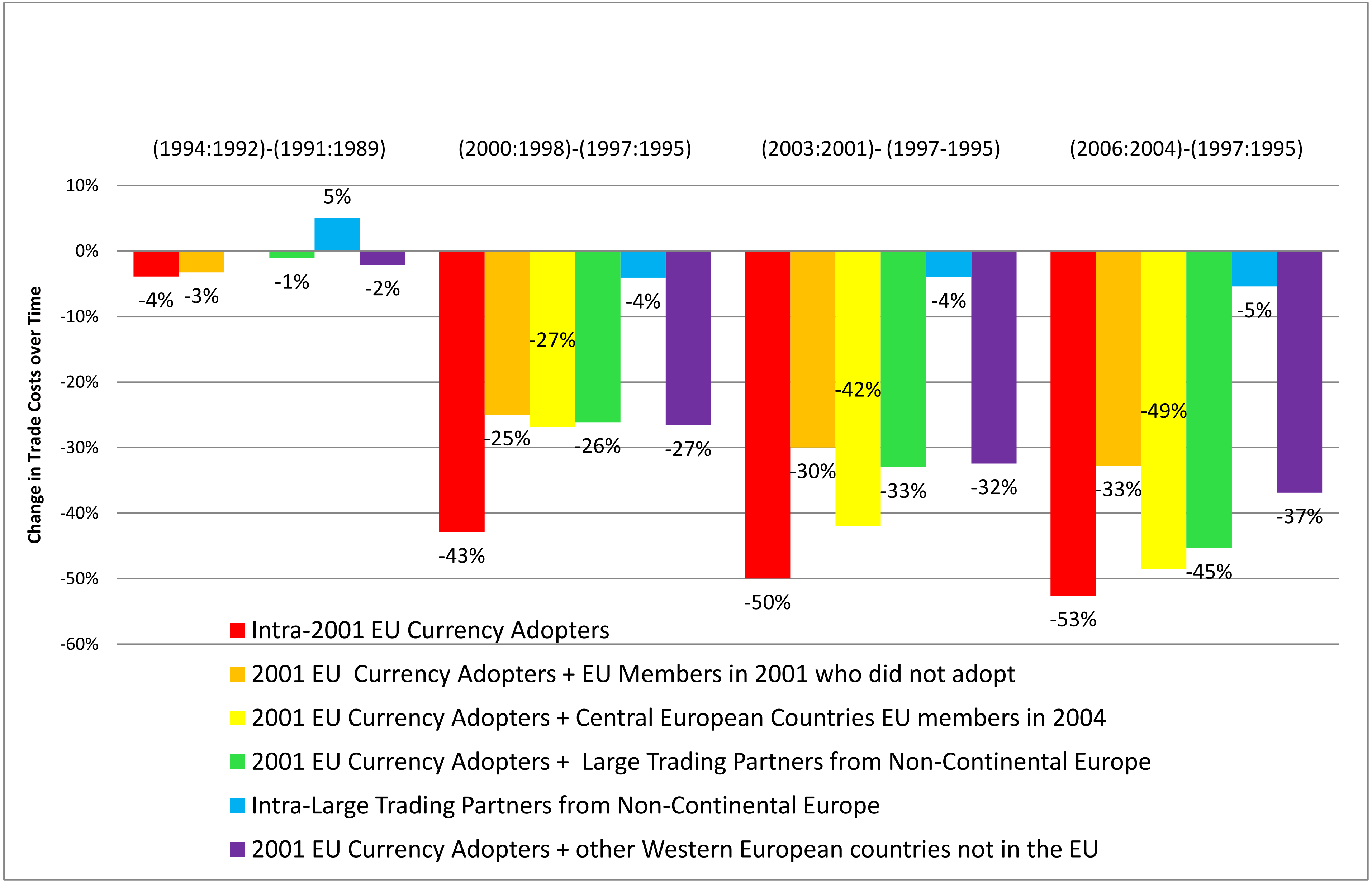
3. Members of the EU in 2001 who did not adopt the common currency include: Denmark, Sweden, and the UK.

4. The Central Eastern European Countries who are EU Accession members and Currency Adopters in 2004 include: the Czech Republic, Hungary, Poland, and the Slovak Republic

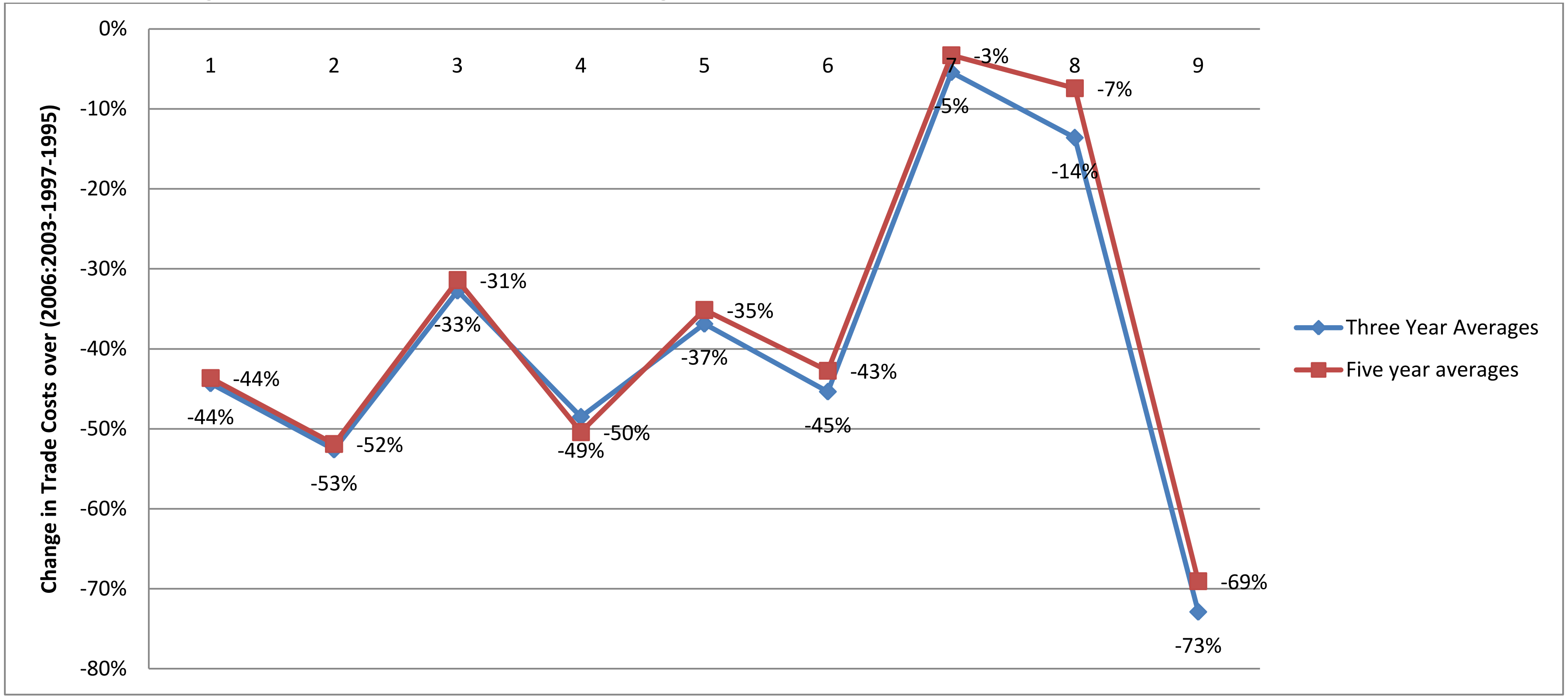
5. Other European Countries not in the EU during this time period include: Iceland, Norway, and Switzerland.

6. Large Trading Partners from Non-Continental Europe include: Canada, Korea, Japan, New Zealand, and the U.S.

**Figure 1 : Difference in Trade Costs over Relevant years for Different Bilateral Trade Groupings**

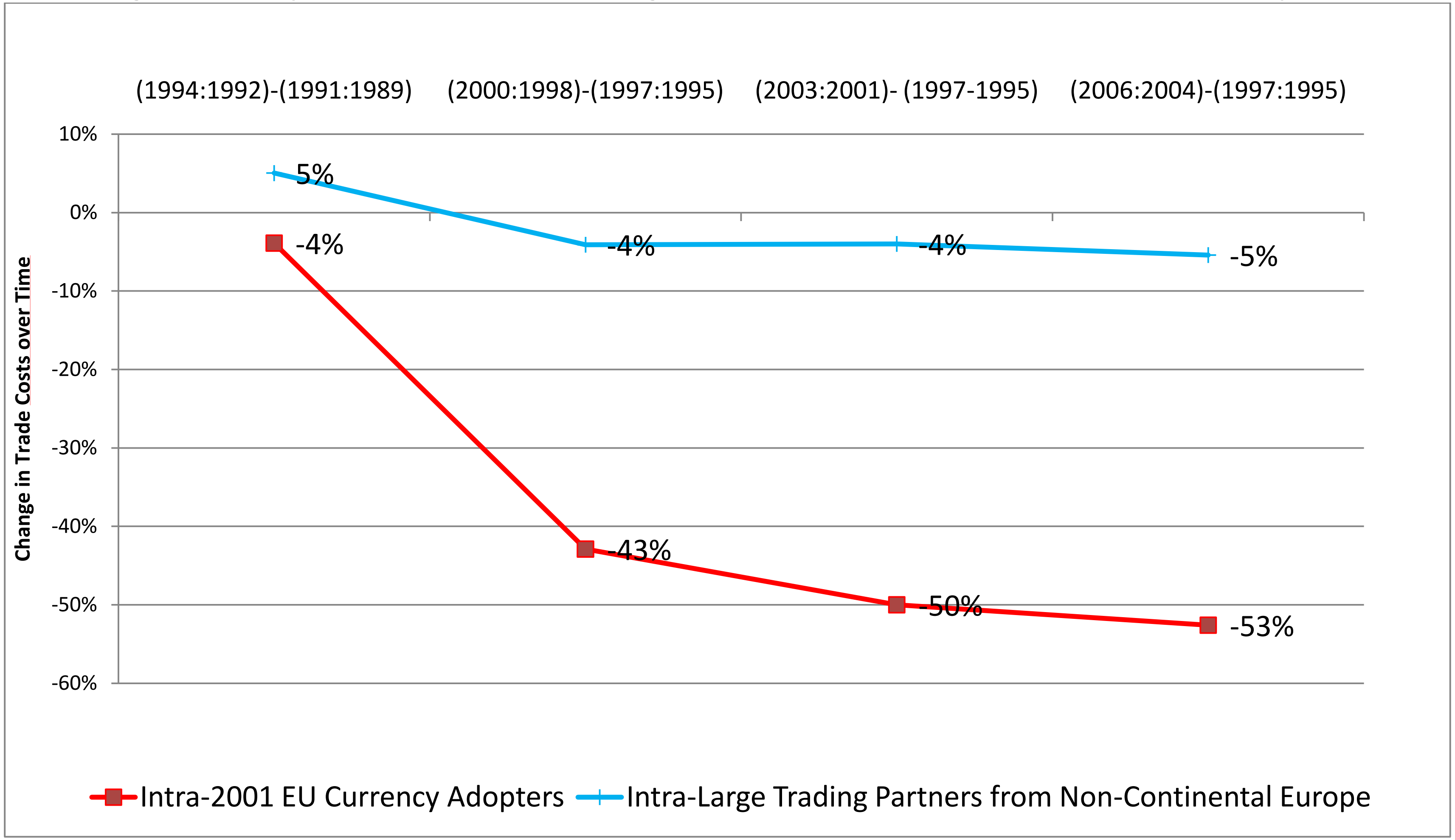


## Figure 2: Three and Five Year Average Differences in Trade Costs for Bilateral Partners 1-9




| Key for Bilateral Trade Partners Represented | |
|---|---|
| 1 | 2001 Euro adopters paired with all Continental Europe Bilateral Trading Partners |
| 2 | 2001 Euro adopters Paired with 2001 EU Member and Currency Adopters |
| 3 | 2001 Euro adopters paired with Members of the EU in 2001 who did not adopt the common currency |
| 4 | 2001 Euro adopters paired with Central European Countries who become EU members in 2004 |
| 5 | 2001 Euro adopters paired with other European countries not in the EU |
| 6 | 2001 Euro adopters paired with Large Trading Partners from Non-Continental Europe |
| 7 | Bilateral Trade between Large Trading Partners from Non-Continental Europe |
| 8 | Bilateral Trade between Large Trading Partners and European states who are not part of the 2001 common currency |
| 9 | Bilateral Trade between Inner Six-France, Germany, Italy, Belgium, Netherlands, and Luxembourg |

**Figure 3: Proxy for Global Trends of Changes in Trade Costs Relative to the 2001 Euro adopters**



## Figure 4: Bilateral Trade Costs for the Central Eastern European 2004 Accession Members

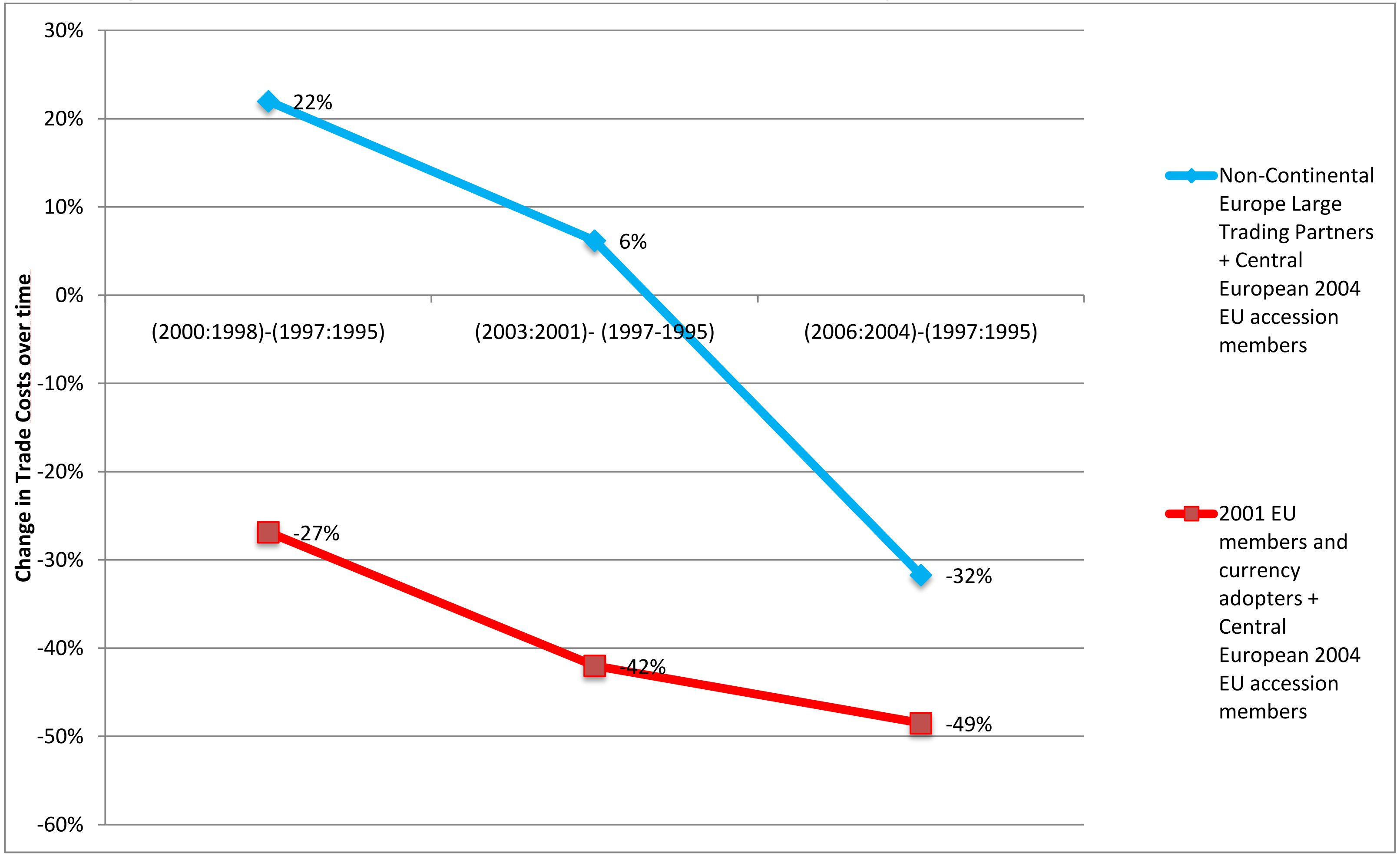


**Figure 5: Difference in Change in Trade Costs between EU Members who do not adopt the common currency Vs. Continental Western Europe nations who are not in the EU in 2006 both partnered with 2001 Euro adopters**

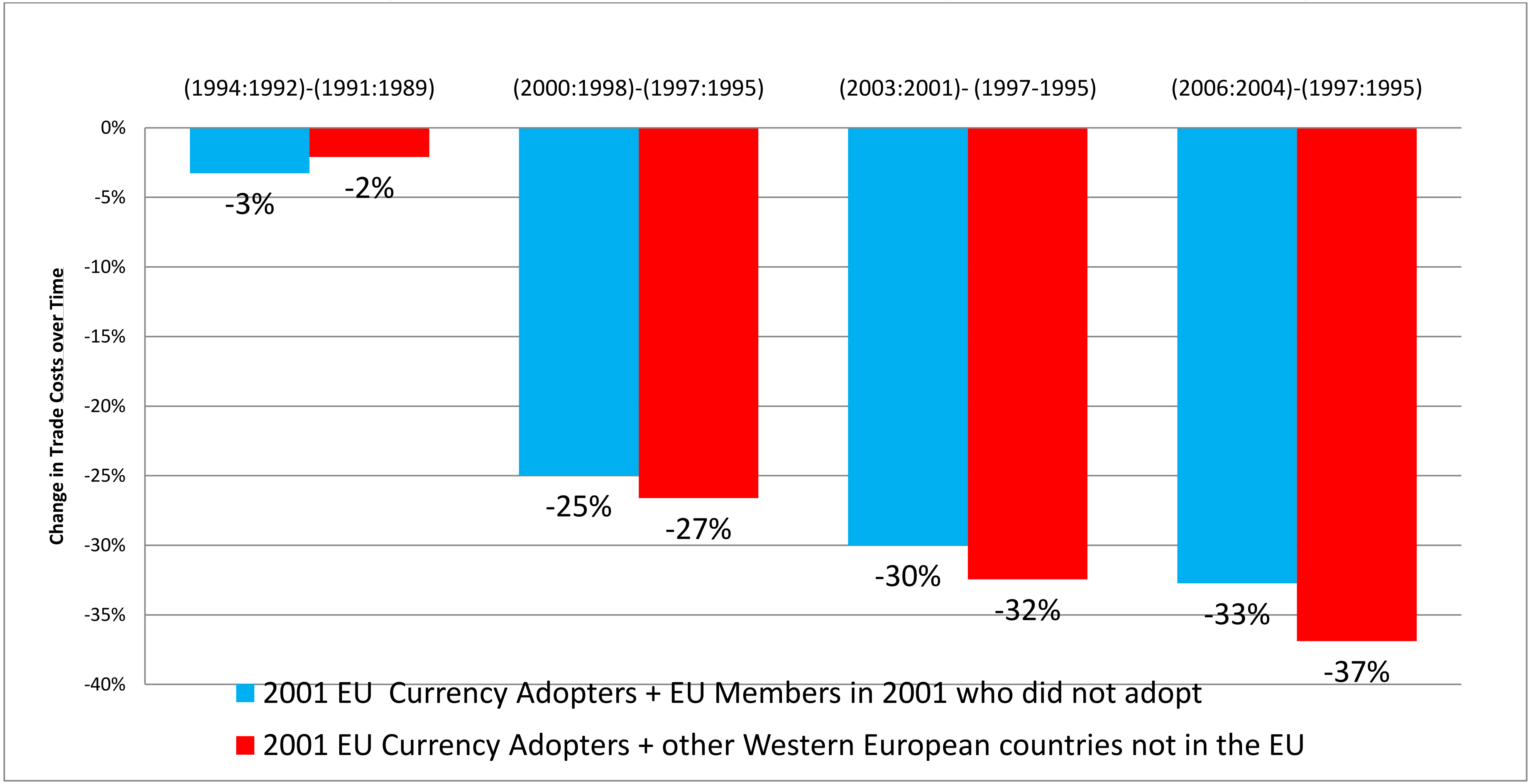
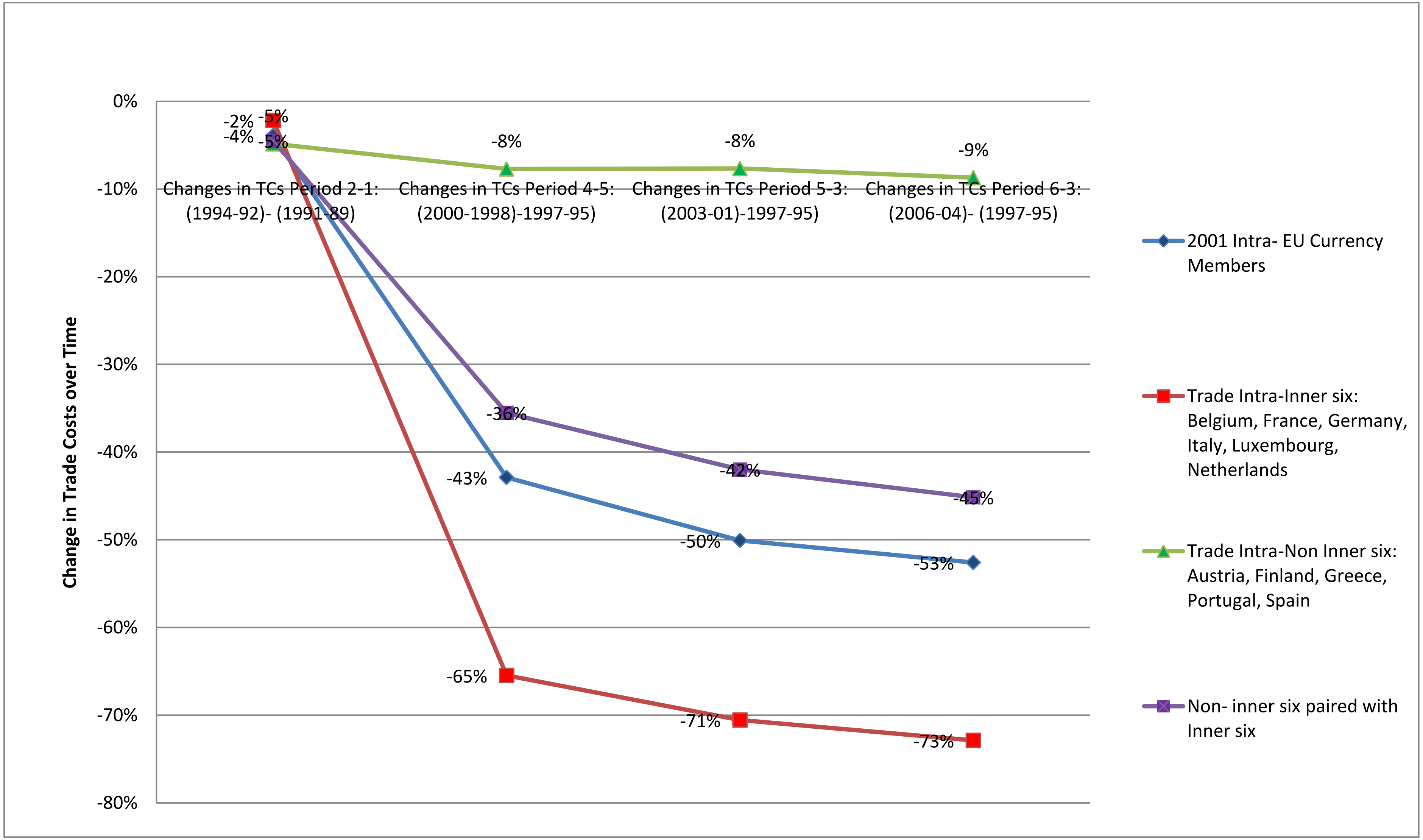
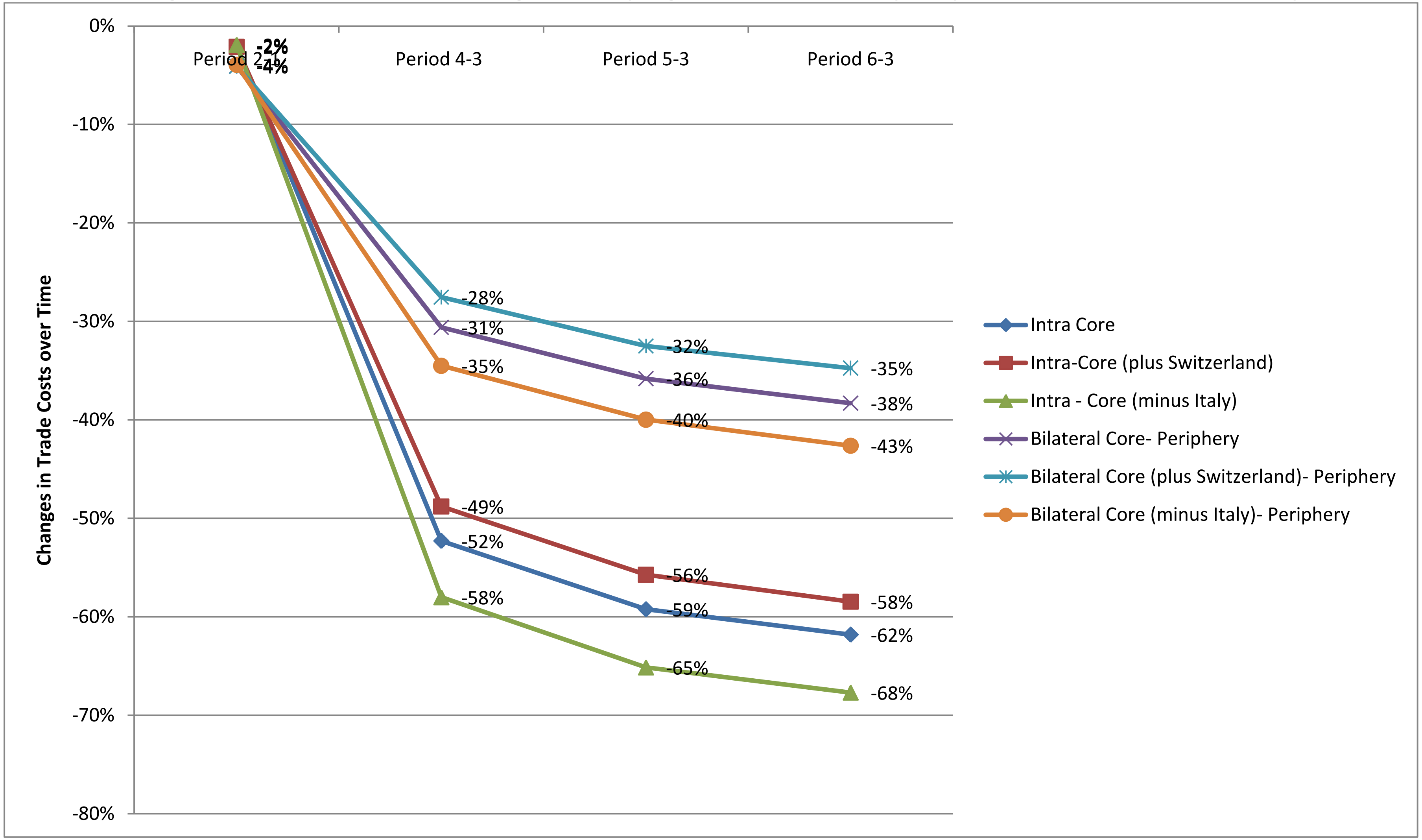


**Figure 6: Trade Costs for intra-EU inner six, intra-2001 Euro adopters and intra 2001 Euro adopters who are not part of the inner six**

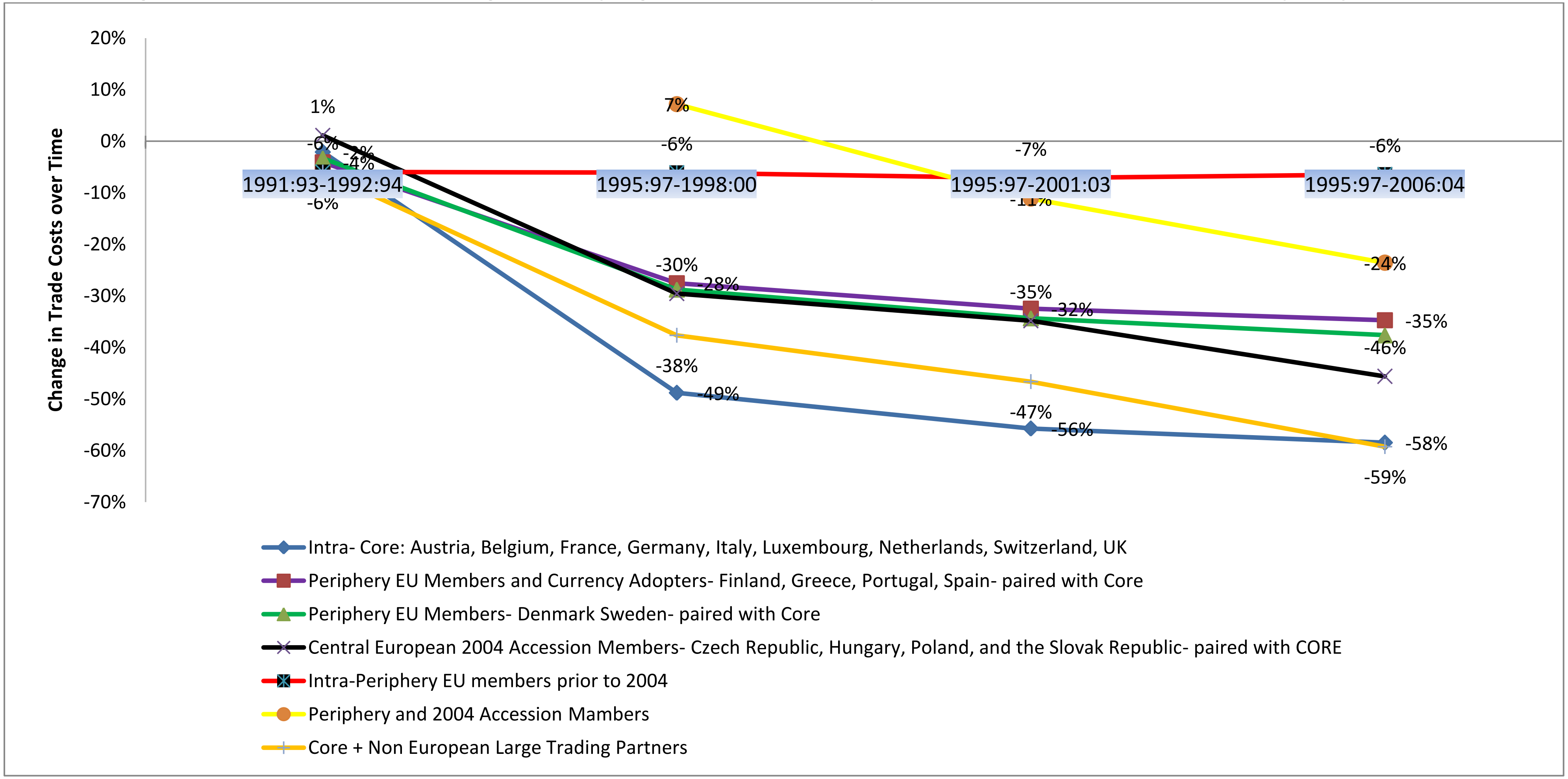


## Figure 7: Trade Costs According to Groupings of Core and Periphery Countries in Western Europe




| Key for Bilateral Trade Partners Represented | |
|---|---|
| 1a | Core represents: Austria, Belgium, France, Germany, Italy, Luxembourg, Netherlands, UK |
| 1b | Periphery: Finland, Greece, Portugal, Spain Switzerland |
| Two additional Core-Periphery Groups are used for comparison. The second Core Group is Core group 1a plus Switzerland. The third group is Core group 1a minus Italy. | |

**Figure 8: Trade Costs According to Groupings of Western European Countries in the Core or Periphery**

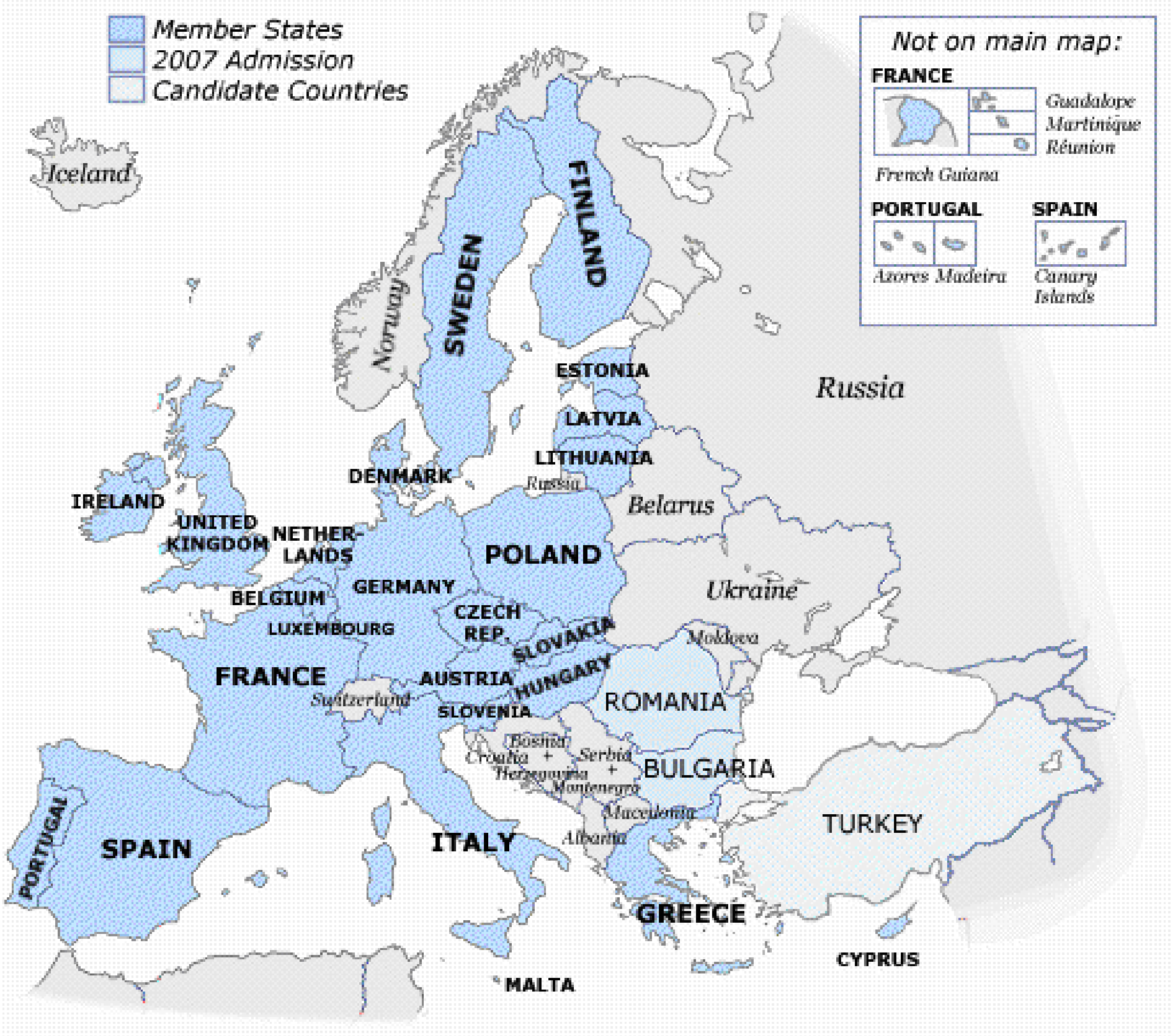


## Annex 1: EU Formation- Brief History of Key Dates

| Date | Countries | Count of Countries who Join EU | Count of Countries in the Euro zone |
|---|---|---|---|
| Up until 1914 | Denmark, Norway, Sweden had common currency but split at outbreak of WWI | 0 | |
| 1951-1952 | Inner Six- France, Italy, Belgium, Netherlands, Luxembourg, and West Germany | 6 (Though this point in history Belgium, Netherlands, and Luxembourg were one entity as the Benelux Countries) | |
| 1957 | Rome Treaty | | |
| 1972 | Norway referendum- No vote on EU | Notably Norway remains not a EU country | |
| 1973 | UK, Denmark, Ireland | 9 | |
| 1981 | Greece | 10 | |
| 1986 | Spain and Portugal | 12 | |
| 1990 | East Germany in reunification joined by default all international treaties of West Germany | 12 | |
| 1992 | Maastricht Treaty | | |
| 1992 | Switzerland- No vote on EU | Though has a number of treaties in place including free movement of people. | |
| 1995 | Austria, Finland, Sweden | 15 | |
| 2001-2002 | The Euro was adopted by Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, and Spain | | 12 |
| 2004 | Central Eastern European Nations who join the EU: Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Malta, Cyprus | 25 | |
| 2007 | Romania and Bulgaria join the EU<br>Slovenia adopts the Euro | 27- Not Included | 13 |
| 2008 | Cyprus and Malta adopt the Euro | | 15 |
| 2009 | Slovakia adopts theEuro | | 16 |

Due to available data eight countries who are members of the EU are not represented in this dataset including: 1). Ireland; 2). 2004 accession members: Estonia, Latvia, Lithuania, Slovenia, Malta, and Cyprus; and 3). 2007 accession members: Both Romania and Bulgaria.

**Annex 2: Member States and Important Historical Dates of European Union Single Market Policy**




Source: www.en.wikipedia.org

# Peer Effects and Usage of the Solar Oven-Evidence from Rural Senegal

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**Abstract:** This paper aims to estimate the behavioral economics aspects of technology adoption using data from a randomized controlled trial of adoption of solar ovens in rural Senegal. Of the many behavioral aspects of technology adoption measured, empirical modeling reveals there is a causal link of peer effects in solar stove usage. This work is based on a unique data set which includes women's self-identified close friends who participate in the solar oven program in their village and the observed time series data for actual solar stove usage for women and their friends in the treatment group. Exploiting the randomization of the study design, the usual problems of endogeneity which typically arise in measuring peer effects dubbed by Charles Manski as "the Reflection Effect" can be controlled for. Women's self-identified close friends participating in the program can be divided into "Strong" symmetric linkages (where women mutually identify each other) and "Weak" asymmetric linkages (where identification of a friend is not reciprocal). Empirical results confirm the presence of social learning in the treatment group's solar stove usage and the usage of her "Strong" symmetric friends. The social multiplier effect is positive and highly statistically significant (99-100% level) with a positive coefficient between 0.42-0.52, indicating a large co-movement in solar stove usage among women and her "Strong" symmetric friends' solar oven usage.

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## Introduction

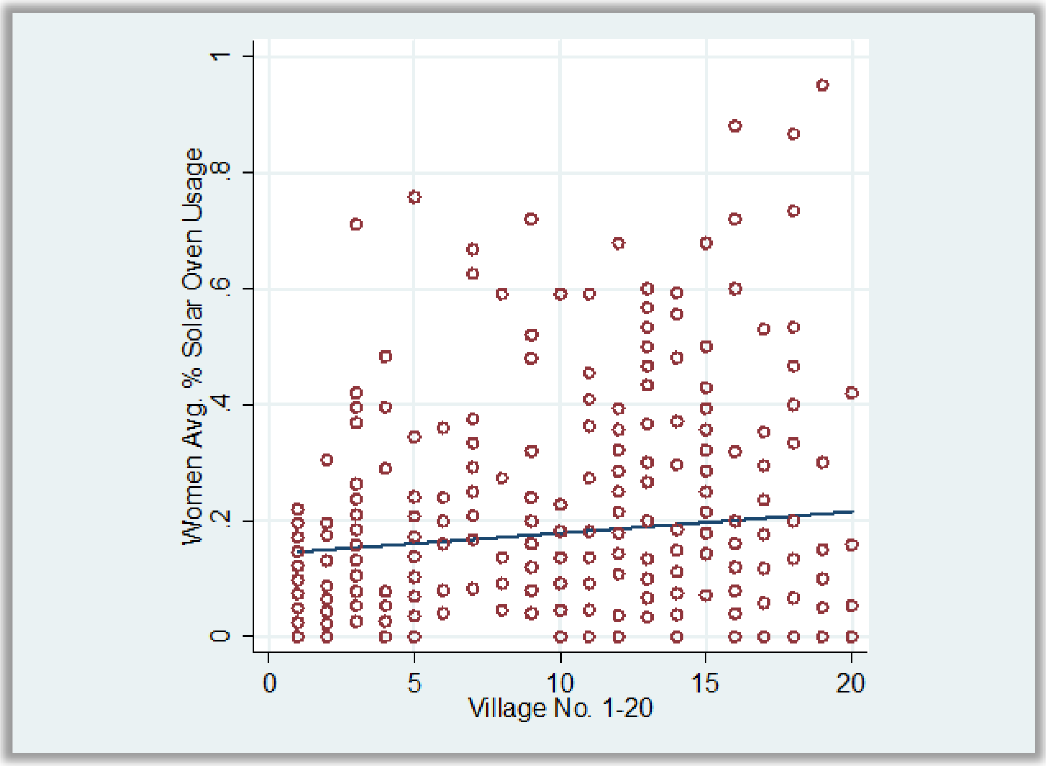
Arguably one of the main reasons for studying economic development is to understand better how individuals are able to make the transition out of poverty. Technology may be viewed as an opportunity to assist in the transition out of poverty. However, to realize the possibility technological innovation can offer to economic development, it is essential for economists to better understand how new technologies are adopted in practice. In the context of the introduction of solar ovens in rural Senegal, several externalities may play an important role in technology adoption decisions. One particularly salient externality present in the actual usage of the solar ovens is learning externalities. If a technology is of uncertain profitability or benefits, some potential adopters may wait until they observe whether others have fared well by using it. It is usually only people we personally know and trust and who we know have successfully adopted the innovation themselves who can give us credible reassurances that our attempts to change won't result in embarrassment, humiliation, financial loss or wasted time. Solar stove owners may care about others' adoption decisions, particularly since our sample lives in small close knit rural villages with strong social networks.

Learning externalities have long been recognized by rural sociologists (Everett Rogers (1995 and 2003)) and have been widely recognized by economists in agricultural technology adoption (See Besley and Case (1993), Bandiera and Rasul (2002) and Conley and Udry (2008)) for quantifiable empirical literature). Understanding the usage of the solar oven, or the daily technology adoption decision among treatment households in our randomized controlled trial, and what role, if any, peer- peer conversations have in the decision to use the solar oven will contribute to the small but growing empirical literature. This literature uses individual-level data to measure the quantitative importance of learning from others. Important examples of this work include Foster and Rosenzweig (1995), Bandiera and Rasul (2002, 2006), Kremer and Miguel (2007), Bayer, Pintoff, and Pozen (2009), and Conley and Udry (2010). These conclusions will not only add value to the economic development and behavioral economic literature but will assist other technology adoption programs be more successful.

The 488 women in the treatment group all received the same marketing messages[2] about the merits of using the solar oven at the village level meeting and additional stove trainings. The mean usage over the sixth month period measured by the Stove Usage Monitors is 19%, with a variance of 18%, confirming a high level of dispersion in the distribution of usage over our treatment sample. There is a large dispersion by village as well (see Graph 1).

[2] Marketing messages included how the solar oven saved time and money spent collecting and/or purchasing fuel, how it cut down on the harmful smoke women breathed in while sitting next to the cookfire, and how the stove benefitted the environment because it does not cut down trees.

**Graph 1: Women's Average Solar Stove Usage at the Six Month Follow-up by Village**




Aside from village effects, individual's solar stove usage is varied and diverse. The benefits of the solar oven are nine times the costs over the life cycle of the product.[3] The solar stove requires some relatively small efforts in changing behavior and how women cook to adopt the stove. However, to explain women's low average rates of adoption (19%), the small relative costs of behavior change must be inexplicably large for Expected Utility Theory to hold. Thus, it is clear that women's use of their solar oven is motivated by other factors outside the cost benefits framework of Expected Utility Theory (EUT). Innovation Theory supports the hypothesis that peer conversations could cause women to use their solar oven. In particular, because the adoption of new products or behaviors involves the management of risk and uncertainty, if women's trusted friends use their solar oven women may be more motivated to use their oven.

To understand whether women use of the solar oven is related to their friends use we ask women to identify their three closest friends at the meeting who are enrolled in the program. The identification of friends takes place on the baseline survey, before we have randomized the women into the two different groups. Because we surveyed the women prior to the randomization into the two groups, we have eliminated any selection bias women could have experienced in selecting friends after they had knowledge of their own or their friend's random selection into the treatment or control group. We are able to identify variations across friendship types differentiating between symmetric "Strong" friendships (where each individual lists the other as a friend) and asymmetric "Weak" friendships (where the link is only one-sided). Foster and Rosenzweig (1995), Conley and

[3] This is accounting for actual monetary savings on wood observed in our study and assuming women continue to use their solar oven at the 19% rate observed over the sixth month period. This does not include a measure for time spent collecting fuel.

Udry (2008) and Oster and Thornton (2009) find peer exposure has a positive impact on technology adoption. Similarly I find that for women and their "Strong" friend's in the treatment group over the sixth month follow-up there is a positive and statistically significant increase of solar oven usage (at the 99%-100% level). The coefficient for prediction of solar oven usage between women and their friends varies depending on the exact regression specification, and is between .42 to .69. This indicates a very high level of influence on solar oven usage between "Strong" friends.

The objective of this paper is to understand better why some individuals adopt solar ovens and others do not. The results are relative to all products and technology adoption discussions. This question is of importance to economists in a variety of fields (industrial organization, labor, development, and marketing), and has both positive and normative implications. On the positive side, knowing determinants of adoption can help predict adoption patterns. While, on the normative side, this may help us understand how to encourage adoption of beneficial technologies in the developing world or understand how to optimally market new goods. The field of behavioral economics provides the tools from which to build on expected utility theory to include psychological aspects involved in decision making, and of particular relevance to this research, what behavioral phenomena exist, if any, when an individual decides to use their new solar oven?

The paper is organized as follows with Section 2 outlining the past empirical and theoretical literature relevant to this work. Section 3 outlines the project overview and data collected. Section 4 outlines the empirical strategy and summarizes the main results. Section 5 concludes.

## Section 2: Theory Review

### 2.1: Rationale for Including Behavioral Economics Phenomena in studying Solar Oven Usage

Traditional economic models of choice under uncertainty assume that people maximize utility by weighting the average of utilities they could get in different uncertain outcomes. Matt Rabin (1998) outlines that there are two basic components of the standard expected utility model of the individual: that she has stable, well defined preferences, and that she rationally maximizes those preferences. Stefano DellaVigna in his 2008 work summarizing the advances in the behavioral economics field suggests that individuals deviate from the standard expected utility model in three respects. Individuals exhibit 1). Non-standard preferences such as time preferences (self-control problems), risk preferences (reference dependence), and social preferences; 2). Non-standard beliefs such as overconfidence; and 3). Non-standard decision-making such as framing of decisions and social pressure and persuasion. Following from Rabin (2002) one can generalize decisions under uncertainty as follows. Given S represents a set of mutually exclusive and exhaustive outcomes a person can experience from a decision, U(s) is the utility for an outcome $s \in S$, and p(s) is the probability of that outcome. The utility of the agent can then be represented:

$$U(s) = \sum_{s \in S} p(s) * U(s) \qquad \text{Model (1)}$$

Generalizing expected utility over time an individual i at time t=0 maximizes expected utility subject to a probability distribution p(s) of the states of the world $s \in S$:

$$\max_{x_i^t \in X_i} \sum_{t=0}^{\infty} \delta^t \sum_{s_t \in S_t} p(s_t) * (U(x_i^t | s_t) \qquad \text{Model (2)}$$

The utility function $(U(x|s)$ is defined over the payoff $x_i^t$ of player i and future utility is time discounted with a time consistent discount factor (δ). From these basic models of EUT individuals make choices so as to maximize their utility function, using the information available, and processing this information appropriately. Individuals' preferences are assumed to be time-consistent, affected only by one's own payoffs, and independent of the framing of the decision.[4] Despite the success of the EUT models, behavioral inconsistencies have spurred large advances in understanding life-like human behavior. Particularly, for the question of technology adoption, the behavioral economics literature helps explain the conundrum of why, too often, households have failed to adopt technologies that traditional expected utility models predict they should adopt. In a recent meta-review of the behavioral economics literature, DellaVigna points out individuals are time-inconsistent (Thaler, 1981), show a concern for the welfare of others (Charness and Rabin (2002) and Fehr and Gachter, (2000)), and exhibit an attitude toward risk that depends on framing and reference points (Kahneman and Tversky (1979)). Individuals violate rational expectations, for example by overestimating their own skills (Camerer and Lovallo (1999)) and over-projecting from the current state (Read and van Leuwen (1998)). They use heuristics to solve complex problems (Gabaix, Laibson, Moloche, and Weinberg (2006)) and are affected by transient emotions in their decisions (Loewenstein and Lerner (2003)). Thus, despite the heavy village and household level training provided by the local NGO partner-Tostan, women over the sixth month use their solar stove just 19% of the time. This is a relatively low percent given the implicit savings of the solar stove in both money spent on fuel for cooking, particularly wood, and time spent collecting wood. Despite the limitations of the solar stove, i.e. it being too small to fit the needs of a significant portion of households, based on the large benefits of the solar stove relative to the costs, we still expect the household to use their stove more frequently. [5] In an attempt to rationalize the technology non-adoption puzzle this work adds behavioral economics phenomenon into our traditional expected utility model. Some behavioral economics research raise more fundamental challenges to expected utility theory (EUT) by questioning the core fundamentals which economists rely on to explain human behavior. This research chooses instead to build on and to maintain the fundamentals of individual choice in EUT theory, and build the behavioral economics measures into the EUT framework.

In the context of the introduction of solar ovens in rural Senegal, several externalities may play an important role in technology adoption decisions. The household surveys were designed to measure a wide variety of behavioral economics concepts potentially relevant to the decision to use the solar oven as well as the main outcome indicators. The main behavioral concepts measured over the three surveys waves include: present versus forward bias, age as a dummy for likelihood to invest in learning a new technology, risk preferences, early (relative) adopter of technology, information on breathing in smoke and

[4] EUT forms the basis of modern microeconomics, for a fuller discussion see Mas-Colell et al. (1995).
[5] The solar stove feeds on average 6 while the average household size is 12 persons.

effects on one's health, beliefs about control over health, beliefs about control over fate, belief that purchasing and collecting fuel is a burden, trust, trust in our NGO partner Tostan, measures of intra-household bargaining power, network effects, and overconfidence. Of all the behavioral economics concepts only two have statistically significant impacts on solar oven usage. The age cohort of 21-30 years of age has positive and statistically significant impacts on solar oven usage (See Appendix 2, Table 2). Second women's "Strong" symmetric friendship links and their solar stove usage have a positive and statistically significant effect on women's own solar stove usage. On a separate note, women's solar stove usage over the sixth month period was positively and statistically significantly correlated with her own usage at the one month period. This shows a path dependence for solar stove usage. Further, results show that individual usage patterns seem not to be correlated with number of trainings attended. The results for the full set of behavioral economics phenomenon are shown in Appendix 2, Table 2. Because this paper aims to explain what aspects of technology adoption have significant effects on solar oven usage, this work will focus mainly on the role of social networks in promoting adoption. However, because ex-ante we did not know which behavioral economics phenomenon may have a statistically significant effect on solar stove usage, we measured a large set of behavioral economics phenomenon. These additional aspects of behavioral economics are outlined in Appendix 2.

The role of learning externalities in the actual usage of the solar ovens could originate from women's desire to avoid embarrassment, humility, financial loss, or wasted time by learning from peers. Dynamic choice theory with externalities offers one possibility to build from the EUT framework and design a set of economic models which condition one's individual behavior on that of others. Relying on work by Besley and Case (1994), we can model this by assuming the state variable for individual *i* evolve in a way that depends on $d_{\_it}$ - or the choice of other women to use their solar oven. The interdependent decision-making that ensues is potentially quite complicated. Moreover, a strategy for woman *i*, $s_{it}$, can depend upon all current and past behavior as well as current and past behavior of the state variables. A common simplification in the literature is to confine strategies to depend only upon the vector of current state variables, denoted by $k_t$.[6] Strategies that comprise a Nash equilibrium at each date are then referred to as *Markov perfect*. The optimal decision by women can then be characterized by the recursion:

$$\hat{V}_t^i\left(k_t^i;\ d_{\_it}\right) = max\left\{\pi_{it}\left(d_{it}, k_t^i\right)\right\} + \delta E\left\{V_{t+1}^i(k_{t+1})|k_t^i, d_{it}, d_{\_it}\right\} \quad \text{Model (3)}$$

The value function,

$$V_{t+1}^i(k_t) \equiv \hat{V}_t^i\left(k_t^i;\left[s_1 k_t^1, \dots, s_{i-1t}\left(k_t^{i-1}\right), s_{i+1t}\left(k_t^{i+1}\right), \dots s_{Mt}\left(k_t^M\right)\right]\right) \quad \text{Model (4),}$$

depends on the whole vector of state variables. This makes this dynamic model of equilibrium behavior very difficult to solve, even theoretically. Despite the model's complexity, the framework of using value functions and dynamic programming to solve the adoption of the solar oven decision is useful to frame the empirical work in this paper and the iterative thinking that women most likely utilize when deciding to use their solar oven.

[6] This simplification cited by Besley and Case (2003) can be attributed to Erik Maskin and Jean Tirole (1988) and used in empirical work by Pakes and Paul McGuire (1991) and Besley and Case (1992).

Other models (see Besley and Case (1992)) use a Markov transition kernel to estimate the parameter values used to simulate dynamic choices in equation (3).

A growing body of economics research suggests that social capital influences a wide range of significant economic and political phenomena. In economic learning models, agents generally learn from their own experience ("learning by doing"), from observation of others ("learning from others"), or from both (Foster and Rosenzweig (1995) and Armantier (2004)). Learning from others generates a social multiplier effect in the diffusion of innovations that can be exploited as a cost effective mechanism for disseminating technology. The fundamental idea is that individuals learn from and imitate the behavior of others within their social network, as suggested by the well-known contagion model for adoption of innovations (Rogers (1995)). Recent studies have shown that, both in developing and developed countries, social networks and peer effects are an important determinant of individual behavior in a variety of settings. For instance, economics research suggests that many individual decisions, as diverse as school attendance, drug use, internet adoption, and welfare participation, are positively correlated with the behavior of the social group within which the individual belongs.[7] In the context of rural economies, it has been shown that farmers within a group learn from each other how to grow new crop varieties.[8] Overall, research to date suggests that network effects are important for individual decisions, and that, in the particular context of agricultural innovations, farmers share information and learn from each other. To build in the role of learning in modeling women's solar stove usage, one must first verify the more basic question that the benefits of the stove outweigh the costs.

## 2.2: Framing the Adoption Decision

### Part A: Costs Benefits Analysis

EUT predicts that rationale agents should use the improved cook stove if the benefits are greater than the costs. One example is the standard model of investment in human capital by Michael Grossman which verifies empirically that an individual investments in a (health) product if the expected benefits outweigh the costs.[9] In the solar oven randomized controlled trial the original price of the solar stove to consumers was the equivalent of $23 and the terms of the contract were the NGO would deliver it directly to the village and women would pay in five month intervals with time payments of about $5 each month.[10] However, the NGO partner decided to lower the solar oven price to the equivalent of $5 from $23 shortly after the project began citing rising fuel prices and gas and charcoal shortages in Senegal causing an extra burden on the household expenditure. Thus, the price

[7] See, for instance, Bertrand et al (2000), Besley and Coate (1992), Borjas (1992 and 1995), Case and Katz (1991), Gleaser et al (1996), Moffit (1983), Goolsbee and Klenow (2002), Gowrisankaran and Stavins (1999), and Woittiez and Kapteyn (1998).

[8] See Foster and Rosenzweig (1995); Conley and Udry (2000); Bandiera and Rasul (2002); and Conley and Urdy (2008).

[9] See Grossman (1972)

[10] The price in CFA was originally 10,000 CFA and using the US Treasury official second quarter average which covers the period of April the exchange rate is $1=429 CFA and thus original price of the solar oven was $23.

of the solar oven fell to less than 1% of the household budget[11] over the five month period, and raised the donor subsidy of more than 90% of the actual cost of the solar oven. Relative to one month's household budget, the total cost of the solar stove ($5.00) was a small portion of total monthly spending (4%).

To measure the benefits of the solar oven we know from Beltramo and Levine (2010) that for households with 7-12 persons the solar oven reduces daily wood consumption by 11-13% for the entire treatment group and lowers by 1% the time households spend collecting wood (both results are statistically significant at the 95% level)[12]. Focusing on the lower end of the wood reduction of 11% daily for treatment households and given households report spending $2.80 on wood weekly at baseline, this represents a monetary savings of $1.23/month. A second cost associated with wood, is the collection of wood. Given our households are all primary wood users, many households substitute purchasing fuel with collecting fuel (varying largely by season).[13] Households report they spend on average 158 minutes (2.6 hours) collecting wood per collection period at the baseline. The average collection period is 4 days. Using the rate of 158 minutes per every 4 days, an average weekly rate is 4.6 hours/week that all members of the household spend collecting wood.[14] We find that the solar oven reduces time spent collecting fuel by 1% (statistically significant at the 95% level). Antidotal evidence of the life cycle of the product suggests at least 3 years duration[15]. While 1% is a minimal savings of households' time spent as a result of solar oven usage, over the three year lifespan of the product, assuming usage remains consistent at 19%, the solar oven will save about 1.5 weeks of households wood collection time. While it is difficult to measure the wage equivalent for household members who collect wood and often studies report a zero or negative wage of non-working household members in rural parts of the developing world; there is some evidence in our sample that household members time spent collecting fuel has a positive cost. In particular, many women report working outside the home on other wage producing activities. 71% of women in the treatment group interviewed at the baseline survey report being employed. And in addition to their household duties, we observe that women often work by selling mangos in roadside stands during April/May and work on the family farm from September to October. Despite the difficulties of measuring the value of rural labor costs in sub-Saharan Africa, we know that over the product life cycle if women continue to use their solar ovens at the observed 6 month usage rate of 19% they will save the household about 1.5 weeks of time spent collecting wood over the 3 year product life span.

Returning to the wood savings, taking the low savings rate of 11% equivalent to $1.23 saved monthly, over the life cycle of the product, households can save $44, or the equivalent of a

[11] To situate the $5 cost of the stove into a monthly household expenditure budget, women in our sample report at baseline a daily salary of $1.55 and report their husbands give them $2.87 on average for household expenditures daily. This is a total of about $31 household budget weekly, or about $3/person/week.

[12] Results are statistically significant at the 95% level.

[13] On average at the baseline 47% of households reported buying wood while 40% at the six month follow-up. The weekly household budget includes the weekly expenditure on fuel for cooking, which we find varies dramatically by season. Both treatment and control households spend on average $11.60 (37% of the total household weekly budget) at baseline and $9.60 (31% of the total household weekly budget) at the six month follow-up on all types of fuel purchased- wood, charcoal, and gas. (see Figure 5 and 6 in Beltramo and Levine (2010)).

[14] See Table 3a: Summary Statistics Baseline Beltramo and Levine (2010).

[15] This is the estimate by the producer of the solar oven. Given the rainy season in Senegal of 2 months on average per year, the 3 year product life cycle is 3 years excluding the rainy season, hence an equivalent of 3.5 years.

month and a half of household income over the three year product life cycle. These findings reveal that even with very low observed adoption rates of the solar ovens (~19%) the solar ovens have significantly greater monetary benefits -$44 monetary savings + 1.5 weeks of wood collection time- than costs -$5 one-time payment.[16]

This raises a series of questions. First, given the realized savings of the solar oven at the 6 month follow-up with relatively low usage of the solar oven- 19% average- why do households not use their solar ovens more frequently to amplify their savings? Take the case that households use their solar oven 90% of the time. and Given solar oven usage of 19% equals a daily fuel savings between 11-13%, it follows that 90% usage rates should equal 57% savings of money spent on wood on average (assuming 12% average from the 11-13% estimate). At the high usage level of 90%- or 9 out of every 10 days- this would save households the equivalent of $230 on expenditure on wood for the life cycle of the product. The roughly $6 savings per month is equivalent to over 5% of the total household monthly expenditure. The question is sustained- why given the large possible savings in money and time do women not use their solar oven more?

## Part B. Behavioral Aspects of the Technology Adoption Decision

Given women are not maximizing their expected utility by using their solar stove more frequently, we turn to behavioral economics phenomena to explain the non-adoption puzzle.

### Hypothesis 1: Small costs have disproportionate effects on decision making

From behavioral economics empirical work, it is shown that small fixed costs can play an important role in behavior decision-making. The solar oven requires some behavior change in how women in rural Senegal cook. Women who are accustomed to sit/stand next to the stove for hours at the time, constantly stirring the meal have to adjust their cooking style to cook efficiently with the slow cooker. In particular, to maximize cooking efficiency with the solar oven women should leave the lid firmly on the pot and not interrupt the slow cooking process by constantly stirring or opening of the pot.[17] Further, unlike the more traditional cooking style where women sit continuously next to the pot and sauté the meal over high heat, the solar cooker operates like a crock pot, stewing the meal and slowly cooking it over time. While the meal takes longer to cook, women are also much less involved. Instead of sitting next to the stove constantly, they are instead required just to orient the solar oven and its' reflector towards the sun about once an hour. The solar stove requires a conscious change in cooking patterns by women, and like any behavior change requires effort. Behavioral economists have shown empirically that even small costs associated with effort can have large disproportionate effects on behavior. The classic empirical examples are optimal 401K decisions by employees (Madrian and Shea (2001), Carrol et. al (2005) and Choi, Laibson, Madrian, Metrick (2004)) and individual decisions to be an organ donor

[16] A mean of number of people women report cooking for at the baseline survey show at least 50% of our households have 12 persons or less. On the one month follow-up survey, at least 57% of the number of household members women report cooking for have 12 persons or less. And on the six month follow-up survey it is 67%. Thus, on average, over the 3 periods, number of people women report cooking for 12 persons or less is 58%. Thus, this result is applicable for 58% of our households.

[17] The solar oven which is a panel cooker by design uses a reflector to concentrate the sunlight and turn it into energy for cooking. The Hotpot uses a second property to convert light to heat through an inner black bowl which absorbs most of the sun's light and then turns it into heat.

(Johnson and Goldstein (2003) and Abadie and Gay (2006)). In both scenarios empirical work shows the presence of small efforts by individuals including making a phone call to enroll in 401k, or filling out a form to be an organ donor, result in sub-optimal behavior, not consistent with expected utility. Choi et al (2004) find that active decision on 401(k) participation raises savings rates and 401(k) participation by employees by 50%. In short, using a default option, which makes the small effort of filling out a form non-optional, has significant effects on consumer's decision making, and in this case, enrollment in 401(k) programs for employees. This is underlined again in the second case of organ donation. Johnson and Goldstein (2003) using the natural experiment of some European countries decision to use organ donation systems with the opt-out option (or automatic enrollment unless citizens opt out) show countries with opt-in policies (including Denmark, Germany, Netherlands, and the UK) have enrollment in the national organ donation program ranging from 4-28%. In comparison, countries with automatic enrollment and optional opt-out policies (Austria, Belgium, France, Hungary, Poland, Portugal, Sweden) have enrollment rates ranging from 86-100%. From these two examples we know that small costs in effort can make a large difference in human behavior and undermine optimal rational decision making predicted by EUT. Because the solar oven requires some small effort in behavior change, we may expect disproportionate lack of usage due to overweighting of small costs.

**Hypothesis 2: Role of time discounting and women who are present bias, future bias, or stochastically present biased**

Another possibility is women buy the stove with the intention to use it frequently but exhibit dynamic inconsistency of preferences over time, more specifically are naïve about their own future preferences. If this is the case, the $(\beta, \delta)$ model captures agents' inability to predict their own preferences accurately in the future due to issues around self control. To capture this type of time inconsistent behavior David Laibson (1997) and O'Donahue and Rabin (1999) introduce the $(\beta, \delta)$ quasi-hyperbolic time discounting model. The model builds on the standard model of expected utility (see Model 1) by adding the parameter $\beta$ which allows agents to be naïve, partially naïve, or sophisticated about their own preferences in future decision-making. DellaVigna and Malendier (2006) in their work, "Paying Not to go to the Gym" apply the model empirically to gym users in the U.S. and demonstrate that users continually select sub-optimal contracts resulting in an overpayment of some $600 on average during their membership due to naivety of their own preferences and inconsistent time discounting. It is feasible that women who purchased the solar oven, like the example of gym memberships, were naïve about their own future preferences. Naivety compounded with the relatively small cost associated with changing behavior in cooking patterns necessary for the adoption of the solar oven, could explain why woman buy the solar oven and then use it sparingly. Thus, even if the cost of the behavior change is small, so long as women discount future utility time inconsistently, even women who plan to use their solar oven will choose to defer incurring the cost until the last moment possible. And women who end up being impatient in the final period will then fail to invest the time necessary to change their behavior and use the solar oven.

**Hypothesis 3: Large Subsidies Distort Usage**

It is possible the low cost of the solar oven may discourage usage.[18] The debate is long-

[18] An additional hypothesis is the NGO's lowering of the price of the solar oven mid-way through the project sent a negative signal to villagers that the stove's value was reduced and hence women used their stove less. Either way, what is

standing on the role of subsidies in development and equilibrium pricing of new technologies. The argument can be traced back to Schultz (1964) and the Chicago School who argue subsidies distort optimal levels of the product usage. Given women pay a final price of $5 equivalent for the solar oven which is less than 1% of the household budget over the time period to pay for the stove, the artificially low consumer price may encourage buyers to buy the stove but not use it given the low fixed cost, or use it for other purposes. Further, the significant lowering of the solar oven's price from $23-$5.00 by the NGO may have sent a negative signal about product quality to the consumers. It is feasible women who purchased the stove may have perceived the drastic lowering of the price to indicate the solar oven was of lesser value than originally anticipated. If this is the case, this could discourage usage over time.

**Hypothesis 4: Women use the solar oven for other purposes than to cook**

There is evidence that two of the villages selected to participate in the program proved to be a poor match with the environmental prerequisites for the usage of the solar oven. The environment of these two villages on the sea proved too windy for the panel cooker to maximize the sun's rays and cook efficiently. Further, the high concentration of sea salt in the soil eroded the reflector. At the sixth month follow-up, these two villages were in the lowest quartile of solar stove usage- respectively 46% and 34% below the total sample mean of 19%- with an average 8% and 6% solar stove usage over the 6 month period. Despite the limitations for cooking in this zone, demand was relatively high as both villages were 40% over-subscribed with requests to buy the oven. The demonstrated high continued demand in these two villages is puzzling. There must be some other utility of the solar stove outside of its' original purpose to cook. Indeed, it became apparent at the sixth month survey visit to the village and to women's homes that the solar oven, which hermitically seals, may be in high demand for a completely different purpose. One potential reason for this high demand is that this zone is a center for fish smelting and, thus, these villages suffer a tremendous burden of flies. Thus, woman may have liked the stove because its casserole dish hermetically sealed and you could store food in it away from the flies. Outside of these two villages the environment is very well suited to solar oven usage.

**Hypothesis 5: Women value their relationships with the NGO Tostan and buy the solar oven to please Tostan**

An additional hypothesis for why some villagers were motivated to buy the solar stove may have been to maintain good relationships with the NGO Tostan. The twenty villages selected to participate in the program were selected from the pool of communities which had already graduated from Tostan's three year community development program and thus Tostan continues to work in the communities only on a project by project basis. Inspired by Glaeser, Laibson, Scheinkman, and Soutter's (2000) work on measuring the role of trust in making decisions, we measure in general whether women are trustworthy of others, and, in particular, if they trust the NGO partner Tostan. Tostan has been working in Senegal for over 20 years and has a very good reputation on the ground. It is possible that some villagers bought the stove, first and foremost because they wanted to keep Tostan happy and keep themselves in the queue for next development project which may be better aligned with the village priorities. Upon early marketing visits to the village Tostan stressed that women

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clear is the reduction of the price of the solar oven mid-way through the project sends a signal to the buyer, one that is hard to disaggregate from the value of the solar oven.

should not buy the stove if they did not need it. Yet due to limited development opportunities communities may have felt pressure to enthusiastically accept the solar oven even if it was not a development priority in their community.

To measure the social norm of trust in the local NGO, on the six month follow-up survey we asked women enrolled in the program to respond to three statements using the five point response-Strongly Agree; Agree; Neither Agree nor Disagree; Disagree; and Strongly Disagree- pertaining to confidence in Tostan as an NGO, Tostan's local village focal point person who coordinated the project, and whether Tostan always has their best interest at heart. The level of trust in the NGO was extremely high and for all three questions women on average throughout our sample answered "Strongly Agreed" to all three questions. Thus, given measured trust in Tostan is so high, it is plausible that any development initiative the NGO deemed as important would almost automatically be invited in, without careful consideration by the communities whether this development initiative fit well with their priorities or needs.

**Hypothesis 6: Young People are More Likely to Change Behavior Patterns**

An additional hypothesis that proves statistically significant is age of the woman who purchased the solar oven affects her outcomes on usage. Dividing women by their age, I test whether age cohorts act as a dummy for the likelihood of investing time in learning a new technology and hence usage of their solar oven. As indicated the solar stove requires an investment in making a small change to women's traditional cooking practices to adopt the solar stove. Thus, it could be younger women, who are more adjustable, may be less traditional in their cooking patterns and more open to embrace new technologies. Recent research (2006) by Forrester using data from the North American Consumer Technology Adoption Study 2006 Benchmark Survey shows that overall young people are more likely to make use of emerging technologies. This includes not only mobile data services but also social networking web sites such as MySpace. And while all age groups in North America were adopting technology broadly, younger generations were adopting first and harnessing the full use of technologies. Thus, empirical evidence suggests that younger women may adopt the solar oven at a higher rate than older women.

To test for whether age had any effect on solar oven usage and adoption I divide the age of the women inscribed into the program into five age groups. Of the women in the treatment group present at the one month follow-up survey, the sample is divided by age cohort as follows. The first age group 20 years and under represents 9%,the second age group of 21-30 years of age-31%-, the third age group 31-40 years of age- 31%- the fourth age group 41-50 years of age- 20%-, and the age group of 50 years or more- 9%- of the entire sample. To test age cohorts' effects on women's solar stove usage I run OLS regression analysis where the y variable is women's solar stove usage over the sixth month period and x variable include common descriptive statistics (including age, education, wealth, and village fixed effects) and the explanatory variables for dummies for age. The results show age cohort 21-30 years of age are positive and consistently statistically significant at the 95% level and thus women aged 21-30 years of age are more likely to use their solar oven (see Annex 2 Table 2).

**Hypothesis 7: Women's solar stove usage depends on her close friend's usage.**

In economic learning models, agents generally learn from their own experience ("learning by doing"), from observation of others ("learning from others"), or from both (Foster and Rosenzweig (1995) and Armantier (2004)).[19] Because the adoption of new products or behaviors involves the management of risk and uncertainty, the best reassurance that experimenting with a new technology will not fail is learning from observation of people we personally know and trust and who we know have successfully adopted the innovation. Early adopters of a technology are the exception to this rule. They are on the lookout for advantages and tend to see the risks as low because they are financially more secure, more personally confident, and better informed about the particular product or behavior. Early adopters may grasp at innovations on the basis of marketing messages received in the village level meeting alone. The rest of the population, however, see higher risks in change, and therefore require assurance from trusted peers that an innovation is do-able and provides genuine benefits. To model early adopters, I regress women's six month solar stove usage on her strong friend's usage over the first month time period can act as an early adopter. The results are positive and statistically significant with a coefficient of 0.52.

**Summary**

Qualitatively we have reason to believe Hypothesis 1 that small costs of behavior change are an obstacle to technology adoption, as well as Hypothesis 4 that for the two villages near the sea, purchase of the solar oven was motivated for reasons not relevant to solar cooking. Of the other hypotheses that are testable quantitatively, Hypothesis 6 proves to be statistically significant and younger women, specifically in the age group 21-30, tend to use their solar oven more. I also find evidence corroborating Hypothesis 7 that women's solar oven usage is directly influenced and increasing with that of her "Strong" symmetric friend's solar oven usage. Finally, I test hypothesis 2 in the empirical analysis and find only that women who are stochastically present biased have a slightly significant positive effect on their solar oven usage (statistically significant at the 10% level). The rest of this paper will discuss the empirical models used to quantify this result.

## Section 3: Data

### 3.1: Overview of Sample and Randomization

The Thies region in Senegal is located in the Western area of the country and consists of 1,541 communities which are predominantly Wolof speaking[20]. The region is semi-desert, and aside from the average two-three months of rain from late June through August, is tropical and sunny. The villages in our study are rural and relatively poor- women report earning a $1.55/day and their husband's give them an average $2.87/day for household expenditures, for a total of an average $31 weekly expenditure for a household of average size of 12 people (~$3/person per week). All 20 villages in our sample are of varying size and distance to the region's largest city, Thies.[21] In each village a total of 50 households were

[19] To understand these questions the founder of diffusion of innovation theory, Everett Rogers tells us that between 49-87% of adoption of new products can be attributed to the following five qualities: 1). Relative advantage- economic, social prestige, convenience, or satisfaction; 2). Compatibility with existing values and practices; 3). Simplicity and ease of use; 4). Trialability; and 5). Observable results.

[20] Source Government of Senegal census year (2002)

[21] See Figure 2: Solar stoves project study region and sample villages in Beltramo and Levine (2010).

allowed to enroll in the program. Due to a limited supply of solar ovens available, the project was phased in where half the women in each village were randomly selected to be in the treatment group and to receive the solar oven after the baseline survey and the other half were selected to be in the control group and to receive the solar stove at the six month follow-up. Of the projected 1000 households in our sample, the project distributed 960 stoves overall. At baseline, less than 25% of our sample own an improved stove, and most households cook on several types of stoves- mainly charcoal, gas, and a wood traditional three stone fire. Despite the variety of cook stoves used daily, households in the study zone used wood as the predominant fuel for their cooking needs.

We collect household level data at the baseline, one month and six month follow-up surveys pertaining to household weekly fuel use, time by entire household spent collecting fuel, cooking practices, self reported respiratory and other health related symptoms for women and their children to cooking, behavioral aspects relevant to technology adoption, as well as descriptive statistics on women and their household including: wealth, education, marital status, and family size.

### 3.2: Well Identified Social Networks and Quantitative Solar Stove Usage

Solar ovens, as a technology are not used widely in rural Senegal. In our twenty villages, no one in our sample had ever cooked with a solar oven prior to the project and hence the product technology was completely unfamiliar to households at the start of the study. This provides the advantage that the households all symmetrically have no preconceived notions about the product.

The data collected is unique in that it collects quantitative measures of stove usage and well identified peer networks of women as it relates to the solar oven. These two factors are extremely unique and advantageous for studying the behavioral aspects of technology adoption. Conley and Udry (2010) point out direct data on information interconnections is typically unavailable to economists.[22] Without directly identified social networks, economists have typically made assumptions that relate observed relationships between individuals- such as geographic proximity- to unobserved flows of information. Proxying networks is at best an approximation, and the results, at best estimates. [23] This dataset has the unique advantage that it identifies women's friends directly by asking women at the baseline survey to name their three closest friends who are participating in the solar oven

[22] According to Conley and Udry (2010) exceptions include Isolde Woittiez and Arie Kapteyn (1998) and Kapteyn (2000), who use individuals' responses to questions about their "social environments" to describe their reference groups. Mattia Romani (2003) uses information on ethnicity and membership in cooperatives in Côte d'Ivoire to infer the probability of information flows. Another exception is Bandiera and Rasul (2006) who have information on the number (though not the identities) of people using a new technology known by direct farmers. Finally Conley and Udry (2010) form part of the exception to the rule by using unique data on farmer's communication patterns to define each individual's information neighborhood.

[23] Most of the existing literature is restricted by not having such rich data available, hence inevitably a number of simplifications have to be made. First, individuals typically do not report their social groups. Rather, social groups are proxied by geographical or cultural proximity. Hence it is assumed that the behavior of individual i in village v, say, is a function of the mean behavior of individuals in the village, $a_v$. The important point to note is that i is no longer an individual specific determinant, but village specific. This makes it impossible to separate out social effects from unobservable characteristics at the village level that may lead to correlated behavior within villages. Second, as a consequence of having to proxy the true social group of i with his village, it is also not possible to control for the common characteristics of the group which may drive adoption decisions, namely, exogenous social effects cannot be identified separately from endogenous social effects.

project. The baseline survey took place prior to the lottery and thus women had no idea whether they or their friends would be selected into the treatment or control group. Importantly, women's selection of their three closest friends who participate in the study is not biased by who is randomly assigned to the treatment or control groups. Further, women were interviewed individually and separated from the group thus we limit the bias to name a close friend solely because the person is nearby. Thus, the dataset has a well-identified social network of close friends in the women's social network per village participating in the solar oven study. When I combine this with quantitative solar stove usage measured by Stove Usage Monitors (SUMs) the data set provides a unique opportunity to measure quantitatively the effects of peer relationships on solar stove stove usage.

I am able to identify variations across friendship types differentiating between symmetric "Strong" friendships (where each individual lists the other as a friend) and asymmetric "Weak" friendships (where the link is only one-sided). Over the entire sample for all the 960 households participating in the study, 74% of households matched at least one friend. 87% of treatment households identified at least one friend, 25% had at least one "Strong" friend linkage and 84% had at least one "Weak" friend linkage. Of the "Strong" friend linkages, the treatment group had 61 equivalent to 50% of their "Strong" friends identified in the treatment group and 50% in the control group (see Table 2).[24]

To measure actual solar oven usage, the research team used a temperature sensor which was installed on the lid of all the treatment households' stoves and programmed the SUM's to take 48 temperature readings per day, or once every 30 minutes. This tactic was first piloted by Kirk Smith and team in their randomized controlled trial of an improved stove in Guatemala, in the RESPIRE study. The device was dubbed a stove usage monitor (SUM). The SUMs provide clear spikes when the solar oven is used and we use the threshold level of 110 degrees or more as an indication of usage of the solar oven[25]. From our average temperature readings in the sun during afternoons in 9 of our 20 villages visited at the baseline survey, we found temperatures to be on average 90 degrees Fahrenheit (32 degrees Celsius). This is a stark difference from the 110 degrees Fahrenheit (43 degrees Celsius) used as a threshold indicator for stove usage and we are thus convinced that 110 degrees F is different enough from average recorded temperatures to clearly represent an indicator of solar stove usage. The SUMs provide two month-long periods which are measured- the first month- April-May and the sixth month- October-November.[26]Data for all the treatment households was collected for a period of roughly 1 month for these two distinct periods of stove ownership.[27]

The SUMs are an important innovation in measuring objective usage/uptake of the product.[28] This objective data is contrasted by self-reported usage rates collected at the one

[24] This perfect division of "Strong" friend's linkages reflects a well done randomization of the sample.

[25] See Appendix 3 in Beltramo and Levine (2010).

[26] A one month survey measuring the above outcomes was also fielded however we do not include data from the one-month follow-up in our core results because only 9% use the solar ovens (according to the stove usage monitor) during the first month. This rate is too low to detect any changes in wood use and thus we focus our analysis on the difference between the baseline and the six month follow-up where usage is up to 19% of the time.

[27] Finally, there is no available weather data for the rural villages and thus we cannot drop the days over the one month and sixth month period which were cloudy. This should not however create a large effect, as both months surveyed are in the dry season and are very hot periods in Senegal where the weather is nearly always optimal for solar cooking.

[28] See Figures A2 and A3 and Appendix 2 from Beltramo and Levine (2010) for more background on SUMs.

month and six month follow-up survey and observed usage rates on the six month follow-up village household level visits. We find that stated usage by women in our sample is 2-3 times that of actual usage of the solar ovens. This reinforces the role of SUM's in future research for accurate measures of stove usage.[29] The one month measure of stove usage shows women in the treatment group who received their stove first used the stove on average 9.8% of the days available (median of 8). The six month SUMs measure shows a doubling of usage to an average of 18.5% of days available and a (median of 14).

Using women's solar stove usage at the 6 month period as the y variable and women's "Strong" friends solar stove usage as the x variable, the basic OLS regression results are statistically significant at the 99% level. Results do not show any statistically significant results of women's usage when regressed on "Weak" friendships.

### 3.3: Present vs. Future Bias

To measure agents' inability to predict their own preferences accurately in the future due to issues around self control and inconsistent time discounting, we attempt to measure women's level of bias towards the present or future. We include four questions on the one month follow-up survey to investigate women's time preference over lotteries by asking households if they prefer varying amounts of money today vs. tomorrow. These questions are consistent with the vast literature in experimental psychology which has studied time preferences by eliciting preferences over various alternative rewards obtained at different times, that is, over reward-time pairs. It occurs, for example, when a subject prefers $10 now rather than $12 in a day, but he/she prefers $12 in a year plus a day rather than $10 now. Reversals of preferences are not consistent with exponential discounting. Psychologists (Herrnstein (1961) de Villiers-Herrnstein (1976) Ainslie-Herrnstein (1981) and Ainslie (1992 and 2001) and also behavioral economists (Elster (1979), Laibson (1997) Loewenstein-Prelec (1992) and O'Donoghue-Rabin (1999)) have noted that reversals of preferences are instead consistent with a rate of time preference which declines with time.[30] To measure women's rate of consistency over time in decision making, women inscribed in the program are asked by surveyors to choose between the following hypothetical lotteries in the equivalent of local currency). $10 today or $20 in a year from now; 2). $10 today or $15 a month from now; 3). $10 today or $12 a week from now; and 4). 2 goats (equivalent of about $80) today or $ 1 sheep (equivalent of $170) in September, or four months later. The final question has been adapted for the local setting. Sheep are in high demand in September for the sacrifice for the Muslim holiday of Tabaski which occurs around that time. [31] Because women in our treatment group are nearly all Muslim (99.99%) this question aims to make the question of lotteries more realistic to the population. All

[29] In fact, at the six month follow-up study individuals report using their solar oven 38% of the time, or double the SUM measured usage of 19% of the time over the six month of ownership. Even more misleading, for the 17 of the 20 villages which had sunny weather conditions conducive to solar cooking on our six month follow-up study visit, 61% of women were using their solar ovens- or more than 3 times the actual measured usage over the sixth month of ownership. This demonstration effect or women's desire to please the research team by demonstrating false levels of stove usage demonstrates the importance of having an objective measure of stove usage. (See Figure 3 in Beltramo and Levine (2010))

[30] Another important regularity pertaining to time preferences, referred to as the *magnitude effect*, is the observation that discounting declines with the amount to be discounted. It has been quite extensively documented, starting with Thaler, 1981, and then notably e.g., by Benzion-Rapaport-Yagil, 1989, and Green-Myerson-McFadden, 1997 (See DellaVigna (2009) for a fuller discussion).

[31] At present the Muslim Calendar at the time of the one month survey in May 2008 fixed the holiday of Tabaski in September, 2008.

questions were arranged so that the value of one would equal she indicated future preferences and the value of two would equal she indicated obtaining the money or goats today. The aggregated responses over all four questions are aggregated to give a more robust measure of time preferences and time consistency. The variable thus has a lowest score of four if she answered future to all the questions and 8 if she answered present, or today, to all the questions. For a total score over the four questions of 5, 6, or 7, which indicate women exhibit some patience in preferences, these women are characterized as exhibiting stochastically present biased preferences. The mean of our time preference variable is 7.32 (the median of the variable is 8) indicating the treatment households are very present bias and rarely if ever prefer to delay sums of money or sheep for larger future payoffs. Our sample is very present biased with 58% of the treatment sample indicating they were 100% present biased. An additional 39% of treatment households indicate being stochastically present biased. Importantly of this 39%, 28% were only stochastically present biased in one of the four questions (or had a score of 7), indicating an overall very strong bias towards receiving the lottery in the present. Finally, 3% of our sample exhibit preferences consistent with being future biased 100% of the time.

### 3.4: Additional Data Collected on Behavioral Aspects of Technology Adoption

There are four main behavioral concepts measured related to: 1). Time Concepts; 2). Information; 3). Social Norms; and 4). Overconfidence. In particular, in addition to the already mentioned effects- age as a dummy for the likelihood to invest in learning a new technology, peer effects, and present vs. future biased; the following behavioral economics concepts were measured over the three surveys waves including: women's attitudes towards risk, early (relative) adopter of technology, women's level of information on breathing in smoke from the cookfire and its relationship to health, beliefs about control over health, beliefs about control over fate, belief that purchasing and collecting fuel is a burden, trust in general and trust in our NGO partner Tostan, measures of intra-household bargaining power, and overconfidence. Appendix 2 outlines the construction of these variables, summary statistics, and the OLS regression analysis used to identify which variables show statistically significant results in affecting solar stove usage. In brief, to test each of these behavioral phenomenon on women's solar usage, the y variable is women's average solar stove usage over the sixth month period. The X variables include a vector of controls- age, baseline number of people for whom women report preparing lunch, household consumption proxies for wealth (kg/person of both flour and rice consumed weekly) baseline lunch kilograms of wood used, time households spend collecting fuel per day, dummy variable if women is employed, and village fixed effects. Each of these behavioral economics phenomenon are run with the individual and village fixed effects, first individually and then collectively.

Of all these different behavioral economics phenomena tested above no results are individually or collectively statistically significant aside from peer effects and age. A detailed outline of variable construction and regression outcomes for these variables is available in Appendix 2.

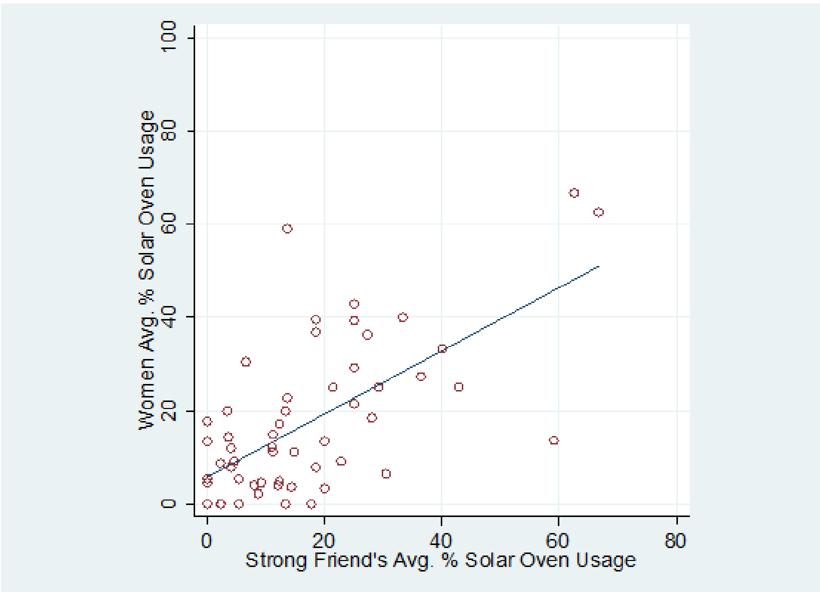
## Section 4: Methodology and Results

### 4.1: Basic OLS Regression Results

Of the 960 households in our sample we were able to match at least one friend for 712 households (see Table 2). Given 792 households completed the baseline survey, the match rate is 90%. The match rate is higher for treatments than it is control because more treatments were present at the baseline survey (465) versus control households (327). This is reflected in the number of friends matched which for treatments results in 87% of total sample while for controls it is 61% of total sample. However, for the "Strong" friend linkages identified by women in the treatment group, the division is perfectly split between those who belong to the Treatment group (61) and those who belong to the Control group (60).

While basic OLS regression results report a positive and statistically significant relationship between women's solar stove usage and that of her "Strong" friend's, more work must be done for these results to be convincing. Considerable attention has been devoted to the econometric problems that typically arise in empirical models concerning peer effects and particularly the inherent endogeneity problems commonly known as the reflection effect (See Manski (1993)). Prior to addressing these issues, first let me quantify the basic relationship observed between women's solar stove usage and that of her "Strong" friend's.[32] Graph 2, below, is a scatter plot of treatment women's usage vs. her "Strong" friends (who are also treatments) usage at the 6 mo. follow-up. Graph 3, represents the same plot as Graph 2, but both variables are demeaned by village mean and hence the constant is removed from the slope.

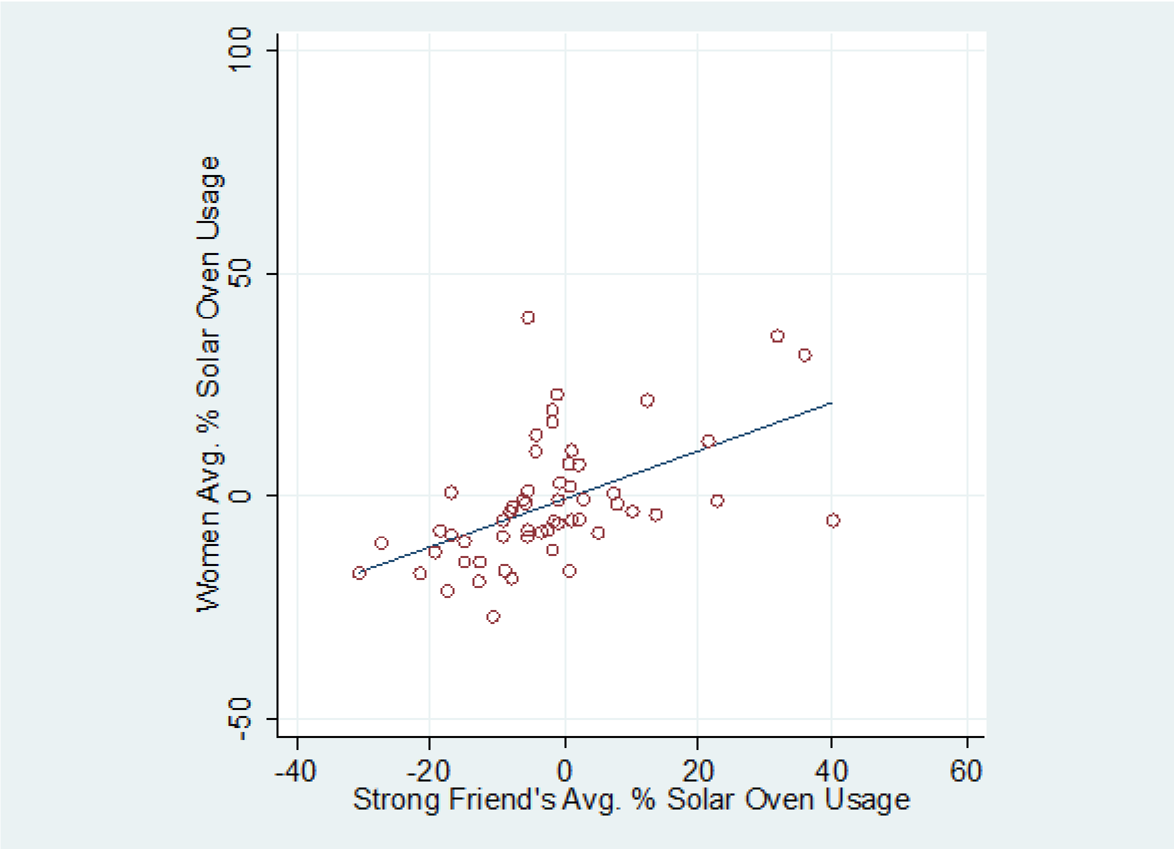
**Graph 2: Women and their "Strong" Friends Avg. Six Month Solar Stove Usage**




[32] For three treatment households there are more than one "Strong" friend's solar stove usage recorded at the 6 month follow-up. Two of the three had two "Strong" friend's solar stove usage recorded while one of the three had three "Strong" friend's solar stove usage recorded. To analyze the data, for these three households, "Strong" friend's solar stove usage was collapsed by the mean.

The trend line in Graph 2 above shows a clear relationship, women's average solar stove usage and that of her "Strong" symmetric friend's solar stove usage in the sixth month period has a positive and increasing slope indicating a strong positive correlation of women's and her "Strong" symmetric friend's solar stove usage. Graph 3 is the same as graph 2 except the data has been demeaned by village average. This is one method of controlling for village fixed effects and given the relatively small sample size (n=58)[33] this is the best way of incorporating village fixed effects.

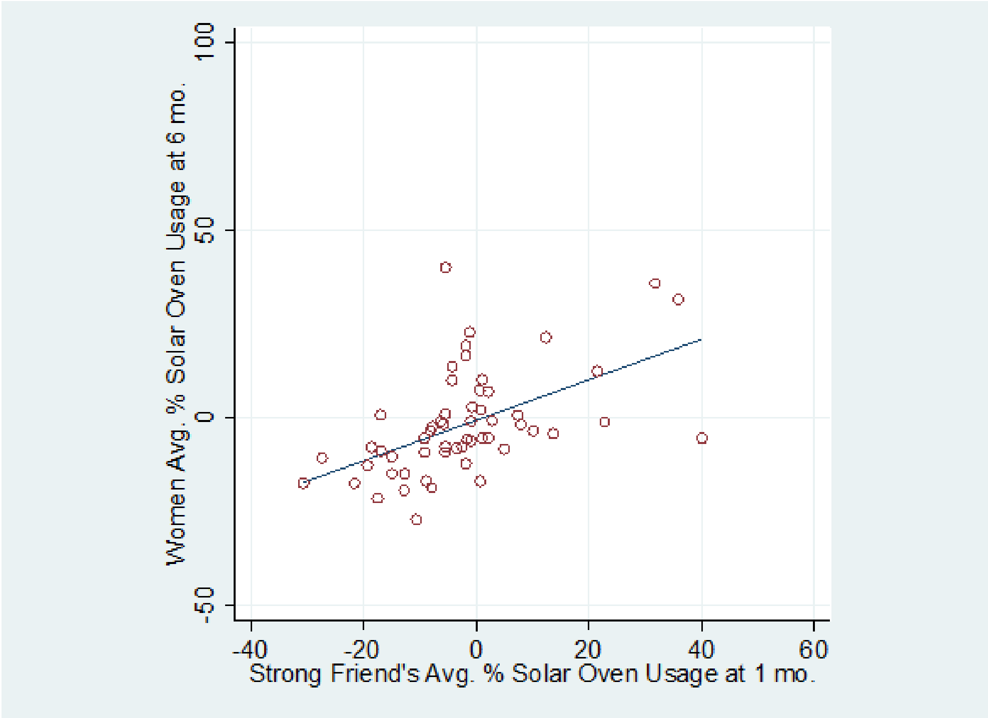
**Graph 3: Six Month Solar Oven Usage Both Variables Demeaned by Village Average**




To measure the possibility that women's "Strong" symmetric friends in the treatment group act as early adopters for women in the treatment group, Graph 4 plots the scatter plot of women's average solar stove usage at the sixth month period vs. the solar stove usage of their "Strong" symmetric friends at the one month. The slope of the line is less steep than that in Graph 2 or 3 when "Strong" friend's solar oven usage is at the sixth month period, though the relationship is still positive and upwards sloping. This is a positive indication for some women their "Strong" friends served as early adopters.

[33] Our sample drops from 61 to 58 because three households have more than one "Strong" friend. For these three households the "Strong" friend's average solar oven usage is averaged together. See footnote 32.

**Graph 4: Early Adopters: Women's (6 mo) & their Strong Friends (1 mo) Solar Stove Usage**




Basic OLS regression analysis confirms the results from the scatter plots. The basic OLS regression model is expressed below in Model 5:

$$woman's\ avg.solar\ stove\ usage_{i,t} = \alpha_{i,t} + Strong\ friend's\ solar\ stove\ usage_{j,t} + \varepsilon_{i,j} \quad \text{(Model 5)}$$

For both women and her "Strong" friend's, average solar oven usage is determined by taking the total number of days the household was observed to use her solar oven, provided by the SUM, and then dividing this number by the total days each household had the SUM installed. This measure, which I refer to as Women's average solar stove usage should be thought of percentage of time women use their solar oven. Four different versions of Model 5 described in Table 1 below are run and results are presented in Table 3.

<table>
<tr><th colspan="3">Table 1: Description of OLS Regression Models 5a-5d.</th></tr>
<tr><th>Model No.</th><th>Dependent Variable</th><th>Explanatory Variable</th></tr>
<tr><td>5a</td><td>Women's Solar Stove Usage (t=6 mo.)</td><td>"Strong Friend's Solar Stove Usage (t=6 mo.)</td></tr>
<tr><td>5b</td><td rowspan="3">Women's Solar Stove Usage Demeaned by Village Average (t=6 mo.)</td><td>"Strong Friend's Solar Stove Usage Demeaned by Village Average (t=6 mo.)</td></tr>
<tr><td>5c</td><td>"Strong" Friend's Solar Stove Usage Demeaned by Village Average and Strong Friends Observations in the Control Group assigned a value of "0".</td></tr>
<tr><td>5d</td><td>"Strong Friend's Solar Stove Usage Demeaned by Village Average (t=1 mo.)</td></tr>
</table>

For Models 5b-5d women's average solar stove usage and their strong friend's usage has been demeaned by the village mean to account for village fixed effects. I do this because the sample size is relatively small given that only 61 "Strong" friends of women in the treatment group have been identified and have data on solar stove usage. Further, for this same reason I leave out other explanatory variables including individual fixed effects in my regression analysis.[34] Model 5a is 100% statistically significant and has a positive coefficient of .007. When I include village fixed effects, Model 5b is 100% statistically significant with a positive coefficient for "Strong" friend's solar oven usage of 0.541. Model 5c is the same regression as 5b except 5c inputs the women in the treatment group's "Strong" friend's who are in the control group to "0" from missing. Model 5c addresses the bias in the OLS regression that socially isolated women may have fewer friends and may use their stove differently. The result for Model 5c are almost the exact same as those in 5b and women's "Strong" friend's have a coefficient of 0.541 (100% statistically significant coefficient). To test whether strong friends may serve as early adopters for women, Model 5d substitutes "Strong" friend's solar oven usage demeaned by village average over the one month period. The results are very similar to Model 5b and 5c and the coefficient of 0.542 is statistically significant at the 100% level. This seems to indicate that women's strong friend's usage at month one may serve the role as an early adopter. If so, women's "Strong" friend's solar stove usage over the one month period sends a positive signal to women which results in increased solar oven usage by women at the sixth month follow-up.

## 4.2: Endogeneity and Controlling for the Reflection Problem

**Reflection Problem**

The results presented above are important first results, yet they are not conclusive. Following the large body of theoretical and empirical literature on peer effects and social networks considerable attention has been devoted to the econometric problems that typically arise. The reflection problem first articulated by Charles Manski arises when a researcher observing the distribution of behavior in a population tries to infer whether the average behavior in some group influences the behavior of the individuals that comprise the group. The term reflection is similar to that of interpreting the almost simultaneous movements of a person and his reflection in a mirror. Thus, in a world with reflection problems where my actions affect your actions which then reflect to my actions, further empirical analysis must be run to confirm the basic OLS regression results are not endogenous.

Bandiera and Rasul (2002) in an empirical paper modeling the role of social networks in individual adoption decisions of a new agricultural technology in Mozambique present the following model to counteract the reflection problem outlined by Manski. In their model, they let $a_{iv}$ equal the behavior of individual *i* living in village *v* and let $n(i)$ denote the social group of individual i. Given that social interactions affect individual decisions, $a_{iv}$ should be estimated as a function of the personal characteristics of individual $i$ $(X_{iv})$ and the characteristics of the behavior of the relevant social group *i*, $a_{i(n)v}$, as well as social group's characteristics $X_{i(n)v}$. Assuming linearity and that the error term $u_{iv}$ is unbiased the model is represented below:

[34] See footnote 35.

$$a_{iv} = \beta X_{iv} + \gamma a_{n(i)v} + \delta X_{n(i)v} + u_{iv} \qquad \text{Model 6}$$

Their model follows from Manski (1993) who shows that $\gamma$ measures the "endogenous" social effects or the impact of group behavior on the choice of individual i while $\delta$ measures the "exogenous" social effects, that is the direct effect of the characteristics on the group in the decision of i. The endogenous social effect operates through any channel in which the fact that members of the network have also adopted will raise the marginal benefits of i adopting. Complimentarily, an example of an exogenous social effect in our study is where i's strong friends have some characteristics which raise the marginal benefit to i adopting irrespective of whether the member of i's social group have themselves adopted. Thus, the actual behavior of a social group may be correlated, but it is the characteristics of the group as opposed to their actual behavior which is the causal mechanism for this correlation.

Although difficulties in the identification of social effects are many and diverse and depend on the particular context of the study, they all derive from two root sources- simultaneity and correlated unobservables. Simultaneity arises because social interactions are symmetric in the sense that i's behavior affects the behavior of the other members of the group- i.e. $a_{n(i)v} = g(a_{iv})$. This is known as the reflection problem- group behavior affects i's behavior- which, in turn, affects the group's behavior.

Thus, to be able to identify endogenous and exogenous effects in the Manski (1993) framework, the econometrician is required to have the following data according to Bandiera and Rasul (2002). First, a complete set of individual characteristics that determine adoption. This includes variables that we typically think of as being unobservable such as farmer ability, entrepreneurship, "openness" towards new ideas, or credit constraints. Second, the behavior of the true social group of i, n(i) which of course assumes that n(i) has been correctly identified. Third, the relevant set of characteristics of the social group, $X_{i(n)v}$. Needless to say, these data requirements are very stringent. In the absence of any one of these sets of controls, the identification of social effects becomes confounded with the correlated unobservables problem. Further, even if our dataset had a complete and well measured set of individual characteristics for women and her "Strong" symmetric friend's due to the low N (61 observations) of women's "Strong" friend's solar stove usage, we could not include all the individual characteristics.[35] Thus, this work recognizes the important theoretical idea of Bandiera and Rasul (2002) and attempts to run a version of Model 6 including $X_{iv}$ ( $X_{n(i)v}$) equal to the women ("Strong" friend's) empirical time consistent preference measure of future, present, or stochastically present biased.[36]

This is clearly an imperfect test of Model 6 as it only includes one set of "exogenous" explanatory variables for women and their "Strong" friend's- future, present, or stochastically biased. I chose this measure because of the argument outlined in Section 2B-Hypothesis 2, and the possibility that the small costs required by the solar oven for behavior change by women have disproportionate effects on their behavioral outcomes and usage of

[35] Because the subset of women's "Strong" friends is very small, using the rule that we include one explanatory variable for every 10 observations, I am limited in the number of explanatory variables to include. For this reason, I only include these 6 explanatory variables.

[36] For variable definitions and constructions of present, stochastically present and future biased women see Section 3.3).

the solar oven. The results presented in Table 3, column 5, show what are defined as the "endogenous" effects are positive and statistically significant and that is women's "Strong" symmetric friend's solar stove usage with a coefficient of 0.492. The exogenous effects are insignificant, or "Strong" friend's time consistent preferences of present, stochastically present, or future biased are not significant. The dummy variable for women of stochastically present biased is positive and statistically significant at the 10% level. Thus, we are still not convinced that the basic OLS regression results are free from endogeneity.

Despite this attempt to address the omitted variables problem that affect usage of women and her "Strong" symmetric friend's with application of empirical Model 6 above, the simultaneity problem remains an issue. As mentioned above, in the absence of any one of these sets of controls, the identification of social effects becomes confounded with the correlated unobservables problem. I conclude the Bandiera and Rasul model (see Model 6) is not a perfect fit for my small sample size and limited number of explanatory variables which I can include. Thus, I continue to explore empirical solutions to address the reflection problem.

**Exploiting the Randomization to Address the Simultaneity Issues**

To address the problem of simultaneity this dataset has a unique advantage- women's friends and women themselves were randomly selected to be part of the treatment or control group. Thus, I can utilize the randomization to determine whether the OLS results are biased. To do so, I use an instrumented variables regression model where average "Strong" friend's usage over the sixth month period is instrumented for the share of women's "Strong" friends who are treatments. This effectively avoids the simultaneity problem and can be modeled as:

$$Women's\ Solar\ Stove\ Usage\ _{i,t=6\ mo.} = \alpha_i + \ ["Strong\ Friend\ Solar\ Stove\ Usage_{j,t=6\ mo.} = Share\ of\ Women's\ \text{"Strong"}\ Friends\ Who\ are\ Treatments_i] + \ \varepsilon_i \qquad \text{Model (7)}$$

Results from Model 7 are represented in Table 4. Column 7a of Table 4 shows the results from Model 7 are not statistically significant and the share of women's friends who are strong friends and treatments is not a statistically significant instrumented variable for "Strong" friends average solar stove usage over the sixth month period.

Models 7b takes a slightly different approach and instead instruments "Strong" friend's average solar oven usage at the sixth month follow-up with the share of women's "Strong" friends whose solar oven usage at the sixth month period is above average. A woman's "Strong" friend's solar oven usage is deemed above average if her solar stove usage is above her respective village's mean. The share of women's "Strong" friends with above average solar oven usage, as before is a dummy variable, where 1 indicates women's "Strong" friend is a treatment and has above average solar oven usage at the sixth month period and 0 otherwise. The results for both Model 7b shows a positive and statistically significant (99% level) with a coefficient of 0.42 for the instrumented variable.

The results from Models 7a and 7b show that the share of treatments alone is not statistically significant as an instrumented variable. However, the share of treatments which are above average users is statistically significant (99% level) and yields a coefficient 0.42

which is very close to the basic OLS regression results coefficient estimates 0.541-0.542. Using the randomization circumvents the simultaneity and identification issues common to peer effects. From the instrumented variable results we learn that by using the randomization in the sample when we instrument “Strong” friend’s solar stove usage for the % of women’s friends who use their solar stove intensively, we find a positive and statistically significant coefficient at the the 99% level. At the same time we learn by instrumenting “Strong” friend’s solar stove usage by the share of “Strong” friends who are treatments our results are insignificant. Thus, we learn that women’s “Strong” friends who use their solar oven above average are at the core of our social multiplier effects. This is consistent with the results from our OLS regression analysis and particularly Model 5d measuring which regresses women’s solar stove usage at the sixth month period on that of women’s “Strong” friend’s stove usage in the one month period. The results from 5d indicate a positive and significant relationship between women’s solar stove usage at the 6 month period and that of her “Strong” friend’s at the one month period. Hence, we have reason to believe women’s “Strong” friend’s may serve as early adopters. Further, I show that “Weak” asymmetric linkages are non-significant and there seems to be no correlation with increased solar oven usage by women due to their “Weak” friend’s solar oven usage.[37] This reinforces that only the technology decisions of close friends whom women have shared trust have a positive effect on their own technology adoption decisions.

**Robustness Checks- The Dyad Problem**

In addition, OLS regression analysis is further biased by the double-counting present for co-identified strong friend links in dyads. The dyad problem exists when Women A and B are strong friends and both women have solar stove usage data in the y and x variables as shown in Model 8 below. If this is the case the standard error is biased up by double-

$$\begin{bmatrix} Women\ A\ solar\ stove\ usage_i \\ Women\ B\ solar\ stove\ usage_j \end{bmatrix} = \begin{bmatrix} \alpha_i \\ \alpha_j \end{bmatrix} + \begin{bmatrix} \beta\ \text{"}Strong\text{"}\ friend\ B\ solar\ stove\ usage_j \\ \beta\ \text{Strong} friend\ A\ solar\ stove\ usage_i \end{bmatrix} + \begin{bmatrix} \varepsilon_{ij} \end{bmatrix} \text{ Model 8}$$

-counting. To control for this I run a random effects model where the y variable is equal to women’s solar stove usage at the sixth month follow-up and the x variable is women’s “Strong” symmetric friend’s solar stove usage, controlling first for village fixed effects and second for dyads. The results in Appendix 1 show for the 19 villages where at least one women’s “Strong” friend identified is in the treatment group and also has solar oven usage has data; the first grouping reads 18 (the 19th is the constant). Next, the second grouping is the number of dyads controlled. The random effects model (see Appendix 1) shows that when we control for dyads, the coefficient on “Strong” friend’s solar stove usage continues to have a positive (0.69) and statistically significant effect (100%) on women’s solar stove usage over the sixth month period. Thus, we conclude that the dyad effect is minimal.

## Section 5: Conclusions

This paper estimates the behavioral aspects of technology adoption of solar ovens in rural Senegal, focused particularly on examining the causal link of peer effects. The solar oven has the potential to reduce household expenditure up to 57% if used 90% of the time in the dry

[37] Results are available by request to author.

season.[38] Yet we find on average at the sixth month period households in the treatment group use their solar oven 19% of the time, or about one in every five days. Of all the behavioral economics phenomenon measured age cohorts 21-30 are positively and statistically significant with increased solar oven usage. Given younger women are more likely to adopt the solar oven one possible policy conclusion is that at least one younger woman per household should be trained in addition to the women who purchased the oven on how to use the solar oven as this is likely to have positive effects on usage. These results are generalizable to other modern technology adoption programs and suggest training younger cohorts alongside older cohorts in a household may yield higher adoption results.

In addition, we find that peer effects matter for solar stove usage. Over the six month period, results show that "Strong" friend's solar oven usage affects women's usage positively and significantly within a range of estimated coefficients of 0.42-0.541 depending on the regression specification. Average "Strong" friend's solar oven usage over the sixth (coefficient of 0.541) and one month period (coefficient of 0.542) both have positive and statistically significant effects on women's solar oven usage over the sixth month period. The positive and statistically significant one month period "Strong" friend's solar oven usage could indicate "Strong" friends may also serve the role of an early adopter. Some women seem to wait to observe their "Strong" friend's outcomes with the solar oven before trying it themselves. Despite the endogeneity problems inherent to measuring network effects, I use the randomization and am able to incorporate measures which circumvent the reflection problem potentially present in our basic OLS regression results. The instrumented variable results give a surge of confidence to the initial OLS regression results. We learn that only when we instrument the x variable of women's "Strong" friend's solar oven usage with a dummy variable for the share of women's "Strong" friend's who have above average usage, do we have a positive and statistically significant result of 0.42 (99% level).[39] This result is close to our OLS regression estimates coefficients of 0.51. In conclusion, the social multiplier effect exists only for women's "Strong" symmetric friendship links and is absent in "Weak" asymmetric links. Further, results reveal it is women's "Strong" friend's who are above average solar oven user's that drive the observed social multiplier link. This suggests, other technology adoption programs could consider training households by "Strong" peer cohorts as this may assist in adoption.

We also observe a path dependence which emerges in women's solar stove usage. Women who use their solar oven more in the one month period are more likely to use their stove in the six month period, regardless of additional training. This phenomenon underlines the importance of targeting behavior change early in the program.

Finally, the demonstration effect observed, or women's desire to please the research team by demonstrating/stating false levels of stove usage, underlines the importance of having an objective measure of stove usage. We see an important role for SUMs in future improved stoves projects. This result can be generalized for researchers to in future technology adoption studies to use creative methods to observe actual adoption behavior by households.

[38] The rainy season runs from mid-June to late August.
[39] Over the sixth month period.

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# Contents for Tables, Figures, and Appendices

**Table 2: Descriptive Statistics for Number of Friends Matched**

| | Sample | Treatment | Control |
|---|---|---|---|
| Total Number of Households | 960 | 488 | 472 |
| Total # of Friends Matched | 896 | 532 | 364 |
| Total # of Hhlds with at least one friend matched | 712 | 424 | 288 |
| Total # of Symmetric "Strong" Friendships | 206 | 121 | 85 |
| Of Which # of hhlds with one strong friend matched | 191 | 110 | 81 |
| Of which # of hhlds with two strong friends matched | 14 | 10 | 4 |
| Of which # of hhlds with three friends matched | 1 | 1 | 0 |
| Total # Asymmetric "Weak" Friendships | 690 | 411 | 279 |
| Of Which # of hhlds with one weak friend matched | 209 | 115 | 94 |
| Of Which # of hhlds with two weak friends matched | 298 | 180 | 118 |
| Of which # of hhlds with three friends matched | 179 | 113 | 66 |
| Of which # of hhlds with more than three friends matched | 4 | 3 | 1 |

| Table 3: OLS Regression Results Peer Effects | | | | | | |
|---|---|---|---|---|---|---|
| Coefficient (standard error) | | Model 5a. | Model 5b. | Model 5c. | Model 5d. | Model 6. |
| y variable | x variable | | | | | |
| Women's Solar Stove Usage (t=6 mo.) | "Strong Friend's Solar Stove Usage (t=6 mo.) | .007*** | ... | ... | ... | ... |
| | | (0.00) | ... | ... | ... | ... |
| Women's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | "Strong Friend's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | ... | 0.541*** | ... | ... | ... |
| | | ... | (0.12) | ... | ... | ... |
| | "Strong Friend's Solar Stove Usage Demeaned by Village Average and "Strong" Links Control imputted to zero (t=6 mo.) | ... | ... | 0.541*** | ... | ... |
| | | ... | ... | (0.11) | ... | ... |
| | "Strong Friend's Solar Stove Usage Demeaned by Village Average (t=1 mo.) | ... | ... | ... | 0.542*** | ... |
| | | ... | ... | ... | (0.12) | ... |
| | "Strong Friend's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | ... | ... | ... | ... | 0.492** |
| | | ... | ... | ... | ... | (0.18) |
| | Woman is present biased | ... | ... | ... | ... | 8.99 |
| | | ... | ... | ... | ... | (11.99) |
| | Woman is stochastically present biased | ... | ... | ... | ... | 12.72Γ |
| | | ... | ... | ... | ... | (7.20) |
| | Woman is future biased | ... | ... | ... | ... | 10.57 |
| | | ... | ... | ... | ... | (11.99) |
| | "Strong" Friend is present biased | ... | ... | ... | ... | ... |
| | | ... | ... | ... | ... | ... |
| | "Strong" Friend is stochastically present biased | ... | ... | ... | ... | 9.37 |
| | | ... | ... | ... | ... | (10.51) |
| | "Strong" Friend is future biased | ... | ... | ... | ... | 7.45 |
| | | ... | ... | ... | ... | (10.45) |
| Constant | | .058* | -0.577 | -0.746 | -0.577 | 17.21 |
| | | (0.02) | (1.58) | (1.53) | (1.58) | (11.99) |
| $R^2$ | $R^2$ | 0.415 | 0.28 | 0.28 | 0.28 | 0.3 |
| Observations | Observations | 58 | 58 | 60 | 58 | 38 |

Notes: {***}** (*) = statistically significant at the{0%} 1% (5%) level while Γ indicates variables which are statistically significant at the 10% level;

| Table 4: Regression Results Peer Effects | | | | |
|---|---|---|---|---|
| Coefficient (standard error) | | | **7a** | **7b** |
| y variable | Instrumented variable | x variable | | |
| Women's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | "Strong Friend's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | Share of All Strong Friends who are Treatments | -0.23 | … |
| | | | -4.06 | … |
| | "Strong Friend's Solar Stove Usage Demeaned by Village Average (t=6 mo.) | Share of All Strong Friends who are Treatments and who Use their Solar Oven Intensively | … | 0.42** |
| | | | … | -0.16 |
| | | Constant | -2.35 | -0.85 |
| | | | -9.58 | -1.62 |
| | | $R^2$ | … | 0.27 |
| | | Observations | 58 | 58 |
| Notes: {***}** (*) = statistically significant at the{0%} 1% (5%) level | | | | |

## Appendix 1: Random Effects Model 8

```
Performing EM optimization:
Performing gradient-based optimization:
Iteration 0:   log restricted-likelihood = -214.54895  (not concave)
numerical derivatives are approximate
nearby values are missing
numerical derivatives are approximate
nearby values are missing
Hessian has become unstable or asymmetric

Mixed-effects REML regression                   Number of obs      =        58
Group variable: village                         Number of groups   =        18
                                                Obs per group: min =         1
                                                               avg =       3.2
                                                               max =         5
                                                Wald chi2(6)       =     35.99
Log restricted-likelihood = -214.54895          Prob > chi2        =    0.0000

------------------------------------------------------------------------------
usage_d2~100 |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
s_friend_s~e |   .6887082   .1182026     5.83   0.000     .4570355     .920381
      age_20 |   9.825066   8.764313     1.12   0.262    -7.352671     27.0028
   age_21_30 |   7.648804   6.318223     1.21   0.226    -4.734686    20.03229
   age_31_40 |   7.092597   6.399489     1.11   0.268    -5.450172    19.63537
   age_41_50 |   8.902034   6.880214     1.29   0.196    -4.582939    22.38701
   age_51_60 |   11.02393   8.143974     1.35   0.176    -4.937969    26.98582
       _cons |  -1.996195   6.128584    -0.33   0.745      -14.008    10.01561
------------------------------------------------------------------------------
  Random-effects Parameters  |   Estimate   Std. Err.     [95% Conf. Interval]
-----------------------------+------------------------------------------------
village: Identity            |
                   sd(_cons) |   1.151299          .             .           .
-----------------------------+------------------------------------------------
village: Identity            |
                 sd(R.hhid1) |   9.599243          .             .           .
-----------------------------+------------------------------------------------
village: Identity            |
              sd(R.hhid1~id) |   8.987793          .             .           .
-----------------------------+------------------------------------------------
                sd(Residual) |   .8368766          .             .           .
------------------------------------------------------------------------------
LR test vs. linear regression:       chi2(3) =     0.00   Prob > chi2 = 1.0000
```

| Annex 2 : Table 1: Summary Statistics | | | | | | | |
|---|---|---|---|---|---|---|---|
| Column 1 | Treatment | | | Column 2 | Treatment | | |
| | mean (s.d.) | median | Obs | | mean (s.d.) | median | Obs |
| Stove Usage Monitor Month 6 (% usage) | 18.45 (18) | 14 | 422 | Household decision maker is husband | 55.5% | ... | 472 |
| Daily Kilograms of Wood Used to Cook with per person in household | 1.03 (.76) | 0.83 | 410 | Household decision maker is other | 16.7% | ... | 472 |
| Baseline no. of people for whom woman prepared lunch | 13.80 (6.72) | 13 | 459 | Household decision maker is first wife | 1.7% | ... | 472 |
| Baseline no. of people for whom woman prepared lunch centered and squared | 45.01 (90.90) | 19 | 459 | Household decision maker is mother or father | 3.6% | ... | 472 |
| Baseline lunch kg. of wood used per person[b] | .57 (.27) | 0.24 | 488 | Liquidity Constrained[a, b] | 11240 (23258) | 1190 | 488 |
| Baseline kg. of flour consumed per person per week[b] | .24 (.12) | 0.23 | 488 | Present vs Future Bias[b] | 7.31 (0.98) | 8 | 488 |
| Baseline kg. of rice consumed per person per week[b] | .25 (.16) | 0.55 | 488 | Risk aversion[b] | 3.43 (1.14) | 3 | 488 |
| Time spent (minutes) by all household members collecting fuel per collection period (# of days fuel lasts)[b] | 161.14 (67.33) | 161 | 488 | Early (relative) Adopter of Technology[b] | 5.97 (1.61) | 6 | 488 |
| Dummy variable for respondent is employed[b] | .76 (.42) | 1 | 488 | Level of Information on Smoke from the Cook Fire and Health[b] | 5.88 (1.21) | 6 | 488 |
| Wealth proxy and ownership of radio, gas stove, cellphone, and television (where if owned is equal each= 1, 0 otherwise)[b] | 3.17 (1.02) | 3 | 488 | Belief- Woman has control over Heath Outcomes[b] | 6.82 (2.58) | 7 | 488 |
| Dummy variable for respondent has no education[b] | .79 (9.39) | 1 | 488 | Belief- Woman has control over fate[b] | 8.08 (2.72) | 8 | 488 |
| Stove Usage Monitor Month 1 (% usage) | 9.8% (10.00) | 8% | 446 | Belief- Fuel is a burden[b] | 12.12 (2.28) | 12 | 488 |
| Age group 1- 20 years of age (% of total) | 8.5% | ... | 468 | Belief-Trust[b] | 3.07 (.56) | 3 | 488 |
| Age group 2- 21-30 years of age (% of total) | 31.2% | ... | 468 | Belief- Trust in Tostan[b] | 3.28 (.73) | 3 | 488 |
| Age group 3- 31-40 years of age (% of total) | 31.4% | ... | 468 | Overconfidence[b] | 0.52 (.76) | 0 | 488 |
| Age group 4- 41-50 years of age (% of total) | 19.9% | ... | 468 | Peer Effects Data Successfully Matched (% of treatment sample with successful match) | 87% | ... | 424 |
| Age group 51 years or more (% of total) | 9.0% | ... | 468 | Peer Effects Data Successfully Matched Number of Strong Friendships (% of treatment with a successful strong match) | 25% | ... | 121 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Household decision maker is grandparents | 2.1% | ... | 472 | Peer Effects Data Successfully Matched Number of Weak Friendships (% of treatment with a successful weak match) | 84% | ... | 411 |
| Household decision maker is respondent | 11.2% | ... | 472 | Peer Effects Mising Data | 13% | ... | 64 |
| Household decision maker is respondent and her husband | 9.1% | ... | 472 | a. top coded; b. missing variables are imputed to the mean | | | |

**Annex 2: Table 2 Main Regression Results**

| Coefficient (standard error) | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Behavioral Economics Concept Category | Dependent variable for models 1-2: Month Six Stove Usage per days measured and Models 3-4: Six Month Follow-up Daily Kg. of Wood used Yesterday. | | | | |
| 0. Household, Individual, and Village level Fixed Effects | Baseline no. of people for whom woman prepared lunch | -0.071 | -0.127 | -0.002 | -0.002 |
| | | (0.2) | (0.22) | (0.01) | (0.01) |
| | Baseline no. of people for whom woman prepared lunch, centered and squared | -0.008 | -0.005 | 0 | 0 |
| | | (0.0) | (0.01) | (0.00) | 0 |
| | Baseline kg of flour consumed per capita per week | 2.159 | 3.13 | -0.471 | -0.393 |
| | | (9.8) | (9.91) | (0.36) | (0.36) |
| | Baseline kg. of rice consumed per capita per week | 0.124 | -0.032 | 0.053 | 0.051 |
| | | (5.8) | (5.76) | (0.25) | (0.25) |
| | Village fixed effects | Yes*** | Yes*** | Yes* | Yes* |
| | Baseline lunch kg. of wood used per person | 0.802 | 0.832 | 0.487* | 0.474* |
| | | (0.5) | (0.47) | (0.21) | (0.21) |
| | Total time (minutes) household spends collecting fuel per day | 0.022 | 0.02 | 0.001 | 0.001 |
| | | (0.0) | (0.01) | (0.00) | (0.00) |
| | Baseline woman respondant is employed (dummy 1=yes; 0=no) | 3.265 | 3.571 | -0.095 | -0.063 |
| | | (2.0) | (2.05) | (0.09) | (0.09) |
| | Solar stove usage month 1 (SUMS) | 0.252** | 0.250** | ... | ... |
| | | (0.1) | (0.10) | ... | ... |
| | Baseline Wealth proxy (4=most items owned; 0=fewest items owned) | 0.338 | -0.242 | -0.065 | -0.064 |
| | | (0.9) | (0.87) | (0.04) | (0.04) |
| | Baseline Respondant has no education (dummy 1=yes; 0=has some formal education) | 1.033 | 1.106 | -0.076 | -0.069 |
| | | (2.2) | (2.17) | (0.10) | (0.10) |
| 1. Time | Age cohort of respondant is age 20 or less | -2.313 | -2.368 | 0.016 | 0.04 |
| | | (3.9) | (3.92) | (0.16) | (0.16) |
| | Age cohort of respondant is age 21-30 years | 6.755* | 6.610* | 0.117 | 0.133 |
| | | (3.1) | (3.16) | (0.11) | (0.11) |
| | Age cohort of respondant is age 31-40 years | -3.967 | -3.8 | 0.208 | 0.218* |
| | | (3.1) | (3.07) | (0.11) | (0.11) |
| | Age cohort of respondant is 41-50 years | -5.25 | -5.732 | ... | ... |
| | | (3.4) | -(3.39) | ... | ... |

| | | | | | |
|---|---|---|---|---|---|
| | Age cohort of respondant is 51 years or more | ... | ... | 0.121 | 0.119 |
| | | ... | ... | (0.16) | (0.16) |
| | Liquidity Constrained | 0 | 0 | 0 | 0 |
| | | (0.0) | (0.00) | (0.00) | (0.00) |
| | Present vs. Future Bias | 0.053 | 0.279 | 0.03 | 0.024 |
| | | (0.8) | (0.83) | (0.04) | (0.04) |
| | Risk Aversion | 0.364 | 0.361 | -0.028 | -0.033 |
| | | (0.7) | (0.73) | (0.03) | (0.03) |
| 2. Information | Early (Relative Adopter of Technology | 0.191 | 0.102 | 0.002 | -0.007 |
| | | (0.6) | (0.60) | (0.03) | (0.03) |
| | Information on Breathing in Smoke is Bad for one's Health | -0.635 | -0.742 | 0.009 | 0.003 |
| | | (0.7) | (0.71) | (0.03) | (0.03) |
| 3. Social Norms | Belief: Destiny vs. Personal Will in Health Outcomes | 0.546 | ... | -0.01 | ... |
| | | (0.4) | .... | (0.02) | ... |
| | Belief: Destiny vs. Personal Will | ... | 0.402 | ... | 0.005 |
| | | ... | (0.34) | ... | (0.02) |
| | Belief: Fuel is a burden | ... | 0.553 | ... | -0.112 |
| | | ... | (0.39) | ... | (0.07) |
| | Belief: Level of Trust | ... | 1.943 | ... | -0.026 |
| | | ... | (1.43) | ... | (0.05) |
| | Belief: Level ofTrust in Tostan | ... | 1.331 | ... | -0.069 |
| | | ... | (1.20) | ... | (0.05) |
| | Baseline household decision maker is respondant | 5.796 | 6.517 | 0.573 | 0.534 |
| | | (6.9) | (7.02) | (0.30) | (0.30) |
| | Baseline household decision maker is jointly respondant and her husband | 0.778 | 1.49 | 0.332 | 0.319 |
| | | (7.0) | (7.11) | (0.30) | (0.30) |
| | Baseline household decision maker is her husband | 6.703 | 7.479 | 0.25 | 0.219 |
| | | (6.5) | (6.65) | (0.27) | (0.28) |
| | Baseline household decision maker is other | 4.292 | 5.193 | 0.284 | 0.246 |
| | | (6.8) | (6.89) | (0.28) | (0.28) |
| | Baseline household decision maker is the first wife of husband | 0.846 | 1.529 | 0.449 | 0.326 |
| | | (8.7) | (8.82) | (0.39) | (0.39) |
| | Baseline household decision maker is her mother or father | 5.896 | 7.353 | -0.176 | -0.263 |
| | | (7.8) | (7.89) | (0.34) | (0.34) |
| 4. Overconfidence | Overconfidence | ... | 0.326 | ... | 0 |
| | | ... | (1.13) | ... | (0.00) |
| Constant | Constant | -8.22 | -26.2 | 0.466 | 0.563 |
| | | (12.7) | (15.01) | (0.57) | (0.68) |
| $R^2$ | $R^2$ | 0.286 | 0.294 | 0.178 | 0.196 |
| Observations | Observations | 422 | 422 | 410 | 410 |

Notes: ** (*) = statistically significant at the 1% (5%) level; All explanatory variables have been inputted to the mean aside from Village FEs, Age Cohorts, and Dummy Variable Missing for Friends. The following variables have been top and bottom coded: Baseline lunch kg of wood used per person

**Appendix 2- Complete Review of Behavioral Economics Concepts Measured**

The four main behavioral concepts measured over the three surveys waves include concepts related to 1). Time: present versus forward bias, age as a dummy for likelihood to invest in learning a new technology, risk preferences, 2). Information- information on breathing in smoke and effects on one's health, and early (relative) adopter of technology; 3). Social norms measures- beliefs about control over health, beliefs about control over fate, belief that purchasing and collecting fuel is a burden, trust, trust in our NGO partner Tostan, intra-household bargaining power, network effects, and 4). Over-confidence.

**Time Concepts**

We measure three behavioral economics phenomena which are related to time over our three survey waves. These include whether the woman who purchased the stove is present vs. future biased, whether the age of the woman affects her stove usage, and whether the woman is risk averse or risk loving.

***Time Concept 1: Present vs. Future Bias***

The time discounting measure is outlined in Hypothesis 2 in the main paper.

***Time Concept 2: Age as a Factor in Technology Adoption***

The second concept related to time is the age of the women who purchased the stove. The age cohorts are outlined in the main paper in Hypothesis 6.

***Time Concept 3: Risk Aversion***

The third concept associated with time is risk aversion. In particular, will households who are risk averse or risk loving use the solar oven more frequently? The adoption decision of the solar oven is similar to the adoption decision of genetically modified crops or fertilizer. Both are an investment in new technologies, previously widely unknown. Given the predominant role of agriculture in developing countries, much empirical work has been done attempting to understand what influences households' decisions to adopt fertilizer or genetically modified crops. This new generation of crops have the benefits of being pest and drought resistant, have higher yields, lower production costs, and even contain added nutrients. Despite the profits promised by new technologies, the adoption of new innovations is often slow and incomplete. Development economists have tried to explain the slow diffusion of new technology, as it is considered key to break the cycle of poverty. Economists studying farmer's use of fertilizer in Malawi found strong linkages between attitudes towards risk and adoption (Simtowe, Franklin (2006). In research examining the adoption decision by farmers in China who faced the decision to adopt genetically modified Bt cotton, Elaine Lui (2008) found that farmers who are more risk averse or more loss averse adopt Bt cotton later. And in particular farmers who overweight small probabilities adopt Bt cotton earlier. To this point there are relatively few empirical studies which measure risk aversion in the context of technology adoption in the developing world. Thus, this study joins a few economics works which have studied the role of risk attitudes in technology adoption.

To measure risk aversion among our sample, from the one month follow-up survey I use three questions to assess risk aversion. The first is: “If you were gravely ill this past year, did you take the risk to pay a doctor even if you did not have the means to pay the bill?' The second question is: “If any of your children were gravely ill during the past year did you take the risk to pay a doctor even if you did not have the means to pay the bill?'. For the third question, women were asked to agree or disagree with this statement using a standard five point responses: 1). yes always; 2). yes, usually; 3). sometimes; 4). No, not always; 5). No, never. The statement is; “In general do you take the risk to pre-finance and complete the weekly household spending when you are not sure that you can repay your debts?” All three questions are coded and summed such that 0 corresponds with extremely risk averse and 5 corresponds with risk loving. The mean for the risk aversion variable is 3.43 (the median is 3) indicating a higher than average tendency to exhibit risk loving attitudes among the treatment group. In the case a positive correlation of this variable with solar oven usage can be interpreted such that every 1% increase in solar oven usage is associated with an increase in risk loving beliefs. A negative correlation, or 1% increase in solar oven usage can be associated with risk-averse attitudes. It needs to be said that this measure is far from perfect, as attitudes towards risk are very difficult to measure. However, we attempt to measure more broadly the relationship, if any, between attitudes of risk and solar oven usage.

**Information Concepts**

While the design of the study included village level meetings and trainings on the product prior to purchase and continuously throughout the 6 months of the project, we test the amount of information consumers in the study have gained and cognitively processed. We measure two concepts related to information and the solar oven. First, we measure whether women have received the message that breathing in smoke from the cook fire is bad for your health. This message was given at every solar stove training in the villages and at the meetings which surrounded each of the survey waves in the village. If women did not receive this information than we would expect them to be less likely to adopt the solar oven. To evaluate this we ask women at the one month follow-up survey to respond to statements using the five point scale: 1). Yes, always; 2). Yes, usually; 3). Sometimes; 4). No, not usually; 5). No, never. The first phrase was: "Smoke from the cook fire is bad for my children's health". The second phrase was: "Breathing in smoke from the cook fire is good for my health". The responses were coded such that the highest understanding of carbon monoxide exposure and smoke from the cook fire is bad for my health is assigned the lowest score, while the highest score is equivalent to misinformation about the relationship of smoke from the cook fire and women's and children's health. To interpret a positive correlation with solar stove usage and information about smoke from the cook fire a 1% increase in stove usage is correlated with an increase of lack of information on the harm from smoke from the cook fire. Meanwhile, a negative relationship means that increased solar oven usage is correlated with the belief that smoke is bad for you and your children. Of the total possible score of 10=absolute understanding that smoke from the cook fire is bad for one’s health, the sample average was 5.88, a median of 6.

The second information piece we test is based on other items women own, including a toothbrush and a mosquito net and whether they boil water before they drink it. Based on this information, I construct a variable to indicate whether women are early or late relative adopters of technology and examine how this may affect solar oven usage or adoption. Obviously this second concept is intertwined with liquidity constraints and overall household wealth level as owning more products could simply be a reflection of the wealth level of the household. To control for this I include a separate relative wealth measure. Despite the imperfections of this measure and the potential conflagration of concepts measured including wealth, early technology adopter, and liquidity constrained, this measure could assist in understanding whether households which own items and have practices which are pro-science and pro-technology are more likely to adopt (have higher usage) of the solar oven. To measure this, based on our field testing for locally appropriate equivalents of high-tech products we surveyed our households for whether they already owned these products in both the one month follow-up and the six month follow-up surveys. In both the one and six month follow-up surveys women responded to whether they owned a toothbrush and a mosquito net. At the one month follow-up survey we asked women if they tended to boil water before they drank it. The questions were all coded such that 1 was equal to the response 'no' and 2 equal to the response 'yes'. Then all five questions were summed such that 5 would indicate not owning any of the products and 10 would be equal to responding yes to owning the product(s) on both surveys. If there is a positive correlation, than a 1% increase in solar oven usage is positively correlated with being an early technology adopter. And if there is a negative correlation, an increase in solar oven usage is correlated with low technology adoption. The mean for this variable is 6 (median is 6 as well) indicating on average some 60% of households own some high technology items.

**Social Norms**

The role of social norms and social capital in decision making has long been reported to be important by economists for technology adoption. A social norm consists of rules of conduct and models of behavior prescribed by a society. They are rooted in the customs, traditions, and value systems that gradually develop in this society. While social norms are rooted in customs and traditions, I argue, they are also consistently changing and morphing to reflect the population of individuals which make up the society and their personal beliefs influence and reflect the collective. To include concepts related to social norms in studying the adoption decision of the solar oven, this work measures beliefs of individuals related to destiny versus personal will, trust, and inter-household bargaining power. In addition, this research measures whether peer effects affect adoption of the solar oven, which are discussed at length in the body of this paper and hence not repeated here. Social norms and social capital are related. Social capital is about the value of social networks. A growing body of economics research suggests that social capital influences a wide range of significant economic and political phenomena. For example, Arrow (1972) and Fukuyama (1995) believe that the level of trust in a society strongly predicts its economic success.

The study measures the opinions of women on whether they believe their health is controlled by destiny or by their own personal will. Our sample- 99.99% Muslim- may well be influenced by the belief that Allah controls one's destiny.[1] To better understand whether individual's beliefs of pro-destiny or pro-free will affect the usage of the solar oven, we

[1] Only one woman in the treatment group self-identified as Christian, while all other self-identified as Muslim.

measure women’s opinions about their control over their health and their children’s health and use this as a proxy to measure individual belief about control over destiny. The first social norm included in the analysis is whether women believe they have control over their own health and/or a wider control over their fate. This is an important follow-up to the previous section on information and particularly even if women understand that breathing in smoke from the cook fire is bad for their health, if they believe that their fate and that of their children is completely out of their own hands, it seems unlikely they will use the smokeless solar oven as an alternative to the smoky traditional cook fire. To measure the woman's believe and particularly that of her control over her and her own children's health there are three questions which pertain to this measure on the one month follow-up survey. We ask women in our sample using the five point response outlined in the information on smoke from the cook fire above whether they agreed or disagreed with the following questions. The first statement is: "I have the ability to improve my children's health." The second statement is: "A person gets sick because of evil spirits." And the third statement is: "The health of my children does not depend on my action but on our fate." The responses from the three variables are all coded to correspond with the lowest value equivalent to belief that the fate of her children and that of her own health are outside her hands. The highest value represents women’s belief that they have control over the health outcomes for herself and her children. The three questions are summed to generate the aggregate variable. A positive correlation between solar oven usage and the belief that women have control over the health of their children and themselves indicates with a 1% increase in solar oven usage is positively associated with a 1% increase in women's believe that she has control over her children's and her own health. A negative correlation signifies an increase in solar oven use is correlated with an increase in belief that her and her children's health is out of her hands. Out of the highest score of 14, the average score is 7 for the group (a median of 6.8) indicating a wide spread of beliefs in destiny versus free will.

The next step is to generalize the social norm variable above to include a wider variable to represent the woman's belief of her control over her own fate versus the role of destiny beyond the realm of health. To do this I include one further question from the six month follow-up survey which asks the women to agree or disagree with the following statement: "I can always resolve difficult problems if I make large efforts." The question is coded as above with the Control over Health variable and the four questions are summed to generate the 'Control over Fate' variable. If a positive correlation is observed with solar oven usage, then solar oven usage increases with believe that women have control over their own destiny. If a negative correlation exists then as solar oven usage increases women's belief of her own control over her destiny decreases. The results are similar for the variable control over health as this control over fate is based on a subset of the control over health questions and out of a total score of 16 the mean (median) is 8.1 (8).

The second social norm our study measures is whether women believe that fuel collection and the costs of fuel for the household are a burden. To do so from the one month follow-up survey we ask women to agree or disagree with three different phrases using the five point response scale outlined above. The first phrase is: "I enjoy the time I spend gathering fuel." The second is: "I wish gathering fuel took less time for me." The third phrase is: "My family spends too much money on fuel." The three questions are coded such that 5 represents fuel or collecting fuel is a burden, while 1 represents fuel or collecting fuel is not a burden, and the intermediate values are follow between these two extreme positions. The three questions are summed into the belief 'Fuel is a Burden'. A positive correlation between solar stove usage and this variable would indicate as household solar oven usage increases, households' belief that purchasing fuel or collecting fuel is a burden also increases. The reverse is true if there is a negative correlation. Given the highest possible score of the three combined questions is 15, indicating that fuel and the collection of fuel is a burden for all three questions, the mean is 12.11. This indicates a high overall belief that the purchasing of fuel and the collection of fuel is above average believed to be burdensome.

The third social norm we look at is that of trust. These questions, inspired from Glaeser, Laibson, Scheinkman, and Soutter (2004) work, probe at the levels of trust woman has of others. The three questions used all follow from the one month follow-up survey and the first question is: "Generally speaking, would you say that most people can be trusted or that you can't be too careful in dealing with people?" The options for the response are: 1).People can be trusted; 2). You cannot be too careful in dealing with people. The second question is true or false, "You can't trust strangers anymore". The third question is the following true or false, "When dealing with extended family, one is better off using caution before trusting them." All the questions are coded such that more trusting is given a higher score and less trusting is given the lower score. The three questions are summed together and there is then a positive correlation between solar oven usage and trust and a negative correlation between solar oven usage and lack of trust. Trust in our sample has an average mean of 4.04 (median of 4) for an average of 8 level scale in total.

For the social norm of trust a second measure is included- the trust women have in Tostan, the local NGO partner. To measure this, on the six month follow-up survey we asked women enrolled in the program to answer using the five point response: 1). their confidence in Tostan, 2). their confidence in the focal point person who works for Tostan, and 3). whether Tostan always has their best interest at heart. Because nearly all participants expressed a very high level of trust in Tostan I make the assumption that there is a large politeness factor and social pressure factor as Tostan members organized the project and are present in the village on the day of the survey. Further, some of the CEGA team surveyors are past employees of Tostan. To eliminate bias, I assume that any response that is not "Strongly Agree with this statement" is some shadow of doubt or lack of confidence. This is a big assumption and I generate Low level of trust equal to 2-5 for each of the three questions above. In so doing, absolute trust for all three questions is equal to an score of 3. The mean of the variable is 3.28 indicating a very high level of trust in our NGO partner Tostan.

Finally, to measure intra-household bargaining power dummy variables are included based on women's response at the baseline survey "Who makes decisions about purchasing major household items?" The responses include grandparents (2%), respondent (11%), respondent and husband (9%), husband (55%), other (17%), first wife (2%), or father/mother (4%).

**Overconfidence**

The study of overconfidence which originated in the psychology literature has migrated into the economics and finance literature, taking its place in the growing list of irrational aspects of human attitudes and behavior. Camerer 1997 asserts that "dozens of studies show that people are generally overconfident about their skills." Debondt and Thaler 1995 assert that "perhaps the most robust finding in the psychology of judgment is that people are overconfident." This research includes overconfidence as a potential behavioral economics phenomenon that affects women's actual usage of solar ovens. One hypothesis is women who tend to be overconfident may expect to use their solar ovens more than they actually do.

To measure overconfidence in our sample in each of the three surveys we ask women about their ability to read in the local language. In the baseline survey we ask women to answer yes or no if they can read in the local language. A woman is deemed overconfident if she claims to be able to read in the baseline survey but cannot read the sentence in the one month survey, "The Chief of my village lives there." A woman is deemed extremely overconfident if the previous scenario is true and then at the six month follow-up survey she claims to be able to read again. In the one month follow-up survey we ask women if they can read the following sentence in the local language:"The Chief of my village lives there." The enumerator then evaluates whether the woman read all, or part of the sentence, read one word, or could not read it at all. Then at the six month follow-up we again ask women if they could read in the local language. The variable for 'Overconfident' is then constructed such that the biggest value 3 is equivalent to extremely overconfident and represents women who respond that they could read in the baseline survey, then were observed to not be able to read at the one month follow-up survey, and then they claim again to be able to read in the six-month follow-up. Overconfident is equal to 2 if a woman claimed to be able to read on the baseline survey but at the one month follow-up could not read. Overconfident is equal to 0 if her view of herself is consistent with others, or that if she claims to read, she actually does read. The mean of overconfident is 0.52 and the median is 0, indicating most of our population does not exhibit overconfidence. Again, this measure is not complete, but one possible indication of overconfidence in the sample.

**Regression Analysis**

Each of the several questions to measure these phenomena was developed by the author and the CEGA team, vetted by peer economists, and tested in the field for legitimacy. Below I explain how each behavioral bias variable is constructed. As is common practice questions are randomly selected to be positively and negatively framed.[2] In this way we check for consistency of beliefs and ensure that women understood the question. To generate variables we reverse coded some responses to be consistent with responses to other questions in the category. Finally, as is common practice, we imputed to the mean missing values for the x variables to preserve sample size and included a dummy for missing values for each x variable imputed to the mean.

Further, as many concepts measured may be related to wealth levels and liquidity constrained levels of households, household's wealth level and liquidity constrained are included in all analysis. For baseline characteristics and control variables I include village

[2] One example of the same question first framed positively than framed negative is the following. Over the three waves of our survey women are asked to both agree or disagree with the Statement 1). I have the ability to improve my children's health as well as Statement 2). A person gets sick because of the evil spirits.

fixed effects or a dummy for each of the 20 villages, age cohorts of woman inscribed in the program, and household decision maker or dummy variables for different responses to who in the household makes decisions about purchasing large household items. Additional control variables include 1). The baseline number of people for whom women prepared lunch; 2). The baseline number of people for whom women prepared lunch centered and squared; 3). Baseline kilograms of wood per person used to prepare lunch meal; 4). Time spent (minutes) by all household members collecting fuel per collection period or the number of days the fuel lasts; 5). Dummy variable if respondent is unemployed; 6). SUM month one percent of days solar oven was used; and 7). Wealth proxy through ownership of radio, gas stove, cell phone, and television.

To determine whether a woman is part of a household which is liquidity constrained questions on both the one and six month follow-up surveys, questions are asked pertaining to the borrowing behavior of the household including: largest loan ever taken, the households' current debts and whether the woman is a member of a rotating savings and credit organization. To construct the x variable 'Liquidity Constrained' I use the response to the same question on both surveys of the quantity the household has borrowed in the last two weeks. The liquidity constrained variable was constructed such that 0 is equal to women had no outstanding debts on both surveys in the last two weeks. Any positive number is a result of the sum of both outstanding debts at the one month and six month follow-up. The mean is 11,240F CFA (about $25) while the median is 1,900F CFA (about $4) borrowed by households on average in both periods. This variable has been top coded[3] to limit the mean being driven by outliers. To interpret the variable in relation to the y variable- % of days solar stove used at the six month of ownership for treatments- a positive correlation or every 1% increase of solar oven usage increase indicates a corresponding increase in amount borrowed in last two weeks. Thus, a positive correlation means more usage of the solar oven is correlated with households' corresponding increase in level of liquidity constrained. Inversely, a negative correlation can be interpreted as usage of solar ovens increase, the amount borrowed in the final two surveys by households decrease and thus usage is not correlated with being liquidity constrained. The liquidity constrained variable as well as wealth and education, as well as village fixed effects are included as control variables in all the OLS regressions.

Using OLS regression analysis outlined below in Model 9, each behavioral economics phenomenon outlined below and in Figure 2 is run alone, then the concepts are run jointly.

$$woman's\ avg.solar\ stove\ usage_{i,t=6\ mo.} = \alpha_{i,t} + Beh\ Econ\ Concept_i + \varepsilon_i \quad \text{(Model 9)}$$

This is done to ensure results are consistent in both cases and one behavioral variable is not correlated with another generating spurious regression results. I find that results are consistent for all the behavioral concepts whether run alone or jointly. Thus, the main results are outlined in Annex 2: Table 2. Finally, the set of regressions is run substituting the y variable from women's solar stove usage over the six month period to women's solar stove usage over the one month period. Results are not significant and thus not included.

[3] The top 5% of the sample is brought down to the 95% level

| Figure 1: Summary of Individual Behavioral Economic Variables by Category |
|---|
| $Time\ Concepts_i = \begin{Bmatrix} Liquidity\ Constrained & Risk\ averse\ or\ loving \\ Present\ bias\ or\ forward\ thinking & Age\ cohorts \end{Bmatrix}$ |
| $Information_i = \begin{Bmatrix} Information\ on\ breathing\ in\ smoke\ is\ bad\ for\ health \\ Early\ (Relative) Adopter\ of\ Technology \end{Bmatrix}$ |
| $Social\ norms\ or\ personal\ beliefs_i = \begin{Bmatrix} Destiny\ vs.peronsal\ will & trust \\ fuel\ is\ a\ burden & trust\ in\ Tostan \\ intrahousehold\ bargaining\ power & peer\ effects \end{Bmatrix}$ |
| $Overconfidence_i = \{overconfidence\}$ |

The following kitchen sink regression analysis can be written in shorthand below where the household characteristics are described at the beginning of this section, and the breakdown of the four behavioral economics concepts into individual variables is shown in Figure 1 above.

$$y\ 6\ mo._i = \alpha_i + \beta_{1\ldots10} Household\ Char_i + \beta_{1\ldots20} Village\ dummies_{1\ldots20} + B_{1\ldots4} Time_i + B_{1-2} Information_i + B_{1-4} Social\ Norms\ or\ Personal\ Beliefs_i + \beta_{1-2} Overconfidence\ and\ Bargaining\ Power_{\ i} + \varepsilon_i \quad \text{Model (10)}$$

Because this is a randomized controlled trial the error term, $\varepsilon_i$, is assumed to be independently and identically distributed (iid) as measurement error has been eliminated through unbiased randomization.[4] To test the robustness of regression results, Model 1 is run for half the behavioral economics phenomenon and Model 2 includes all the behavioral economics phenomenon, except for peer effects, together. This is to demonstrate the consistency of results.

Several additional hypotheses were explored. One hypothesis that emerged was whether the solar oven required a cultural change of cooking outdoors. This supposed change was hypothesized to being a significant change for women because it required women to put out in the open the food they are eating or disclose more publicly their meals.[5] This idea rests on the premise that if you have something (and it is observed) due to Muslim faith you will be required to share with your neighbors. Thus in an attempt to avoid the social pressure to share with your neighbors scarce resources, the solar cooker which requires cooking under the tropical sun would compromise the need to cook in secret. To test this hypothesis I include data on the type of kitchen either: 1).completely enclosed or no windows (23%), 2).semi-enclosed at least one window (44%), 3).a hut with open air thatch roof but no walls (23%), or 4).completely open air (11%).[6] When I regress Models 1 and 2 including the four types of kitchens, the results are not significant and thus I do not find evidence of this hypothesis in the data.[7]

[4] For a fuller discussion and proof that this sample has been correctly randomized see Beltramo, T. and D. Levine (2010).
[5] This hypothesis was discussed at the Katholieke Universiteit Leuven LICOS seminar
[6] At the six month follow-up sub-group of women we measured Carbon Monoxide Inhalation over the lunch meal (N=367) in both the treatment and control groups our enumerators visited the kitchen of each of these women and noted the type of kitchen women had.
[7] Data is available upon request.

**Robustness Checks**

For each of the behavioral economics phenomena I ran regressions individually for each behavioral economics variable along with village fixed effects, age cohorts of woman respondent, dummy variables for household decision maker, as well as other baseline predictor variables summarized above. The rationale for first running separately each behavioral economics X variable is to ensure that effects remain constant when I add all the variables in together. In short some of the behavioral economics X variables may be correlated, leading to endogenous regression specification. To avoid this, I run each of the behavioral economics phenomenon alone and then I run them all together. I find there are no substantive changes in significance when I run the regressions individually than when I run them all together. Thus, I do not include the regression runs for each individual variable but include the outcomes from the regressions modeled below where all the behavioral economics phenomena are run in the same regression.[8] This leads me to believe that endogenous specification is not driving results

All of the behavioral economics phenomena are individual beliefs that ideally are captured by the same woman each survey. At the baseline and the one-month follow-up there was no formal space for enumerators to record if the woman was represented by another household member. We find for the treatment group in the baseline 35 of the 488 people are represented. At the one-month follow-up we record 36 of the 488 women are represented. On the third and final six-month follow-up survey we include a formal question on the survey to indicate if the household is represented. On the six-month follow-up survey we find 227 of the 488 women are represented. This is more than six times the quantity of women found to be represented on either the baseline or the one month follow-up. While it could be that there was a significant higher level of representation at the six month follow-up due to a higher economic period, this seems unlikely. It is more reasonable to believe that we do not capture all the households who are represented at both the baseline and one month follow-up because of measurement error. Despite this probable measurement error, I run the regressions again for only the sub-sample of the treatments that we have identified as not being represented on any of the three surveys. The results for this sub-sample are consistent with that of the wider sample and importantly none of the behavioral economics phenomena become significant that previously were not. Notably the problem of representation does not apply to observed solar oven usage by SUMs and observed solar oven usage by peers as the SUMs were installed on the lids of the stoves by the CEGA research team, and thus avoid the problem of representation.

Finally, as an alternative measure of the y variable solar stove usage, I run the same regression results using Kilograms of Wood Used Daily per person at the six month follow-up as an alternative y variable.

**Impacts**

Models 1 and 2 represented in Annex 2: Table 2 show the effects of all behavioral economics phenomena on solar stove usage, except for peer effects. The y variable is solar stove usage at the six month time period. In both models 1 and 2, the village dummy

[8] These regression runs are available by request.

variables are consistently significant at the 99% level indicating solar oven usage varies significantly by village. It could be that village level fixed effects represent social properties not measured, which increase stove usage. Regardless of the interpretation, women's solar stove usage is interdependent on the characteristics associated with the village where she lives. A second control variable which is consistently significant is SUMs usage over month one. Usage is significant for both Models 1 and 2 at the 99% level with a coefficient of 0.25. This coefficient can be interpreted that with every 1% increase in solar stove usage over the 6 month period this was significantly correlated with a quarter of a percentage increase in the one month period. This result indicates path dependence in behavior or particularly usage at the one month level is correlated at the 99% level with usage at the six month level. This could indicate either that behavior is quick forming in our population or it is pre-determined by other factors. In particular, there was a significant amount of solar stove training that took place between the time the one month SUM data was collected and the six month SUM data at the village level. This intensive training on how to use the solar oven seems qualitatively to be correlated with solar stove usage as solar stove usage more than doubled between the two periods. To understand whether the number of total trainings a woman has attended since her purchase of the stove measured on the six month follow is an important factor, I include this variable in an additional regression run. However, number of solar stoves trainings reported at the six month follow-up is not a statistically significant result. Thus, women's usage of the oven cannot be quantitatively attributed to the number of trainings she attends. This result is surprising since we assumed that the more than doubling of solar oven usage was a result of the intensive village level training model of our NGO partner Tostan. Thus, women's stove usage at the six month period is positive and significantly correlated with her usage at the one month period and is not correlated with the number of trainings she attended over the six months she owned the stove. The mystery of early path behavior, or why some women use their solar ovens immediately, may be correlated with individual qualities not related to number of trainings she attends. Indeed, one alternative explanation emerges from our empirical work- solar stove usage seems to be much more related to peer's usage.

Setting aside peer effects, the only behavioral economics phenomenon which is significant is the age cohort 21-30 years of age. This age group which represents 31% of the total women in the treatment group is consistently significant at the 95% level for both Model 1 and 2. The coefficient for the age group 21-30 years of age is positive. This could be interpreted to mean that the women aged 21-30 years of age are significantly more likely to adopt the solar oven than other age groups.

In models 3 and 4 the y variable is the kilograms of wood used daily per person. Average wood kilograms per person used daily is a proxy for solar stove usage and the results are run only for the treatment households. In these two regressions, village fixed effects remain significant at the 95% level. Baseline kilograms of wood used per person is significant in both models at the 95% level and can be interpreted as a positive correlation between baseline fuel usage and that at the six month follow-up by the treatment households. Thus, as before with the solar oven usage, wood use has a similar aspect of path dependence. Thus households who use more wood at the baseline survey per person to cook with are consistent and at the six month follow-up use similarly more wood per person. This phenomenon underlines the importance of learned behavior and the difficulty related to changing behavior patterns. Past actions affect the present and future actions tremendously. Finally, again the time concept of age is significant and positive at the 95% level. This time when the y variable is wood use, the ages 31-40 seem to use significantly more wood per person.

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Ciclo:22

Titolo della tesi : Tre Temi su Microeconomia Applicato

**Riassunto:** La tesi porta un contributo allo studio delle subdiscipline dell'economia includendo il Comportamento, lo Sviluppo ed il Commercio internazionale, ed in una certa misura anche l'Economia Ambientale, Energia, e di Salute. Un filo comune tra i tre papers è l'uso di misure quantitative, invece di proxies, per quantificare le conseguenze o i principali risultati. Nel primo studio della tesi gli autori quantificano i risultati principali in termini di riduzione di uso di combustibile e di inalazione di monossidio di carbonio derivanti dall'utilizzo di forni fotovoltaici mediante quantità osservate direttamente. Nella seconda parte della tesi l'autore usa un nuovo modello per misurare i costi al commercio internazionale direttamente dai flussi di commerciali osservati relativamente a 26 nazioni. Il modello misura i costi commerciali bilaterali senza dover formulare alcuna assunzione riguardo la funzione ti tali costi e permette di ottenere una misura completa dei costi, sia diretti che indiretti, connessi all'introduzione di un bene all'interno di un mercato. Il terzo paper valuta invece l'influenza del gruppo (*peer* effect) sull'impiego del forno fotovoltaico usando una rete sociale osservata fra le donne e le loro amiche. L'autore usa i dati di utilizzo del forno fotovoltaico che sono stati monitorati attraverso un microchip ed ha la possibilità di misurare gli effetti della rete amicale regredendo l'utilizzo del forno fotovoltaico delle donne appartenenti al gruppo di trattamento rispetto all'utilizzo effettuato dalle corrispondenti amiche "forti" (legame di amicizia simmetrico) e "deboli" (legame di amicizia asimmetrico) appartenenti anch'esse al gruppo di trattamento. In ognuno dei tre lavori, i dati diretti relativi all'impiego del forno fotovoltaico, ai costi al commercio internazionale e alla rete di informazione permettono all'autore di contribuire alla recente letteratura, di dimensioni contenute ma in crescita, che impiega dati a livello micro per studiare quantitativamente un fenomeno di natura economica.

Titolo della tesi: Three Essays on Applied Microeconomics

**Abstract:** The dissertation contributes to the sub-disciplines of economics including Behavioral, Development and International Trade, and to a lesser extent, Environmental, Energy, and Health Economics. A common thread among all three empirical papers is the use of quantitative measures, instead of proxies, to quantify impacts or results. In the first dissertation paper, the authors quantify the main outcome indicators- wood usage, carbon monoxide inhalation, and solar oven usage with actual observed quantities. In the second paper the author uses a new trade costs model which derives international trade costs directly from observed trade flows for 26 nations. The model measures bilateral trade costs without making any assumption on the trade costs function and allows for economists to measure all the trade costs associated -both indirect and direct- with bringing a good to market. The third paper is able to evaluate peer effects on solar oven adoption by using an observed social network between women and their friends. The author uses observed solar oven usage data, measured by a microchip, and is able to measure peer effects by regressing the treatment group's solar stove usage on that of the solar stove usage of her "Strong" and "Weak" friends who are in the treatment group. In each of the three works, the direct data on solar stove outcome indicators, international trade costs, and information networks allows the author to contribute to the recent small, but growing literature using observed micro-data to measure quantitatively a natural phenomenon in economics.

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